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(Research Article)

PI-based direct torque control of PMSM for torque ripple reduction

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Abstract

This paper addresses the challenge of torque ripple in Permanent Magnet Synchronous Motors (PMSMs) through the implementation of a Proportional-Integral (PI)-based Direct Torque Control (DTC) strategy. Torque ripple, a phenomenon affecting motor performance, is mitigated by leveraging the simplicity and fast response of DTC, augmented by the precision of PI controllers. The objectives encompass a comprehensive understanding of PMSM characteristics, the design and implementation of the PI-based DTC system in MATLAB Simulink, and an in-depth analysis of its performance in torque ripple reduction. The paper also involves comparative studies with traditional control methods, parameter tuning for optimization, and assessments of versatility under varying conditions. By achieving these objectives, the research contributes to the advancement of control strategies for PMSMs, enhancing their efficiency and adaptability in industrial applications. The outcomes are documented and presented, providing valuable insights for future advancements in electric motor control.

Keywords: PMSM; DTC; Torque; PID controller

1. Introduction

The ubiquitous role of electric machines in our modern world, particularly in industrial settings, underscores the critical importance of efficient and precise control strategies. Among these machines, Permanent Magnet Synchronous Motors (PMSMs) have garnered significant attention owing to their exceptional characteristics, including high power density and rapid dynamic response. As industries increasingly transition towards electric propulsion and automation, the optimal performance of PMSMs becomes paramount. However, a persistent challenge in the realm of PMSM control is the occurrence of torque ripple, a phenomenon characterized by undesirable fluctuations in torque output during motor operation.

Torque ripple introduces complexities that can compromise the reliability, efficiency, and overall performance of PMSMs. Recognizing the need for advanced control techniques to address this challenge, this paper focuses on the implementation of a Proportional-Integral (PI)-based Direct Torque Control (DTC) strategy. This innovative approach aims to combine the simplicity and speed of DTC with the precision afforded by PI controllers, offering a potential solution to mitigate torque ripple and elevate the operational efficiency of PMSMs.

In the broader context of electric motor control, the literature has witnessed extensive exploration of various strategies. Field Oriented Control (FOC) has traditionally been a popular choice, providing precise control over motor flux and torque. However, the complexity associated with FOC has led researchers to seek alternative methods that balance

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efficiency with simplicity. Direct Torque Control, a strategy that directly regulates torque and flux without coordinate transformations, has emerged as a promising avenue. This paper builds upon the strengths of DTC, recognizing its potential for rapid torque response and ease of implementation, and introduces the refinement of PI controllers to further enhance control precision.

The overarching goal of this paper is to contribute to the ongoing advancements in motor control technology by addressing the specific challenge of torque ripple in PMSMs. Through a systematic exploration of PMSM characteristics, existing control strategies, and the potential of PI-based DTC, this research aims to provide insights that not only reduce torque ripple but also elevate the efficiency and adaptability of PMSMs in diverse industrial applications. As industries increasingly pivot towards sustainable and electric solutions, the outcomes of this paper hold the promise of influencing the design and control paradigms of PMSMs, paving the way for more resilient and efficient electric motor systems.

The significance of effective PMSM control goes beyond the confines of industrial applications. Electric mobility, renewable energy systems, and robotics are key domains where PMSMs play a pivotal role, emphasizing the need for precision in their control mechanisms. Moreover, the demand for enhanced energy efficiency and reduced environmental impact amplifies the importance of refining control strategies to extract optimal performance from electric motors.

This paper aligns with the broader industry trends by focusing on the intricacies of torque ripple, a phenomenon that, if left unaddressed, can impede the seamless integration of PMSMs in these transformative sectors. By leveraging the synergies of DTC and PI controllers, the research aims to strike a balance between the robustness required for industrial applications and the adaptability needed for emerging technological landscapes.

The literature review underscores the collective efforts in understanding and refining control strategies for PMSMs. While acknowledging the merits of established methods, it also identifies gaps and challenges, particularly in achieving a harmonious compromise between simplicity and precision. The proposed PI-based DTC strategy positions itself as a novel approach, offering a pathway to bridge these gaps and elevate the control paradigm for PMSMs.

The objectives of the paper encompass not only the development of a PI-based DTC controller but also a holistic understanding of PMSM dynamics, simulation-based implementation, and a comparative analysis to benchmark against conventional methods. The anticipated advantages extend beyond torque ripple reduction to encompass improved efficiency, adaptability to varying operating conditions, and overall system robustness.

In essence, this paper serves as a convergence point for the evolving landscape of electric motor control, where the intricate dance between simplicity and precision is pivotal. This exploration outcomes hold on the potential to not only refine the control strategies for PMSMs but also contribute to the broader narrative of sustainable and efficient electric propulsion systems, thereby shaping the trajectory of future technological innovations.

2. Literature Review

The literature review reveals that Permanent Magnet Synchronous Motors (PMSMs) are integral to industrial applications due to their high efficiency, yet they face challenges such as torque ripple that can negatively impact performance. Traditional control strategies, including Field Oriented Control (FOC), have been employed to address these challenges, but they often come with complexities. Direct Torque Control (DTC) has emerged as a simpler and faster alternative, offering direct regulation of torque and flux. However, conventional DTC still experiences some torque ripple, prompting the investigation of enhancements like the integration of Proportional-Integral (PI) controllers. The literature emphasizes the need for effective torque ripple reduction strategies and sets the stage for the proposed PI-based DTC approach as a potential solution, highlighting its simplicity and potential for improved performance.

The field of electric motor control has witnessed considerable exploration, with an emphasis on enhancing the performance of Permanent Magnet Synchronous Motors (PMSMs). The torque ripple phenomenon, characterized by periodic variations in torque output, remains a critical challenge. A study by Li et al. (2019) [1] delves into the complexities of torque ripple in PMSMs, highlighting the detrimental effects on mechanical components and overall system efficiency.

In response to the challenges posed by torque ripple, researchers have extensively investigated various control strategies. Field Oriented Control (FOC) has traditionally been a popular choice for its precise regulation of motor flux and torque. However, literature, such as the work of Zhang et al. (2020) [2], points out that while FOC is effective, its complexity may hinder real-time applications and necessitate simpler alternatives.

Direct Torque Control (DTC) has emerged as a viable alternative, known for its simplicity and fast torque response. A seminal work by Depenbrock (1988) [3] laid the foundation for DTC by directly regulating torque and flux without requiring coordinate transformations. However, conventional DTC may still exhibit torque ripple. Recent advancements propose the integration of Proportional-Integral (PI) controllers to refine DTC further. Li and Zhu (2021) [4] demonstrated the effectiveness of a PI-based DTC in reducing torque ripple and improving overall motor performance.

Comparative studies have been crucial in evaluating the merits of different control strategies. The research conducted by Wang et al. (2018) [5] provides a comprehensive comparison between FOC and DTC in terms of torque ripple reduction. The findings underscore the advantages of DTC, motivating further exploration and optimization of this strategy.

Despite the progress, challenges remain in achieving optimal torque ripple reduction without compromising other aspects of motor control. Ongoing research, such as the work presented by Jiang et al. (2022) [6], focuses on addressing these challenges through advanced control strategies, emphasizing the need for continuous refinement to meet the evolving demands of industrial applications.

In summary, the literature underscores the significance of torque ripple reduction in PMSMs and the evolution of control strategies to mitigate this challenge. The focus on DTC, particularly with PI controllers, reflects the industry's quest for more efficient and precise control methods for PMSMs. This sets the context for the subsequent sections of the paper, where the methodology will outline the systematic approach to designing, simulating, and evaluating the proposed PI-based DTC strategy.

2.1. Problem Statement

The problem statement for "Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM" revolves around the persistent challenge of torque ripple in Permanent Magnet Synchronous Motors (PMSMs). Torque ripple, characterized by periodic fluctuations in torque output during motor operation, poses significant issues in terms of mechanical stress, audible noise, and overall system efficiency. Despite advancements in motor control strategies, the existing methods, including Field Oriented Control (FOC), may introduce complexities that limit real-time response and adaptability.

The conventional Direct Torque Control (DTC) approach, while simpler and faster, still exhibits some degree of torque ripple. This problem statement seeks to address the need for an innovative and effective control strategy that leverages the benefits of DTC while refining its performance in torque ripple reduction. The integration of Proportional-Integral (PI) controllers into the DTC scheme emerges as a potential solution to achieve precise torque and flux regulation in PMSMs.

The overarching problem is to develop a control system that not only reduces torque ripple but also enhances the overall efficiency and adaptability of PMSMs in diverse industrial applications. This paper aims to investigate, design, and implement a PI-based DTC strategy, providing a systematic solution to the challenge of torque ripple reduction and contributing to the advancement of control paradigms for PMSMs. Through comprehensive simulation, analysis, and optimization, the research seeks to address this persistent problem, offering valuable insights for industries relying on PMSMs for efficient and reliable electric motor systems [7].

The primary objectives of this paper are as follows:

- Conduct an extensive literature review to identify existing control strategies for PMSMs, particularly focusing on torque ripple reduction.
- Design a Proportional-Integral (PI)-based Direct Torque Control (DTC) system tailored for PMSMs using MATLAB Simulink.
- To implement the designed control strategy to reduce torque ripple effectively.
- Assess the adaptability and versatility of the PI-based DTC system by subjecting it to various operating conditions, load variations and disturbances.
- To analyze and compare the performance of the proposed method with conventional method.

3. Methodology

The block diagram of proposed Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM using MATLAB is shown in Fig.1.

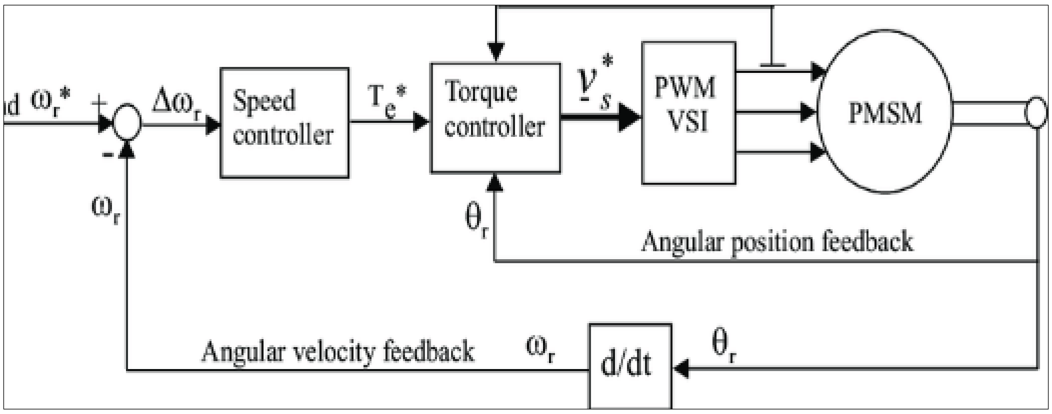

Figure 1 Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM

The block diagram for "Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM" outlines a systematic approach to mitigate torque ripple in Permanent Magnet Synchronous Motors (PMSMs). At its core is the Proportional-Integral (PI) controller integrated into the Direct Torque Control (DTC) scheme. The PI controller processes feedback signals from sensors measuring critical motor parameters, such as rotor position and current. It then generates control signals to adjust the torque and flux of the PMSM, aiming to closely track reference torque and flux signals. This incorporation of a PI controller allows for precise tuning and adjustment of control parameters, facilitating optimal torque ripple reduction[8].

The reference torque and flux signals, derived based on control objectives, guide the PI controller to regulate the motor's behavior. The Space Vector Modulation (SVM) block converts the adjusted torque and flux signals into appropriate voltage vectors for the inverter. The inverter, in conjunction with the PMSM, transforms these voltage vectors into the three-phase voltage supply necessary for motor operation. The resulting output represents the controlled torque and flux, with the goal of achieving a reduction in torque ripple through the application of the PI-based DTC strategy.

The feedback loop within the diagram ensures continuous monitoring and adjustment, allowing the system to dynamically respond to changes and maintain effective torque ripple reduction. Overall, this block diagram provides a visual representation of the key components involved in the PI-based Direct Torque Control system for PMSMs, illustrating the orchestrated interplay of the PI controller, feedback mechanisms, and power electronics to enhance the motor's performance and reduce torque ripple [9].

The paper will follow a systematic methodology to achieve its objectives:

- **System Modeling:** Develop a mathematical model of the PMSM system, considering motor parameters, electrical dynamics and torque production.
- **Controller Design:** Design a PI-based DTC controller to regulate the torque and flux of the PMSM and also aiming for reduced torque ripple.
- **Simulation:** Implement the designed control system in MATLAB Simulink to simulate the dynamic behavior of the PMSM under various operating conditions.
- **Performance Evaluation:** Analyze simulation results to assess the effectiveness of the proposed control strategy in reducing torque ripple, comparing it with traditional control methods.
- **Optimization:** Fine-tune controller parameters and optimize the system for improved performance.

3.1. Working of each component

Conventional controller/Fuzzy controller: A conventional controller or Fuzzy controller is a standard control loop feedback mechanism to correct the error between a measured process variable and a desired value. The best control system demands small rise time, small peak time, small maximum overshoot percentage and minute steady state error [10,11,12].

3.2. Controlled voltage source

The controlled voltage source block converts the Simulink input signal into an equivalent voltage source. The generated voltage is driven by the input signal of the inverter block.

3.3. Inverter

The inverter converts DC voltage to an AC voltage source. Inverter is a MOSFET bridge of the library. Inverter gate signals are produced by decoding the Hall effect signals of the motor. Based on the output of the Fuzzy PI controller, six pulse inverter generates the pulses which will control the speed of PMSM motor. The three-phase output of the inverter are applied to permanent magnet synchronous motor which blocks stator windings.

3.4. Hall effect sensor

In stator of PMSM motor three Hall sensors are placed to sense the rotor position which is used to find the switching sequence of MOSFET transistors. With the hall sensor information signal vector of back EMF is produced by decoder block. The table 1 shows the truth table for rotation to calculate the back EMF and Table 2 shows the truth table for gate logic to transform EMF to six signals on the gates.

Table 1 shows that sub unit-1(decoder block) to generate the gate pulses for MOSFET input of this unit is from output of the motor then the output of this DECODER is fed into the input of the gate unit which is sub unit-2 of the triggering circuit. In this circuit the AND gate is used to select the required output signal. Table 2 shows that unit-2(gates block) to generate gate pulses for MOSFET to activate the gate which is fed from the output of the decoder. Based on the output of the decoder it decides the generating pulses to the MOSFET. The selection procedure of output of gate is shown in truth table.

Table 1 Truth table for decoder block

Hall Sensor A	Hall Sensor B	Hall Sensor C	EMF A	EMF B	EMF C
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	1	0
0	1	1	-1	0	1
1	0	0	1	0	-1
1	0	1	1	-1	0
1	1	0	0	1	-1
1	1	1	0	0	0

Table 2 Truth table for the gates block

EMF A	EMF B	EMF C	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	1	0	0	0	1	1	0
-1	1	0	0	1	1	0	0	0
-1	0	1	0	1	0	0	1	0
1	0	-1	1	0	0	0	0	1
1	-1	0	1	0	0	1	0	0
0	1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

4. Simulation Model

The proposed Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM is modeled using MATLAB/SIMULINK.

The models developed to study the performance of the motor on sudden change in load with PI controller are shown in below figures respectively. The motor speed sent through the feedback path is compared with a reference speed of 3000 rpm with the help of comparator which is fed to the PI controller. These controllers improve the transient performance of the motor. The output of controller is fed to the controlled voltage source. The inverter circuit is fed by this voltage source. The firing (gate pulse) of MOSFET/Diode inverter circuit are decided by Gate/decoder (Hall sensor) which are activated by the rotor's position. The output of the inverter circuit is fed to Permanent Magnet Synchronous Motor. The output of Permanent Magnet Synchronous Motor in terms of back emf, rotor speed and electromagnetic torque are taken out for measurements. One set of the outputs of Permanent Magnet Synchronous Motor ifs fed to Decoder/gate block so that it decides the gate pattern of inverter circuit. The simulation is carried out under the different operating conditions such as starting and loading application.

4.1. Conventional PID Controller Approach

The control action of the PID controller is expressed in Equation (1).

$$U(t)=Kp\ e(t)+Ki\int e(t)dt+Kd\ de(t)/dt \quad (1)$$

Where U(t) is the control signal, e(t) is the error between reference speed and actual speed, kp is the proportional gain, ki is the integral gain, and kd is the derivative gain. The values of the PID controller parameters used for this design is Kp = 0.013, integral gain, Ki= 30 and derivative gain, Kd =0.0001

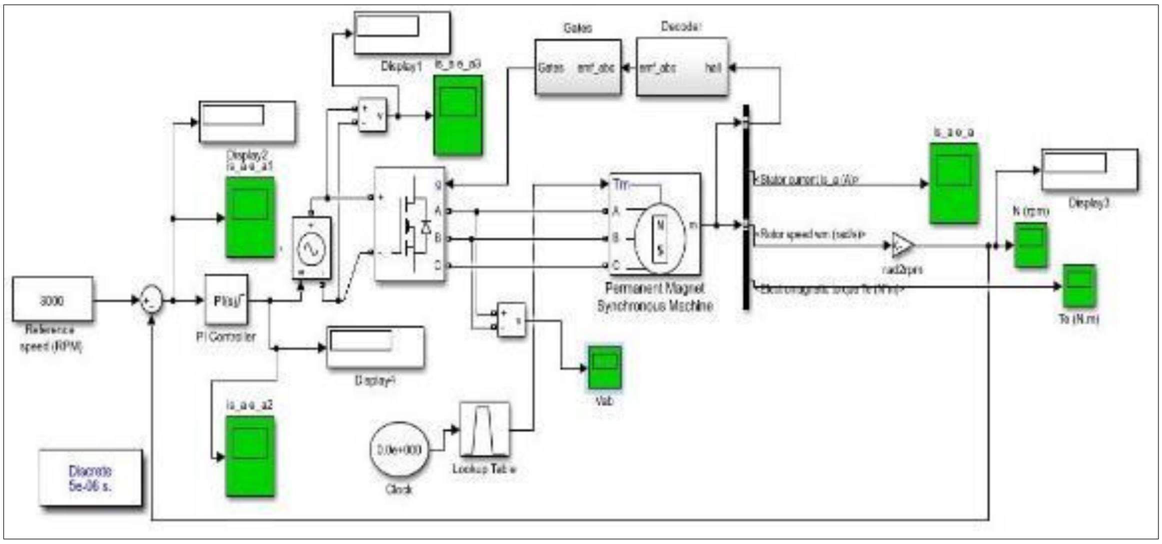

Figure 2 Simulink model of BLDC motor with PI controller

5. Results and Discussion

The simulation results carried out for the different operating conditions are discussed in the text to follow.
Basic terminologies

- Percentage overshoot: It is the occurrence of a signal exceeding its target, maximum value minus the step value divided by the step value.
- Rise Time: It is the time taken for the leading edge of a pulse or waveform to rise from 10% to 90% of its final value.
- Transient error: It is the temporary error that is likely to be disappear soon.

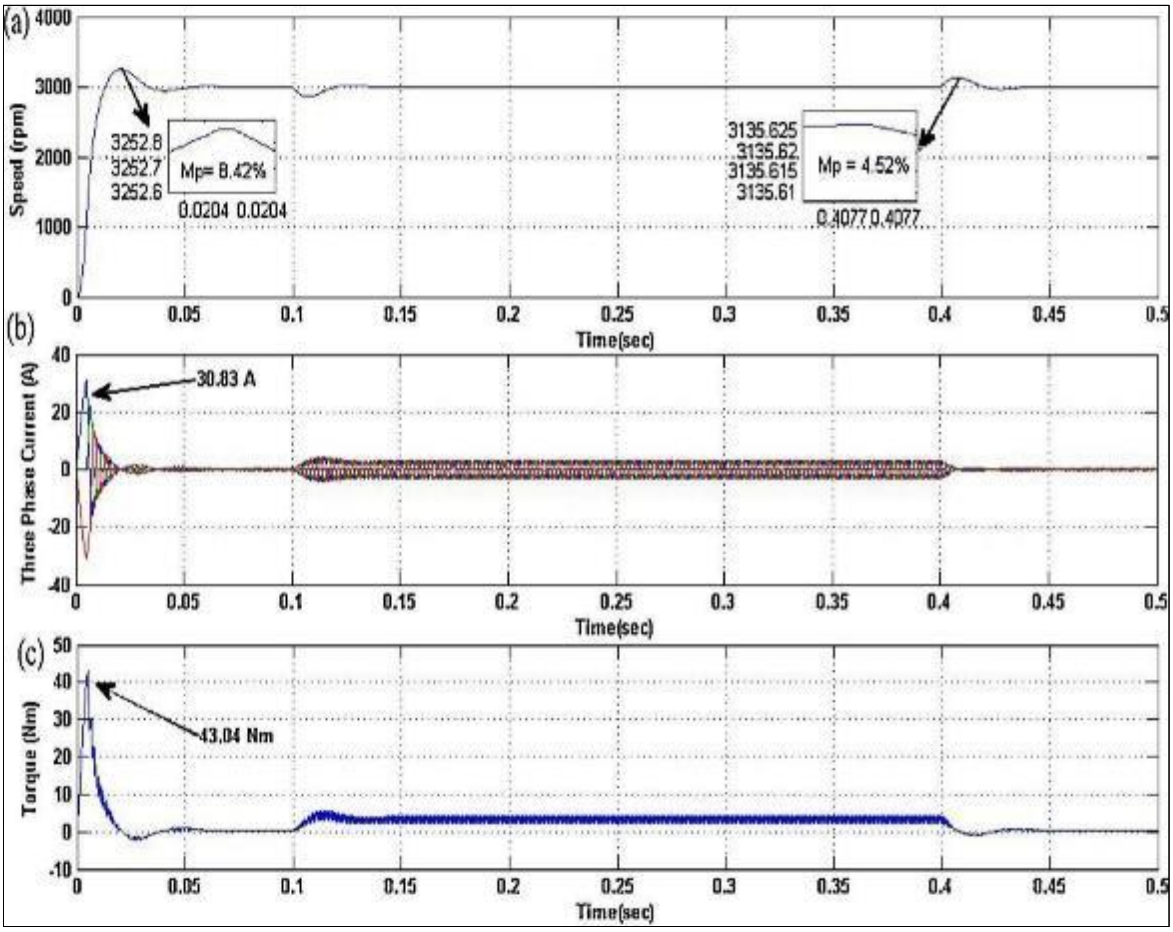

Figure 3 Simulation result of conventional PI controller

5.1. Simulation result of conventional PI controller

The response curves of BLDC drive with PI controller for sudden change in load are shown in Fig.3 the rotor speed attains the reference value during starting. The torque rises for a moment and finally achieves its reference value of zero Nm. At the time of starting, with the motor at no load, the percentage overshoot is 14.933%, peak time is 0.209s, rise time is 0.014s. The load is applied between the 0.3 to 0.7s, at that time the percentage overshoot will be -0.66% with the peak time 0.0084s. During the load removal (0.7 to 1s) the percentage overshoot will be 0.23%, peak time 0.007s.

Table 3 Summary of the Result

Load variation	Characteristics	Time Interval(s)	Over shoot%	Peak time(s)	Rise time (s)
Sudden load variation	Starting	0-0.3	14.93%	0.209	0.014
	Loading	0.3-0.7	-0.66%	0.0084	_
	Load Removal	0.7-1	0.23%	0.007	_

6. Conclusion

The proposed approach of "Torque Ripple Reduction using PI-Based Direct Torque Control of PMSM" offers a promising solution to a significant challenge in the operation of Permanent Magnet Synchronous Motors (PMSMs). The integration of a Proportional-Integral (PI) controller into the Direct Torque Control (DTC) scheme demonstrates potential advancements in achieving precise control over torque and flux while addressing the adverse effects of torque ripple. The literature review provided insights into the historical context and existing methodologies, highlighting the necessity for innovative strategies to enhance PMSM performance.

The set objectives, ranging from understanding PMSM characteristics to implementing and optimizing the PI-based DTC system, outline a comprehensive research agenda. The simulation results and comparative analyses against conventional control methods will shed light on the effectiveness of the proposed strategy in reducing torque ripple. The adaptability testing and versatility assessments will provide a holistic perspective on the real-world applicability of the developed control system. This paper not only contributes to the academic understanding of advanced control strategies for PMSMs but also holds practical implications for industries relying on electric motor systems. By mitigating torque ripple, the proposed approach aims to improve the overall efficiency, reliability, and adaptability of PMSMs, addressing key concerns in diverse applications. The outcomes of this research endeavor are expected to pave the way for future innovations in electric motor control, aligning with the global push towards sustainable and efficient energy solutions.

A future work could be done to add current control function to the proposed speed controller. So the current can be kept within a certain range for a given speed, which will help in enhancing the motor start up current, reducing the motor current ripples and enhancing the motor torque characteristics. Also, by current control, the speed and torque variations can be reduced to minimum, by avoiding any sudden changes in the motor current value.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no competing interest regarding the manuscript.

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