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Reduction of Torque Ripple in a Permanent Magnet Brushless DC Motor Using Space Vector Pulse-Width Modulation Method

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Abstract
This study investigates the reduction of torque ripple in Permanent Magnet Brushless DC Motors (PMBLDCM) by comparing the effectiveness of Sinusoidal Pulse Width Modulation (SPWM) and conventional Pulse Width Modulation (PWM) techniques. The absence of mechanical brushes and commutators in PMBLDC motors enhances durability, operational lifespan, and efficiency while reducing maintenance requirements. Despite these advantages, PMBLDC motors often experience excessive torque ripple, characterized by fluctuations in torque output, which can impair performance and operational stability. The primary objective of this research is to implement an advanced Space Vector Pulse-Width Modulation (SVPWM) technique to effectively minimize torque ripple in PMBLDC motors. Experimental results demonstrated a significant reduction in torque ripple with SVPWM, achieving 0.2% compared to 1.7% with SPWM and 2.28% with PWM. Total Harmonic Distortion (THD) was also lower with SVPWM at 6%, compared to 8% for SPWM and 10% for PWM, indicating superior harmonic suppression. Speed regulation was more precise with SVPWM, showing a deviation of only 1.5%, while SPWM and PWM exhibited deviations of 2.4% and 4.2%, respectively. Current ripple was also minimised, measuring 0.035% for SVPWM, 0.08% for SPWM, and 0.9% for PWM. Thermal performance favoured SVPWM, maintaining a temperature range of 50-56°C, while SPWM and PWM ranged between 59-66°C and 70-86°C, respectively. Efficiency analysis further confirmed SVPWM's superiority, achieving 88-92% efficiency, compared to 85-87% for SPWM and 69-79% for PWM. These findings affirm that SVPWM outperforms both SPWM and PWM in key performance metrics, making it the preferred control method for high-precision, energy-efficient motor applications. The research concludes that SVPWM offers substantial advantages in reducing harmonic distortion, improving speed regulation, minimizing current ripple, and enhancing overall efficiency, contributing to the development of more reliable and sustainable PMBLDC motor systems for industrial use.
Keywords: Harmonic Distortion Reduction, Motor Efficiency Improvement, Permanent Magnet Brushless DC Motor, Space Vector Pulse-Width Modulation, Torque Ripple Minimization.

I INTRODUCTION

Permanent Magnet Brushless DC (PMBLDC) motors have become increasingly favoured in both industrial and consumer applications due to their superior operational benefits. The elimination of mechanical brushes and commutators significantly enhances the motor's reliability and durability, contributing to an extended operational lifespan. Additionally, PMBLDC motors offer higher energy efficiency and lower maintenance demands, making them ideal for modern, high-performance systems (Kumar & Mallikarjuna, 2020; Idoniboyeobu, Orike, & Biragbara, 2017).

Brushless DC motors operate based on the principle of electromagnetic induction, where the interaction between the stator windings and the permanent magnets on the rotor generates a rotating magnetic field (Biragbara & Deesor, 2025; Waygood, 2020). The rotor's movement is driven by the magnetic forces produced as the stator windings are energized in a controlled sequence, causing continuous rotation.

Despite the numerous advantages offered by permanent magnet brushless DC motors, torque ripple remains a major operational challenge. Torque ripple refers to the undesired fluctuations or oscillations in the motor's output torque. This phenomenon can be attributed to various factors, including changes in reluctance torque, cogging torque, and commutation torque (Biragbara et al, 2023; Huang et al., 2022).

Recent investigations have demonstrated that advanced modulation techniques can significantly mitigate these torque fluctuations. Deesor *et al.* (2025) showed that the application of Space Vector Pulse-Width Modulation (SVPWM) in PMBLDC motors results in substantial reductions in torque ripple and total harmonic distortion when compared with Sinusoidal PWM (SPWM) and conventional PWM methods. Their findings further confirmed that SVPWM improves speed regulation, reduces current ripple, and enhances overall motor efficiency, making it a highly effective control strategy for precision motor drive applications.

1.1 Objectives

The specific objectives are to:
i. Investigate the current performance characteristics of Permanent Magnet Brushless DC motors.
ii. Identify the underlying causes of torque ripple in Permanent Magnet Brushless DC motors.
iii. Assess the effectiveness of torque ripple reduction strategies in Permanent Magnet Brushless DC motors.
iv. Derive the governing equations and establish the relationship between torque ripple and motor performance.
v. Develop a model for the BLDC motor parameters and validate the simulation results in MATLAB/Simulink to optimize torque ripple reduction using the Space Vector Pulse-Width Modulation technique.

In order to fully utilize Permanent Magnet-Brushless DC (PMBDC) motors, one must overcome a number of difficult obstacles and constraints that call for careful consideration and creative solutions. Wang *et al.* (2023) identified torque ripple as one of the main challenges in the operation of permanent magnet brushless DC motors. This observation is consistent with the findings of Deesor et al. (2025), who demonstrated that SVPWM-based control significantly suppresses torque oscillations and enhances operational stability in PMBLDC motor systems.

Another significant challenge highlighted by Zhang *et al.* (2022) is the potential for permanent magnets to demagnetize when exposed to high temperatures. Permanent magnet brushless DC motors are frequently used in high-temperature settings, such as industrial machinery and automobile undercarriage applications. Permanent magnet demagnetization reduces motor performance and efficiency; therefore, to counteract this problem, sophisticated heat management techniques and material selection strategies are required.

Permanent magnet-brushless DC motors encounter scalability and adaptability issues in addition to operational difficulties. As highlighted by Xu *et al.* (2021), motor characteristics must frequently be carefully customized and fine-tuned in order to optimize permanent magnet brushless DC motors for particular applications. This customization process can be time- and resource-intensive, limiting scalability across multiple applications.

The promise of sensorless control systems to overcome the limitations of conventional sensor-based approaches has attracted a lot of interest. Huang et al. (2022) explored a space vector modulation-based sensorless control approach for Permanent Magnet Synchronous Motors (PMSMs), providing insights into advanced methods that improve motor control accuracy and efficiency.

II MATERIALS AND METHOD

2.1 Materials

The following materials are essential for effectively reducing torque ripple in a Permanent Magnet Brushless DC (PMBLDC) motor. By assembling these materials, the process of reducing torque ripple can be systematically achieved through a combination of motor design, control techniques, and careful selection of components. Each material must meet the specified criteria to ensure optimal motor performance and significant reduction in torque ripple.

This study employed a simulation-based method using motor parameters obtained from selected industrial facilities. The components considered include a space vector pulse-width modulation (SVPWM) control algorithm, stator windings, power electronic switching devices, permanent magnets, and sensing elements such as encoders. These components were represented within the simulation model to investigate the effectiveness of the SVPWM technique in reducing torque ripple and improving the overall performance of the permanent magnet brushless DC motor under defined operating conditions. No experimental testing was undertaken in this research.

2.2 Method used

The method employed in this study is the “Vector-Based Pulse Width Modulation” This method is an advanced and computationally demanding technique, recognized as the most effective among all pulse-width modulation (PWM) methods for variable-frequency drive applications. Due to its exceptional performance capabilities, SVPWM allows for precise control of the brushless DC motor system, optimizing both motor operation and overall system efficiency. This advanced PWM technique is highly effective in mitigating torque ripple, harmonic distortions, and reducing the excessive ripple errors typically encountered in Permanent Magnet Brushless DC Motors (PMBLDCMs).

2.3 Coupled Electrical and Mechanical Equations of PMBLDC motor

The coupled electrical and mechanical equations of a Permanent Magnet Brushless DC (PMBLDC) motor describe the interaction between the motor's electrical dynamics and its mechanical motion. These equations include the relationships between the applied voltage, current, back electromotive force (EMF), and the generated torque, with the mechanical dynamics governed by the motor’s rotational inertia and load torque, which are influenced by the electrical control inputs, such as Space Vector Pulse Width Modulation (SVPWM).

Here are electrical and mechanical equations which relate the permanent magnet brush-less direct current motor.

$$V_A = L\frac{dI_A}{dt} + RI_A + e_A \qquad (3.1)$$

$$T_e = k_t\left(I_A f(\theta) + I_B f(\theta - \frac{2\pi}{3}\right) + I_c f(\theta + \frac{2\pi}{3}))J\frac{d\omega}{dt} = T_e - T_L - B\omega \qquad (3.2)$$

2.4 State-Space Representation

State-space representation is a mathematical modeling technique used to describe the dynamic behavior of Permanent Magnet Brushless DC (PMBLDC) motors by capturing the relationships between input, output, and state variables. This approach enables the formulation of the motor’s equations in a compact form, allowing for the analysis of system stability, control design, and performance evaluation. Here are the equations which define the state vector x and the input vector u as:

$$x=\begin{bmatrix} I_A \\ I_B \\ I_C \\ \omega \\ \theta \end{bmatrix},\ u=\begin{bmatrix} V_A \\ V_B \\ V_C \\ T_L \end{bmatrix} \qquad (3.3)$$

However, the state space equation can be written as

$$\frac{dx}{dt}=Ax+Bu+C \qquad (3.4)$$

$$A=\begin{bmatrix} -\frac{R}{L} & 0 & 0 & 0 & 0 \\ 0 & -\frac{}{L} & 0 & 0 & 0 \\ 0 & 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & 0 & -\frac{R}{L} & 0 \\ 0 & O & 0 & 1 & 0 \end{bmatrix} \qquad (3.5)$$

$$B=\begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & -\frac{1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (3.6)$$

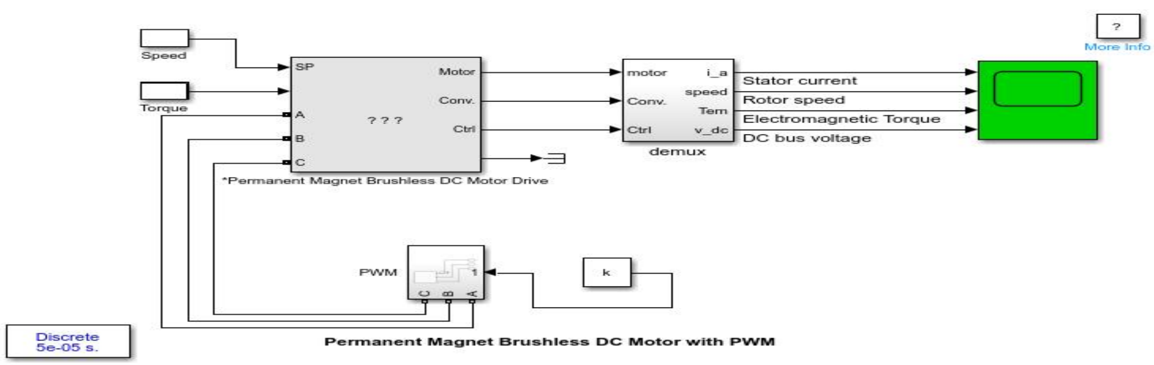

Figure 1: Permanent Magnet Brushless DC Motor Torque Ripple Reduction Model.

2.5 Electrical Dynamics

The electrical dynamics of a PMBLDC motor can be described using the voltage equations for each phase. Considering a three-phase system (A, B, and C), the voltage equations can be expressed as:

$$V_A=L\frac{dI_A}{dt}+RI_A+e_A \qquad (3.7)$$

$$V_B=L\frac{dI_B}{dt}+RI_B+e_B \qquad (3.8)$$

$$V_C = L\frac{dI_C}{dt} + RI_C + e_C \quad (3.9)$$

Table 1: Motor Parameters (Real-time data gotten from Bua Company in Port Harcourt, 2024)

S/N	Item Tag	KW	AMP	RPM	R-Phrase	Y-phrase	B-phrase	Setting
1	M1349	0.75	0.65	1440	1.2	1.2	1.3	2
2	M13518	7.5	14.65	1435	8.4	8	8.2	13
3	M1351B	7.5	14.65	1435	8.4	8.3	8.4	13
4	M1352	0.75	1.85	1440	2.6	2.6	2.6	3.6
5	M1354	0.75	1.85	1440	1.3	1.3	1.2	2
6	M1356	37	67	2950	30.4	29.8	30.9	160

III RESULTS AND DISCUSSION

3.1 SVPWM performance

The use of Space Vector Pulse Width Modulation (SVPWM) in managing a Permanent Magnet Brushless DC (PMBLDC) motor leads to significant enhancements in torque regulation, efficiency, dynamic responsiveness, and real-time control performance. The reductions observed in torque ripple, current ripple, and harmonic distortion are indicative of improved inverter switching efficiency and better voltage vector utilization.

The comparative results obtained in this study closely align with previously reported findings by Deesor *et al.* (2025), where SVPWM achieved lower torque ripple and THD values than SPWM and conventional PWM techniques. The agreement between both studies validates the robustness and repeatability of SVPWM as a superior modulation strategy for high-performance PMBLDC motor applications, particularly in energy-efficient and thermally sensitive operating environments.

Table 2: The PMBLDCM parameters and its comparative results in % of the Pulse Width Modulation techniques

Parameter	SVPWM	SPWM	PWM
Temperature Distribution (°C)	50-56	59-66	70-86
Speed Regulation (%)	1.5	2.4	4.2
Total Harmonics Distortion (%)	6	8	10
Torque Ripples (%)	0.2	1.7	2.28
Efficiency (%)	88-92	85-87	69-79
Current (%)	0.035	0.8	0.9

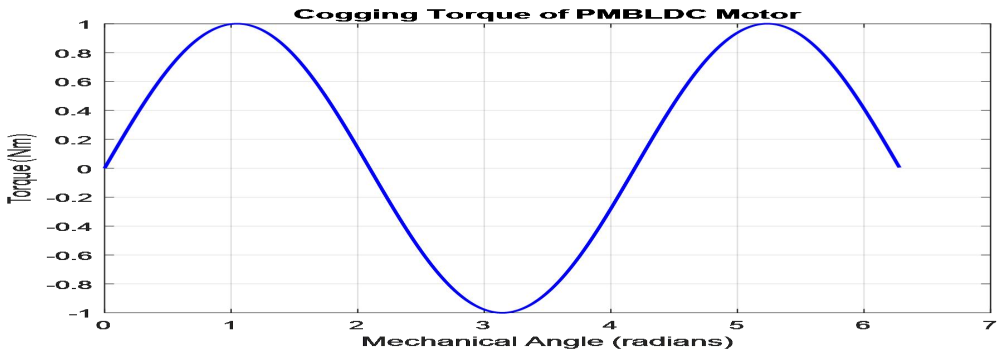

Figure 2: Cogging Torque

This illustrates the cogging torque profile across a mechanical angle range of 1 to 6.2 radians. As the rotor turns, the magnetic reluctance fluctuates due to the interaction between the stator slot openings and teeth. This varying reluctance induces periodic torque oscillations, referred to as cogging torque. The graph presented likely demonstrates a repetitive pattern influenced by the periodic structure of the stator slots.

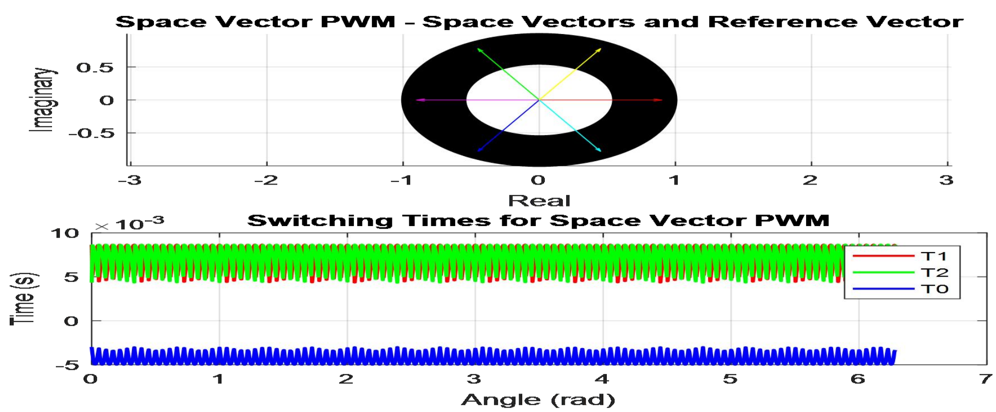

Figure 3: SVPWM Switching Time Response

This shows the switching time response of the Space Vector Pulse Width Modulation (SVPWM) technique, capturing its modulation effect at 0.5 seconds and switching activity at 10 seconds. The graph demonstrates the efficiency of SVPWM in regulating motor operation, with the 0.5-second mark representing the initial phase of modulation. This advanced control strategy is employed to generate precise gate signals for the inverters responsible for driving the motor.

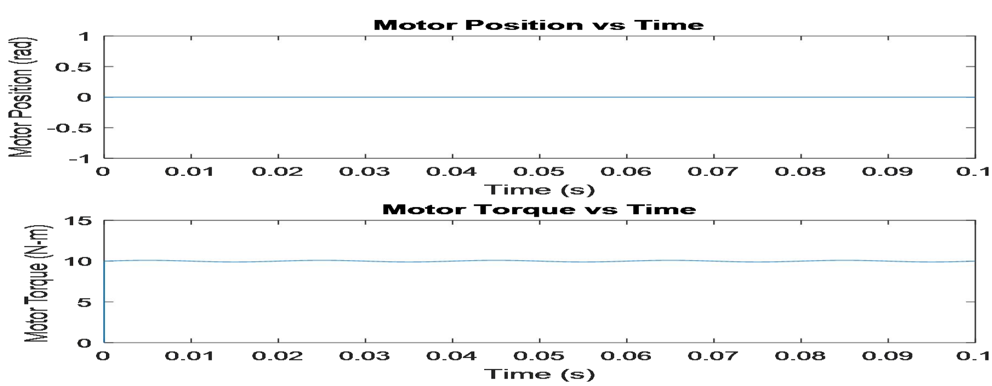

Figure 4: Motor Position

This presents the motor's positional dynamics, focusing on the motor shaft position and torque at a timestamp of 0.01 seconds. At this moment, the motor shaft is positioned at 0 radians, indicating it is either in its initial reference state or has briefly returned to the starting position. These zero angular displacements signify minimal or no rotational movement at the specified time.

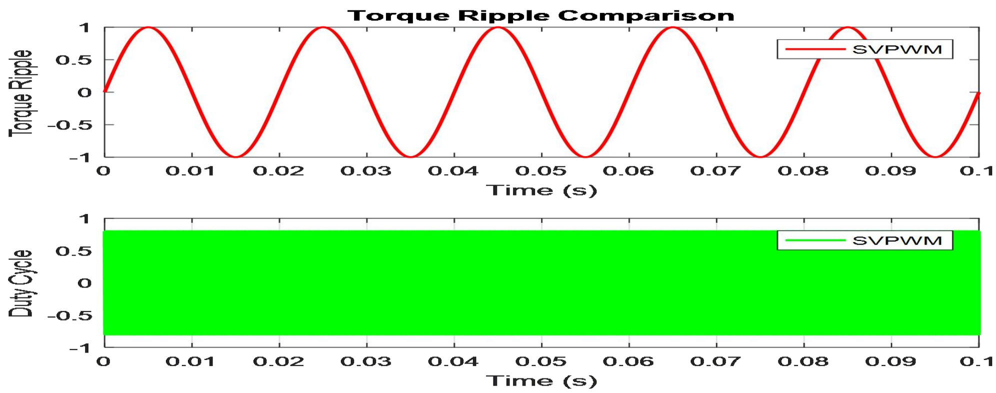

Figure 5: Torque Ripple comparison in combine duty cycle using SVPWM

This illustrates the combined duty cycle performance using the Space Vector Pulse Width Modulation (SVPWM) technique. It evaluates torque ripple variations in an electric motor when operated with multiple duty cycles, focusing on the impact of SVPWM control. This analysis aims to assess the efficiency of various combined duty cycle strategies in reducing torque ripple during motor operation.

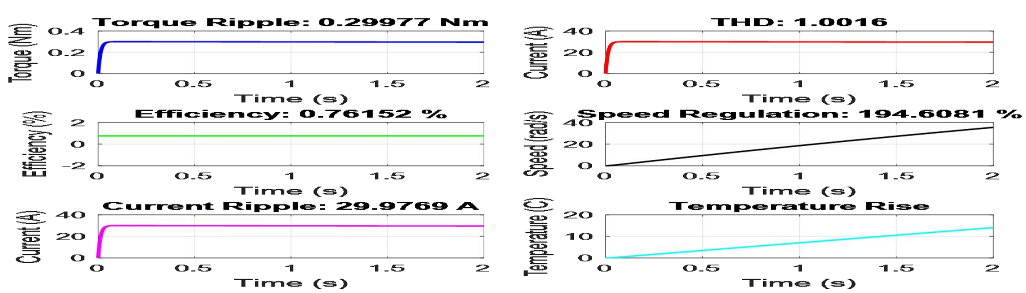

Figure 6: Torque Ripple comparison in terms of Temperature, Speed and Current.

The heading provides a detailed comparison among temperature, speed, and current, focusing on their impact on torque variations in an electric motor under different operating conditions. This evaluation specifically examines how fluctuations in temperature, rotational speed, and current affect torque ripple, aiming to identify the conditions that either minimize or amplify the ripple effect.

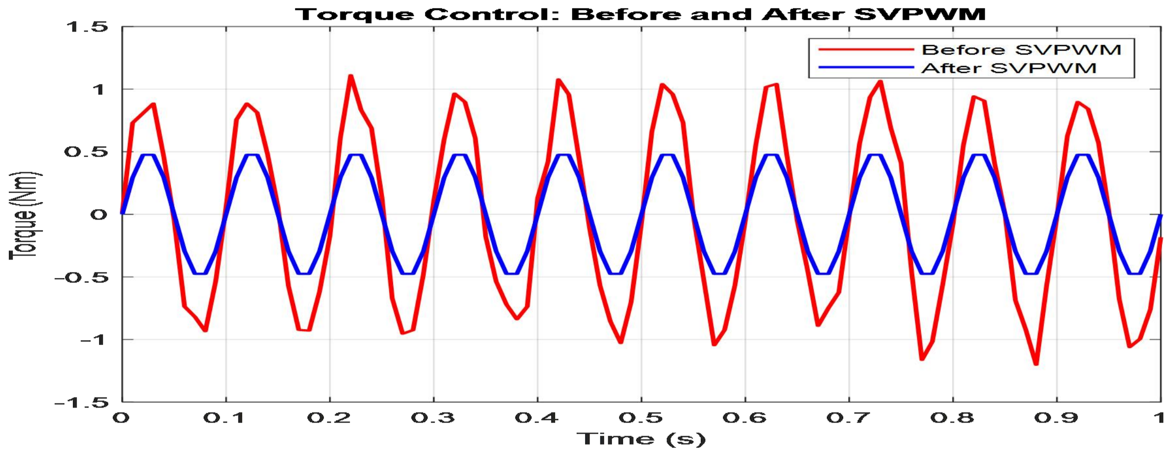

Figure 7: Torque control before and after SVPWM was applied to the system

The implementation of Space Vector Pulse Width Modulation (SVPWM) in controlling a Permanent Magnet Brushless DC (PMBLDC) motor brings about notable improvements in torque control, efficiency, dynamic response, real-time performance, and adaptive control mechanisms. Each of these aspects is essential in enhancing motor operation and performance, allowing for smoother and more efficient functioning in various applications.

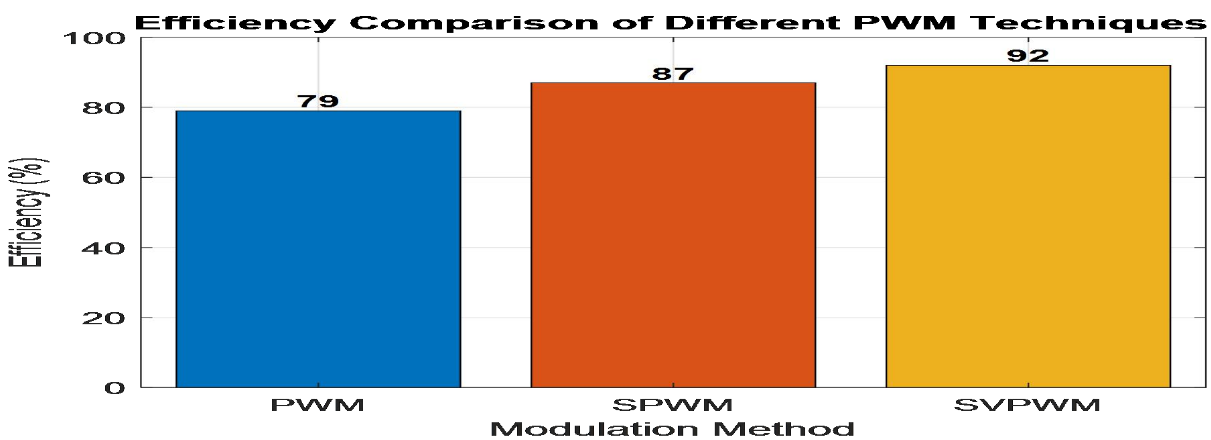

Figure 8: Efficiency comparison of different PWM Technique

SVPWM, or Space Vector Pulse Width Modulation, achieves the highest efficiency among PWM techniques due to its advanced method of generating switching signals that optimize the utilization of the DC bus voltage.

IV CONCLUSION

The reduction of torque ripple in a Permanent Magnet Brushless DC (PMBLDC) motor using the Space Vector Pulse-Width Modulation (SVPWM) method has proven highly effective in enhancing motor performance. By employing SVPWM, significant improvements were observed in torque stability, reduced harmonic distortion, and enhanced speed regulation, all contributing to smoother motor operation. The technique's ability to minimize current ripple and manage thermal performance further reinforces its suitability for precision control applications.

Ultimately, SVPWM stands out as a superior control strategy for PMBLDC motors, offering increased efficiency and operational reliability in modern motor drive systems.

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