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Design and Real-Time Implementation of Robust Permanent Magnet Synchronous Motor Control System

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ABSTRACT

This article examines the design of an Interior Permanent Magnet Synchronous Motor (IPMSM) control system, beginning with a study of IPMSM structure and mathematical modeling, which is vital for accurate control system. Control strategies, particularly vector control, and drive method like space vector modulation, are explored and designed. The core contribution is a maximum torque per ampere-based controller for the IPMSM, designed to optimize torque and efficiency. The article validates the controller's performance through MATLAB Simulink simulations and real time hardware in the loop (HIL) experiments using the GatherTech HIL, bridging simulation and real-world testing. Simulation results for both non-maximum torque per ampere (N-MTPA) and maximum torque per ampere (MTPA) strategies are analyzed, demonstrating the proposed controller's performance. Results show improved torque and speed response compared to N-MTPA strategies, indicating faster acceleration, robust stabilization and enhanced the efficiency. This research provides a framework for high-performance IPMSM controllers.

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1. Introduction

The relentless drive towards electrification across diverse sectors, from transportation to industrial automation, has solidified the pivotal role of Interior Permanent Magnet Synchronous Motors (IPMSMs) [1]. Their superior power density, efficiency, and dynamic performance make them ideal for applications demanding high-performance drives, such as electric vehicles (EVs) [2], renewable energy systems [3], advanced robotics [4], aerospace applications [5], and high-speed machinery [6]. A key factor in realizing the full potential of IPMSMs is the implementation of advanced drive systems. Field-Oriented Control (FOC) remains a foundational technique, enabling decoupled control of torque and flux [7]. However, recent research has focused on enhancing FOC to address the specific challenges posed by IPMSMs, particularly in high-performance applications. One significant area of focus is the development of advanced control strategies to improve dynamic performance and efficiency. Model Predictive Control (MPC) has gained prominence due to its ability to optimize performance based on predicted system behavior [8]. Researchers are exploring novel MPC formulations that incorporate constraints and optimize for multiple objectives, such as torque ripple minimization and efficiency maximization [9], as well as reduced switching losses [10]. Advanced sliding mode control methods are also being investigated for robust performance [11]. Furthermore, the integration of wide bandgap (WBG) semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), has revolutionized power electronics for IPMSM drives [12]. WBG devices enable higher switching frequencies, reduced losses, and increased power density, leading to significant improvements in drive system performance [13]. The design and optimization of WBG-based inverters for IPMSMs are active areas of research [14], including thermal management considerations [15]. Another crucial area is the development of robust control strategies that can handle parameter variations and uncertainties. Adaptive control and online parameter estimation techniques are being explored to ensure stable and high-performance operation under varying operating conditions [16]. Machine learning (ML) techniques, particularly deep learning, are also being applied to improve the robustness and adaptability of IPMSM drives [17]. ML-based approaches are used for parameter estimation, fault diagnosis, and control optimization [18], and also for predictive maintenance [19]. The improvement of sensorless control is also a topic of many research papers. The reduction of system costs, and the increase of reliability, are major drivers for sensorless control. Novel observer-based sensorless control algorithms are being developed to estimate rotor position and speed accurately, even at low speeds [20]. The use of high frequency injection methods is also being studied [21], as well as methods that are robust to magnetic saturation [22]. Fault-tolerant control is becoming increasingly important for safety-critical applications. Research is focusing on developing fault detection and isolation (FDI) algorithms and reconfiguration strategies to ensure continued operation in the event of component failures [23], including the study of open-circuit faults [24]. The optimization of IPMSM drives for specific applications, such as EVs, is also a key research area. Research is focused on improving the performance of IPMSM drives in EVs, including the development of advanced control strategies for traction applications, battery management systems, and thermal management [25]. Also, research is focusing on the reduction of acoustic noise from the IPMSM drive systems [26]. Additionally, the use of advanced magnetic materials, and new motor topologies, are being researched to increase the power density and efficiency of IPMSM drives [27]. Research is also being conducted into the impact of rare earth element reduction within IPMSM's [28]. The development of advanced magnetic field observers is also a current research topic [29].

This paper aims to contribute to the advancement of IPMSM drive technology by investigating and implementing a novel control strategy that addresses the aforementioned challenges, focusing on improved performance and robustness in high-performance applications. This paper aims to contribute to the advancement of IPMSM drive technology by investigating and implementing a novel control strategy that addresses the aforementioned challenges, focusing on improved robustness and efficiency under varying operating conditions. The article validates the controller’s performance through MATLAB Simulink simulations and real-time hardware-in-the-loop experiments using the GatherTech HIL. Simulation results for both non- maximum torque per ampere **(**MTPA) and MTPA strategies are analyzed, demonstrating the proposed controller's performance.

2. Interior Permanent Magnet Synchronous Motor Mathematical Model

This part should be described in detail the ways or methods, materials, devices necessary to solve the research problems. They should be described with sufficient detail so that other researchers can replicate and build on published results. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited. The approach might be by theoretical developing, empirical researching, surveying, etc. Applied approach should be explained the advantages and, if possible, be compared with previous studies. In the case of theoretical developing research, it should be present theoretical bases to find out solution to research problems. The motor investigated is ADLEEPOWER MA2-3700M Match servo Motor with the specifications listed in Table 1.

The voltage and torque equations in d-q rotating reference frame are given as:

$$\begin{cases} v_d = R_s i_d + L_d \dfrac{d}{dt} i_d - \omega_e L_q i_q \\ v_q = R_s i_q + L_q \dfrac{d}{dt} i_q + \omega_e \left(L_d i_d + \lambda_m \right) \end{cases} \tag{1}$$

$$T_e = \frac{3}{2} P \left[\lambda_m i_q + \left(L_d - L_q \right) i_d i_q \right] \tag{2}$$

Where i_d and i_q represents d-q currents and d-q inductances, respectively; stator’s phase winding resistance R_s; maximum flux linkage of each phase produced only by the PM λ_m; constant angular frequency ω_e.

For the sake of design and control, certain current and voltage limits must be set. These limits are core for defining other operating limits. Surpassing such limits exposes the PMSM to threats such as overheating of the windings, tripping of the protective components, discontinuation of industrial processes related to PMSM, etc.

The stator current in terms of d-q reference frame currents must be smaller than the stator current limit, which is also the rated current of the PMSM:

$$i_s = \sqrt{i_d^2 + i_q^2} \le i_{sL} \tag{3}$$

Table 1. *ADLEEPOWER MA2-3700M specifications*

PARAMETER	Value	Unit
Rated voltage	220	V
Rated current	18.5	A
Rated Torque	11.78	N.m
Rated Speed	3000	rpm
d-axis inductance	0.00076	H
q-axis inductance	0.00161	H
Stator resistance	0.175	Ω
Flux linkage	0.0864	Wb

3. Controller Design for Ipmsm

A speed controller implementing vector control for an IPMSM is proposed with optimum torque operation. The control system consists of a vector controller and a drive system. The details are discussed in the following sub-sections.

3.1. Control system for IPMSM

The main model depicted in Figure 1 consists of a speed controller, current controllers and Space Vector Modulation (SVM) pulse generator, a 2-level inverter and the IPMSM model.

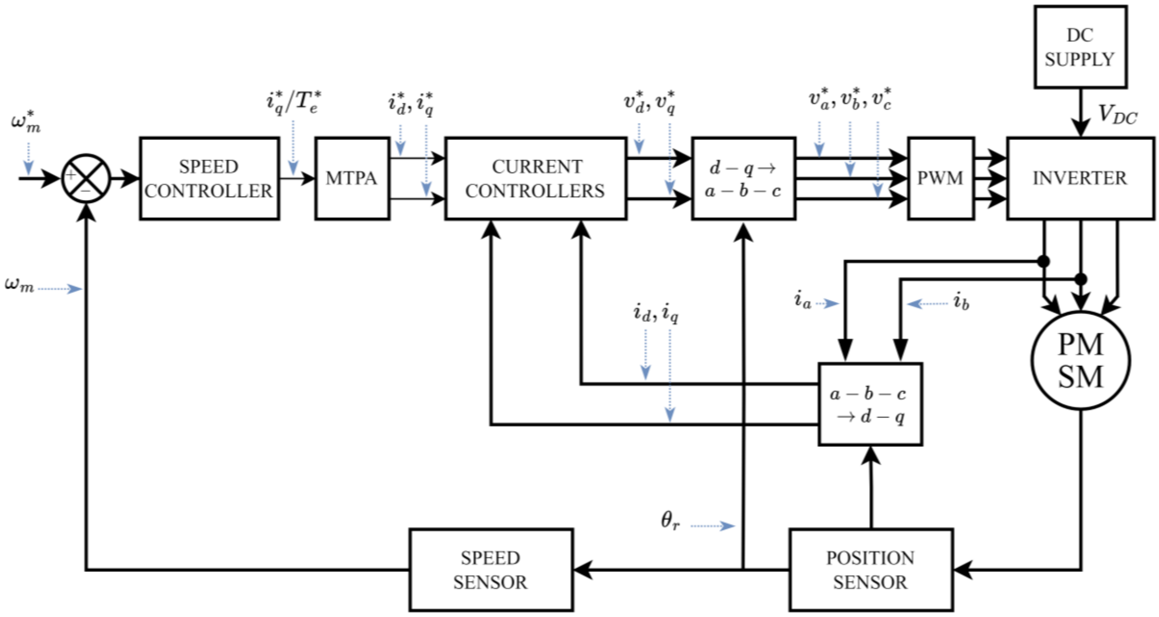


Figure 1. *Control system model.*

The speed is controlled by the PID controller. Although non-linear and machine-learning-based control methods were considered, the selection of a PID controller was predicated on its balance between performance and practical implementation, given the substantial computational complexity and hardware challenges associated with advanced techniques.

In such cases where the motor needs to generate a high torque, it is preferable to achieve the highest torque possible for each unit of stator current to take full advantage of the machine's torque production capability. This operation of maximum torque per ampere (MTPA) is the same as achieving a particular torque with the least amount of current. As a result, although high torque production is not required from the machine, it is still beneficial to implement MTPA to minimize losses in motor stator copper and switching losses in the electronics. The d-axis current command is calculated from the the q-axis current command and inductances. This function is given as [30]:

$$i_d^* = \frac{\lambda_m - \sqrt{\lambda_m^2 + 4 i_q^{*2} \left(L_q - L_d\right)^2}}{2\left(L_q - L_d\right)} \tag{4}$$

The system input current signals i_d^*, i_q^* after calculating through MTPA block. These signals from the d-q reference frame are then transformed into phase reference frame signals i_a^*, i_b^*, i_c^* with the use of an encoder-detected rotor position signal θ_r. Meanwhile, the currents i_a, i_b are measured by using sensors and fed back into the closed loop. The real currents are compared to the commanding currents from the speed controller to create error input to the phase current controller. This current controller gets the current difference and outputs the voltage commands v_a^*, v_b^*, v_c^* to the PWM-generating inverter. This inverter accordingly provides the supply voltage for the PMSM for it to operate at the right load-dependent torque and speed.

3.2. Drive system for IPMSM

Due to lower voltage optimization in SPWM, SVM rises as an alternative for driving PMSMs. In order to generate output voltages using SVM, there are specific steps that needs to be done, as depicted in Figure 2. These steps correspond to those in Figure 1. Further explanation continues below.

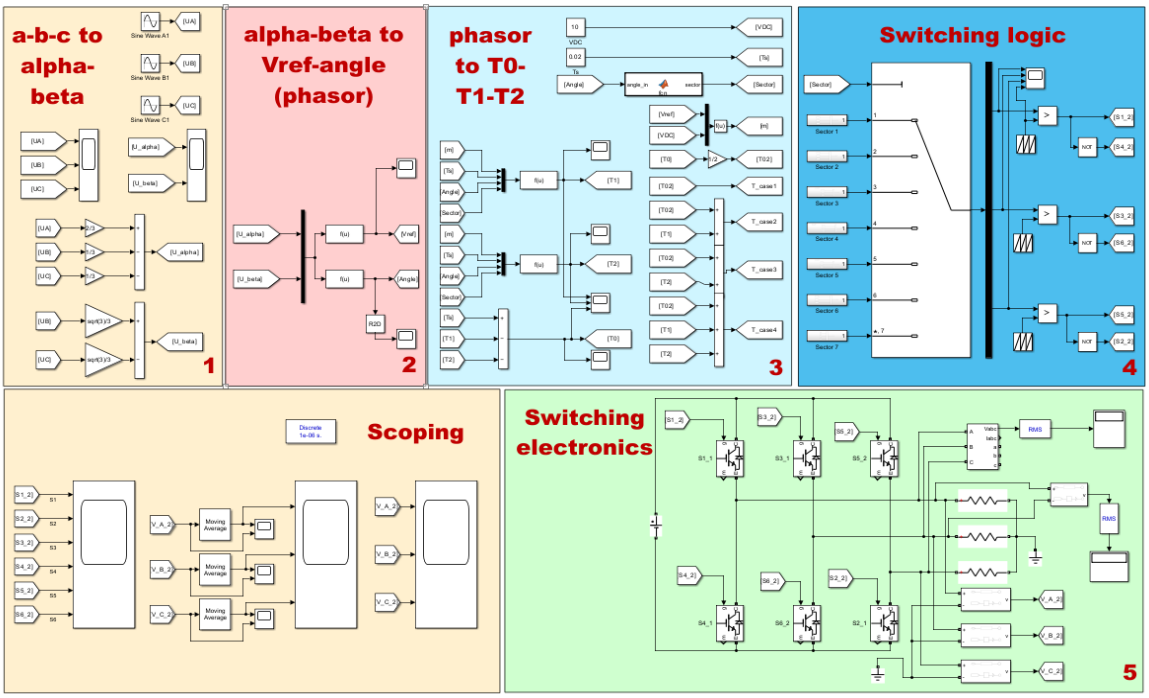


Figure 2. *Drive system MATLAB implementation*

Firstly, conversion from phase variable reference frame into stationary reference frame is needed. Secondly, from the stationary reference frame, the phasor values of the reference voltage and its angle is derived. Thirdly, from those values, the angle is then used to determine the current section the vector is in. Then, the switching time for the switching electronics are calculated using the below equations.

$$T_1 = \frac{2}{\sqrt{3}} m T_S \sin\left(\frac{\pi}{3} - \theta + \frac{(n-1)\pi}{3}\right) \tag{5}$$

$$T_2 = \frac{2}{\sqrt{3}} m T_S \sin\left(\theta - \frac{(n-1)\pi}{3}\right) \tag{6}$$

$$T_0 = T_S - \left(T_a + T_b\right) \tag{7}$$

Fourthly, based on the section the vector is in, the switching logic section outputs the switching signal with the right amount of ON-state switching time to the switching electronics [31]. Then, the system output voltages to drive the PMSM. SVM utilizes the DC Voltage source around 10% more. Furthermore, the SVM experience less total harmonic distortion.

3.3. Microcontroller implementation of control system.

This experiment is conducted in discrete time as the microcontroller processing capability is finite, through expression of sampling rate. The discrete implementation of PID is given as:

$$u(z) = K_{P\_PID} + \frac{K_{I\_PID} T_S z}{z-1} + \frac{K_{D\_PID}(z-1)}{(1+T_S)z-1} \tag{8}$$

The used HIL and microcontroller are Gathertech MR2 PRO and C2000 Launchpad XL TMS320F-283790, respectively. The experiment setup is presented in Figure 3.

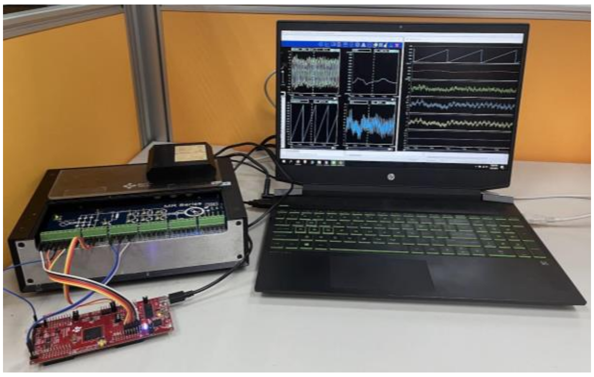


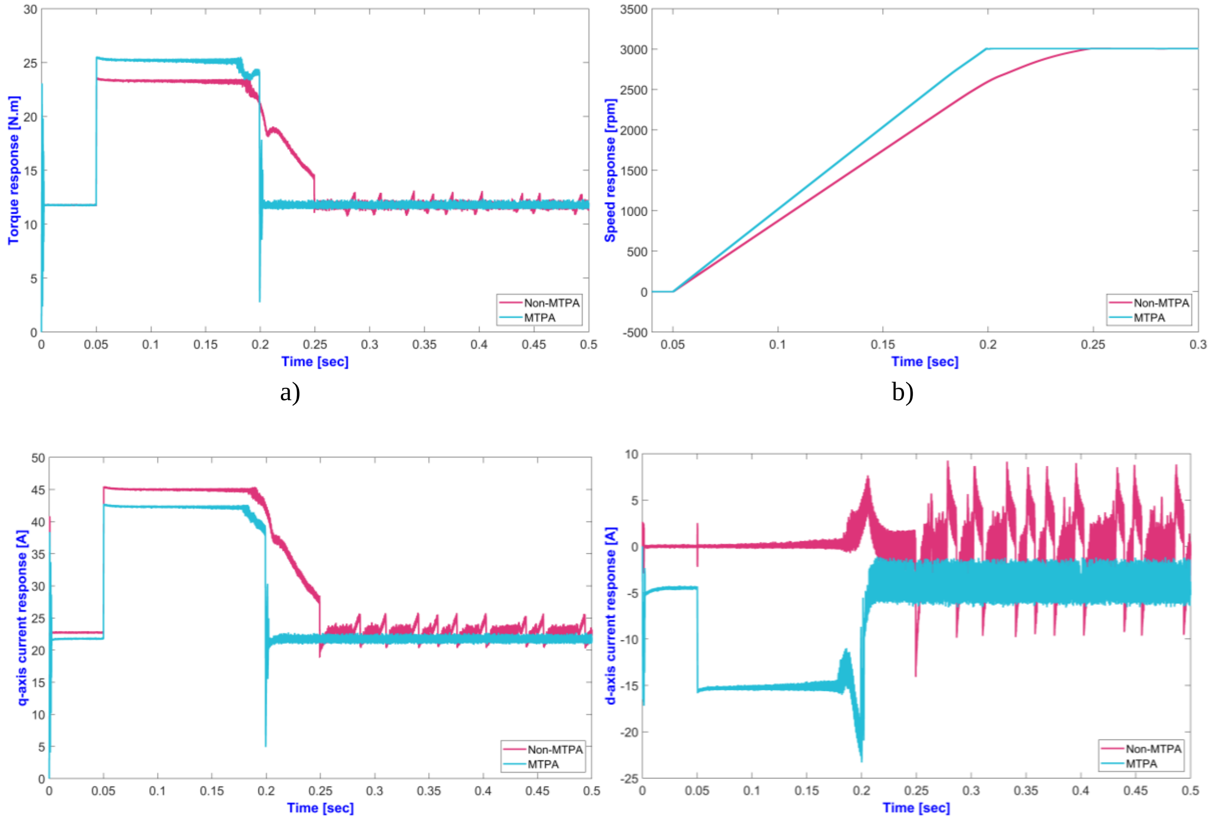
Figure 3. *HIL experiment setup.*

4. Simulation Results and Discussion

The integration of controller hardware with auxiliary system components, including power supplies, sensors, and communication networks, presents significant challenges. Comprehensive system-level validation is imperative to guarantee operational integrity across diverse operating conditions. This study initially validates the controller through software simulation within the MATLAB Simulink environment, followed by rigorous testing within the Gathertech HIL simulation platform.

4.1. MATLAB Simulink Simulation

Firstly, a basic controller of PID speed controller with $I_d^* = 0$ will be implemented, namely Non-MTPA. Then the proposed controller, the MTPA approach will be implemented to be compared with the Non-MTPA. The following figures present the comparison of torque (Figure 4a), speed (Figure 4b), and dq-axis currents (Figure 4c and Figure 4d), respectively, at full rated speed at 3000rpm and full rated torque at 11.78Nm. The torque load for all cases is introduced at t=0.05s.



a) b)

c) d)

Figure 4. *MATLAB d-axis current response comparison. a) torque comparison, b) speed comparison, c) q-axis current comparison, d) d-axis current comparison.*

The torque response of MTPA converges to steady-state faster and ripples at steady-state way less than Non-MTPA. The tuned PID speed controller proves its superiority in responses. When introduced to load disturbance at 0.05s, it reaches a steady state with almost no oscillation.

The following tables present the numerical and important comparative values of the MTPA and Non-MTPA controllers. Table 2 presents how much faster the proposed controller reaches the settling state.

Table 2. *Speed response settling time comparison*

	10% Torque	50% Torque	100% Torque
10% Speed	1.23%	1.8%	3.58%
50% Speed	3.75%	5.25%	8.97%
100% Speed	7.99%	11.01%	20.04%

As shown in the table, with higher operation status, the MTPA significantly increases its responsiveness. The difference is insignificant at lower speeds and torque. At rated speed and torque, the speed response controlled by the MTPA controller reaches steady-state over 20% faster than Non-MTPA.

Table 3 presents how much lower the MTPA's stator current is compared to the Non-MTPA approach.

Table 3. *Stator current utilization at steady state comparison*

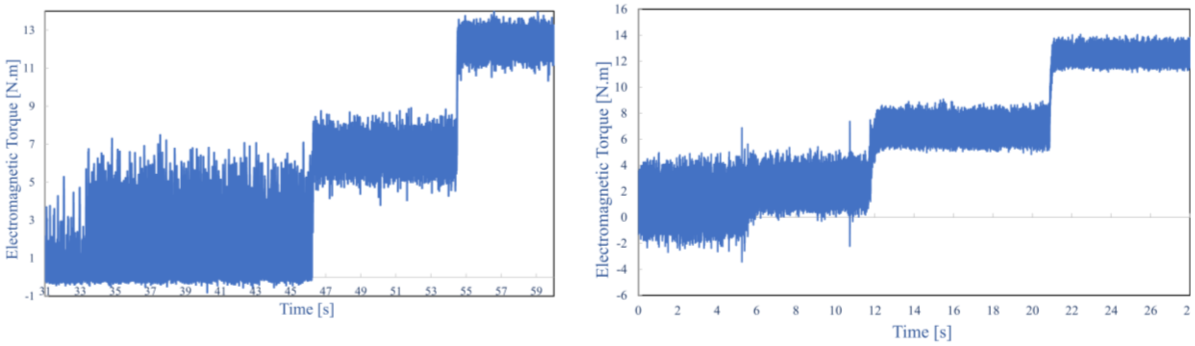
	10% Torque	50% Torque	100% Torque
10% Speed	0.01%	0.6%	2.22%
50% Speed	0.11%	0.62%	2.22%
100% Speed	0.43%	0.63%	2.44%

MTPA basically introduces a negative d-axis current to optimize the stator current. By doing this, the torque response can be better with less current used. From the above table, it can be concluded that in all speed and torque ranges, the MTPA uses less current and, therefore less power, than the Non-MTPA approach.

4.2. Hardware-in-the-loop simulation

In this experiment, the controller is set at 3000rpm speed and the torque is changed to 10%, 50%, and 100% rated torque.

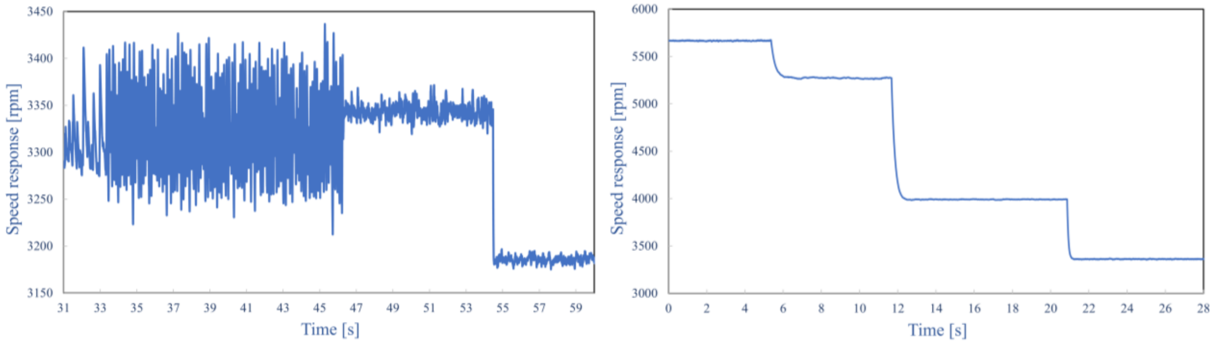
The torque response of MTPA (Figure 5a) is compared with the torque response of non-MTPA (Figure 5b). The speed response of MTPA (Figure 6a) is also compared with the non-MTPA speed response (Figure 6b). The MTPA q-axis current (Figure 7a) is then compared to the non-MTPA q-axis current (Figure 7b). Finally, the MTPA d-axis current (Figure 8a) is compared with the non-MTPA d-axis current (Figure 8b).



(a) *(b)*

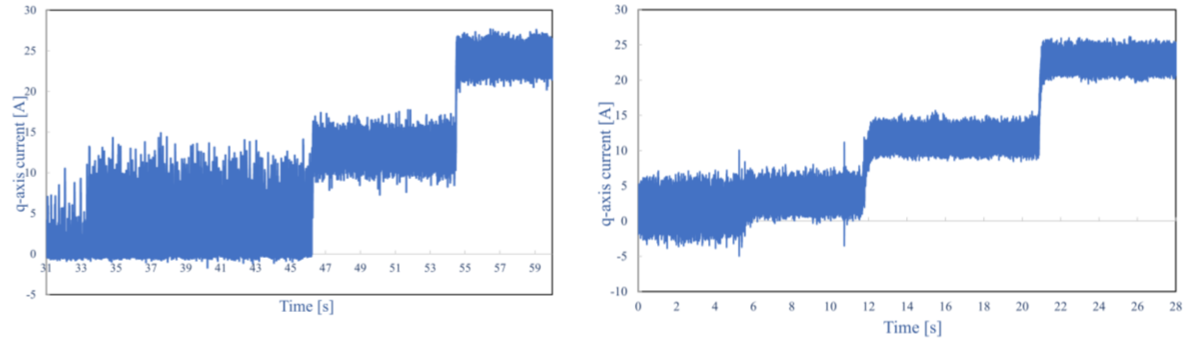
Figure 5. *HIL torque response. a) Non-MTPA, b) MTPA.*

At first, the non-MTPA signal appears to have significant fluctuations. The torque response ripples and fluctuates significantly. This shows the controller is unstable.



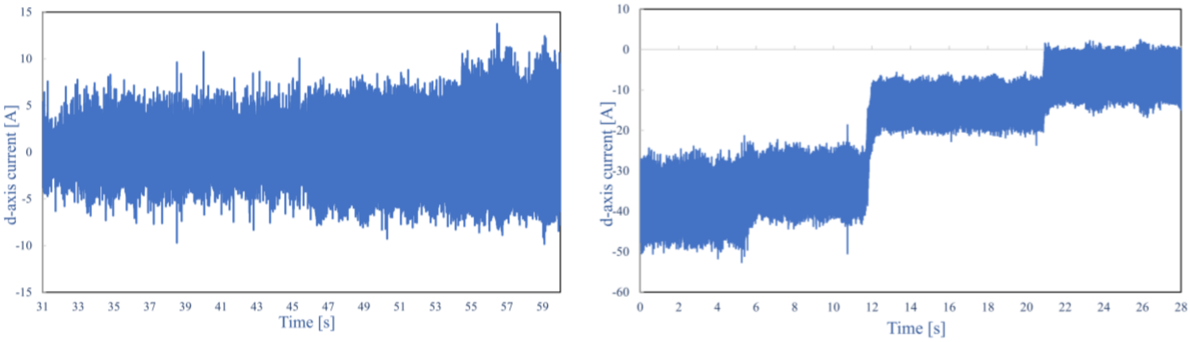
(a) *(b)*

Figure 6. *HIL speed response. a) Non-MTPA, b) MTPA.*



(a) (b)

Figure 7. *HIL q-axis current response. a) Non-MTPA, b) MTPA.*



(a) (b)

Figure 8. *HIL d-axis current response. a) Non-MTPA, b) MTPA.*

As seen from the figures, the oscillations in response to torque, speed, and current fluctuate way less than those of Non-MTPA. Through calculation and evaluation of the achieved data, the stator current of MTPA is 1.67% less than the Non-MTPA approach, which is close to software simulation. Significantly, the speed response is stable with almost no fluctuation. The d-axis current of the MTPA approach always stays below zero, this indicates that the experiment and the implementation of MTPA are valid.

Discrepancies between MATLAB and simulation results stem from the fundamental difference in their execution environments. HIL incorporates real-world hardware, introducing physical component variations and interface complexities absent in purely computational MATLAB models. Real-time execution constraints in HIL necessitate model simplifications, while MATLAB allows for more complex, non-real-time simulations. Furthermore, environmental factors affecting the physical HIL setup, such as temperature and noise, are typically not accounted for in MATLAB.

5. Conclusion

In conclusion, MTPA and non-MTPA controllers were designed, analyzed, and compared. The MTPA controller was designed to maximize the electromagnetic torque output while minimizing current consumption, optimizing the system's efficiency. In contrast, the non-MTPA controller did not prioritize this efficiency goal, leading to observable differences in performance. The analysis including software simulation and HIL simulation validates that the MTPA strategy is essential for achieving high efficiency with optimum torque operation in IPMSM. Overall, the MTPA controller outperformed the non-MTPA controller in terms of torque response, current usage efficiency, and speed stability.

Despite observed discrepancies between validation methodologies, future research will focus on refining the proposed controller. This refinement will encompass the implementation of an extended observer and a finer tuning approach for the PID speed controller. To mitigate differences between MATLAB and HIL simulation results, subsequent investigations will explore the integration of filtering techniques. These may include, but are not limited to, low-pass and high-pass filters for sensor data, with the potential for advanced Kalman filtering implementations.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the article.

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