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Design and Performance Analysis of a Three-Phase Inverter for Driving A BLDC Motor Using the Six-Step PWM Method Based on Matlab Simulink

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ABSTRACT

This study analyzes the design and performance of a three-phase inverter for BLDC motor drives in electric vehicles using the Six-Step PWM method. The research aims to overcome the low efficiency of conventional inverters (56–57%) by increasing efficiency above 70% while also targeting a Total Harmonic Distortion (THD) level below 5%. MATLAB/Simulink simulations were carried out with a 48V, 1000W BLDC motor at duty cycles of 60%, 70%, and 90%, tested under no-load and loaded conditions. Validation was conducted by comparing the results with a commercial Votol EM-50S controller employing SPWM modulation. The results show that Six-Step PWM achieved efficiency ranging from 88.99% to 98.37%, with an average improvement of 13.60% compared to the SPWM controller (72.01%–84.57%). However, THD values remained very high (61.70%–107.82%), significantly above the <5% target. This confirms a fundamental trade-off: Six-Step PWM offers much higher efficiency but at the cost of poor waveform quality. This work highlights the research gap by directly benchmarking Six-Step PWM simulations against a commercial SPWM controller. The findings indicate that Six-Step PWM is optimal for applications prioritizing energy efficiency and extended driving range, while additional harmonic mitigation measures would be necessary for compliance with strict THD standards.

Keywords: Three-Phase Inverter, BLDC Motor, Six-Step PWM, Efficiency, THD

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1. Introduction

The development of electric vehicle (EV) technology in Indonesia has shown significant growth, with electric motorcycle sales reaching 62,409 units in 2023, representing a 262% increase compared to the previous year [1]. However, the relatively low efficiency of conventional inverters, ranging from 56–57%, remains a major obstacle to optimizing the performance of EV drive systems [2]. Brushless DC (BLDC) motors are widely adopted in EVs due to their high efficiency, high power density, and low maintenance requirements [3]. The three-phase inverter is a key component that converts DC voltage into AC to drive BLDC motors. Commonly used switching strategies include Six-Step Commutation and Sinusoidal PWM (SPWM), each with distinct advantages and limitations.

Previous studies have shown that conventional Six-Step commutation typically results in high Total Harmonic Distortion (THD), approximately 62% for phase voltage, due to the trapezoidal waveform's strong low-order harmonic content [4], [5], [6]. THD is a crucial parameter for evaluating waveform quality in power systems [7], [8], [9]. Although SPWM can significantly reduce THD, it generally produces lower efficiency compared to Six-Step methods [10], [11], [12].

Despite these findings, few studies provide a direct performance comparison between Six-Step PWM simulation and a commercial SPWM controller as a practical benchmark [4], [12], [13], [14]. This represents a key research gap addressed in this work by evaluating Six-Step PWM against the Votol EM-50S controller, a widely used commercial SPWM-based controller.

The objectives of this study are therefore twofold: (1) to evaluate whether Six-Step PWM can achieve efficiency levels above 70%, and (2) to assess whether it can reduce THD below 5%. By explicitly quantifying the trade-off between efficiency and THD, this work aims to provide insights into the suitability of Six-Step PWM for EV applications where energy efficiency and driving range are prioritized.

2. Research method

2.1 Three-Phase Six-Switch Inverter Concept

A three-phase inverter is a power electronics circuit designed to convert DC voltage into three-phase AC voltage [3], [15]. The six-switch configuration consists of six MOSFETs arranged in three legs to generate three-phase outputs (A, B, and C). This configuration uses a three-phase bridge topology with upper switches (S1, S3, S5) and lower switches (S2, S4, S6) for phases A, B, and C, respectively [16], [17].

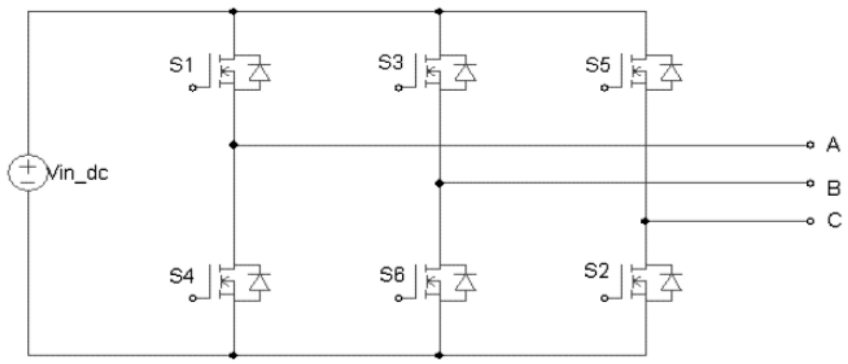

Figure 1. Three-phase inverter configuration with six switches

The inverter operates based on the Six-Step PWM switching strategy, which combines the simplicity of six-step commutation with PWM modulation to achieve voltage control. The switching sequence follows the rotor position detected by Hall effect sensors, ensuring proper commutation timing while PWM modulation controls the output voltage amplitude.

The Six-Step PWM method works by:

1. Maintaining the six-step commutation sequence (120° electrical intervals)
2. Applying PWM modulation to both active switches in each step
3. Varying the duty cycle to control output voltage amplitude
4. Operating at a switching frequency of 20 kHz

2.2 Simulation System Design

This study employed MATLAB/Simulink simulations to model the three-phase inverter system for driving a BLDC motor using the Six-Step PWM method. As shown in Figure 2, the system was designed with a 48V DC input to ensure consistency with comparative testing and align with the standard specifications of electric two-wheel vehicles.

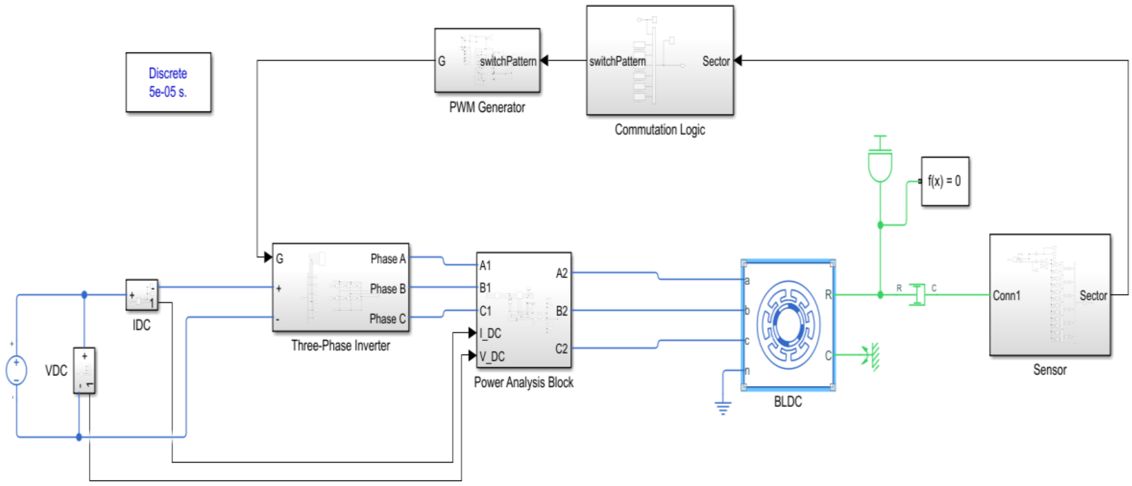

Figure 2. Block diagram of the three-phase inverter simulation system for a BLDC motor using Six-Step PWM

The simulation model consists of five primary components:

1. 48V DC power supply representing the battery system
2. Virtual Hall sensor system for rotor position detection
3. Six-Step commutation logic integrated with 20 kHz PWM generation
4. Three-phase six-switch inverter with MOSFET switching elements
5. BLDC motor with adjusted parameters

Table 1. BLDC motor parameters for simulation

Parameter	**Value**	**Unit**	**Description**
Rated voltage	48	V	Actual motor specification
Rated power	1000	W	Motor specification
Stator resistance (Rs)	0.4	Ω	Simulation parameter
Stator inductance (Ls)	0.8	mH	Simulation parameter
Back-EMF constant (Ke)	0.153	V·s/rad	Calculated from specifications
Power factor	0.85	-	Typical BLDC motor

2.3 Test Methodology and Duty Cycle Selection

The testing methodology was designed to evaluate system performance across different operating conditions through systematic duty cycle variations. Three specific duty cycles were selected: 60%, 70%, and 90%. These values were chosen based on the available settings in the commercial Votol EM-50S controller (Speed levels 1, 2, and 3), ensuring consistent comparison between the Six-Step PWM simulation and the commercial SPWM controller.

Basis for Duty Cycle Testing:

1. 60% Duty Cycle: Represents low-power operation, typical for urban driving conditions with frequent stops and starts
2. 70% Duty Cycle: Represents medium-power operation, suitable for steady cruising speeds
3. 90% Duty Cycle: Represents high-power operation, required for acceleration and hill climbing

2.4 Test Conditions

Two test scenarios were applied to evaluate system performance:

1. No-Load Condition: The motor operates without an external mechanical load, used to observe the switching characteristics of the Six-Step PWM algorithm under ideal conditions.
2. Loaded Condition: The system represents an electric motorcycle carrying a total mass of 130 kg. In the simulation model, this load was represented by mechanical parameters: inertia (J = 6.065 kg·m^2), damping (c = 0.4 N·m·s/rad), and wheel radius of 0.216 m. For the Votol EM-50S controller validation, the same 130 kg load was applied in practice, consisting of the combined weight of the rider and the motorcycle frame. This ensured that both simulation and validation tests were conducted under equivalent load conditions.

Table 2. Mechanical load parameters for simulation

Parameter	Value	Unit	Description
Total mass	130	kg	Rider + motorcycle frame
Inertia (J)	6.065	kg·m²	130 kg mass, 0.216 m wheel radius
Damping (c)	0.4	N·m·s/rad	Estimated operational resistance
Wheel radius	0.216	m	Standard motorcycle wheel size

For comparison, the same two test scenarios were also applied to the commercial Votol EM-50S controller. In this case, the 130 kg load was represented by the combined weight of the rider and the motorcycle frame. The results from the Votol controller serve as a benchmark for evaluating the performance of the Six-Step PWM simulation.

2.5 Performance Evaluation Parameters

System performance was evaluated using two primary metrics:

Efficiency Calculation:

$$\eta = \frac{Pin}{Pout} \times 100\% \tag{1}$$

where:

$$Pout = \sqrt{3} \times V_{L-L}RMS \times I_{out}, Pin = Vin \times Iin \tag{2}$$

Total Harmonic Distortion (THD):

$$THD = \frac{\sqrt{V_2^2 + V_3^2 \ldots V_n^2}}{V_1} \times 100\% \tag{3}$$

THD analysis was performed on line-to-line voltages (Vab, Vbc, Vca) using FFT analysis within MATLAB/Simulink to evaluate signal quality and harmonic content. In the simulation, FFT was conducted with a sampling frequency of 20 kHz to ensure accurate characterization of dominant harmonic components. For SPWM validation, THD measurement was carried out using a GW Instek digital oscilloscope with its built-in FFT Math function, analyzing the line-to-line voltages (Vab, Vbc, Vca).

Benchmark Approach: Performance validation was conducted through comparison with a commercial Votol EM-50S controller using SPWM modulation. This controller was selected as it represents mature commercial technology with proven field performance, providing a realistic benchmark for the Six-Step PWM method evaluation.

3. Results and discussion

The results obtained consist of both simulation data and experimental observations using the Votol controller, which serve as a comparison to evaluate the consistency between theoretical analysis and practical implementation. The simulation results show the successful conversion of 48 V DC input into three-phase AC output with characteristics influenced by duty cycle and load conditions, while the experimental results from the Votol controller provide additional insight into the system's real-world behavior.

Output Voltage Characteristics

Line-to-neutral voltages (Va, Vb, Vc) under no-load conditions showed excellent balance with maximum deviations of 0.09V: 6.69V (60%), 12.26V (70%), and 20.18V (90%). Under loaded conditions, voltage drops ranged from 0.47V to 3.61V due to motor impedance effects: 6.09V (60%), 10.74V (70%), and 17.21V (90%). The linear relationship between duty cycle and output voltage confirmed the effectiveness of PWM control in the Six-Step method. Line-to-line voltages (Vab, Vbc, Vca) exhibited a clear linear trend with increasing duty cycles. No-load conditions produced: 11.50V (60%), 21.02V (70%), 34.63V (90%), while loaded conditions resulted in: 10.71V (60%), 18.50V (70%), and 29.85V (90%). Voltage balance between phases remained excellent under no-load conditions but decreased by up to 13.4% under load, indicating the challenge of maintaining balance under real operating conditions

Output Current Characteristics

Current measurements revealed significant increases from no-load to loaded conditions, demonstrating the system's ability to adapt to varying power demands. No-load currents were: 5.57A (60%), 10.49A (70%), 17.36A (90%), while loaded conditions produced: 12.55A (60%), 24.30A (70%), 40.28A (90%). Current balance between phases was excellent under no-load conditions with deviations of only 0.1%-0.4%, but varied by up to 17.3% under load due to uneven load distribution in the mechanical system.

Efficiency Analysis

The Six-Step PWM method achieved exceptional efficiency across all tested conditions, ranging from 88.99% to 98.37% as shown in Figure 3. The highest efficiency was recorded at 60% duty cycle under no-load conditions (98.37%), while the lowest was at 90% duty cycle under loaded conditions (88.99%). This demonstrates that Six-Step PWM comfortably exceeded the 70% efficiency benchmark, with margins of up to 28%. The efficiency trend showed a slight decrease with increasing duty cycle, which can be attributed to higher switching losses as PWM activity increases. Nevertheless, even under the heaviest load at 90% duty cycle, efficiency remained at 88.99%, still above typical conventional inverter systems reported in literature.

Table 3. Six-Step PWM Simulation Efficiency Results

Duty Cycle	Condition	VLL (V)	Iout (A)	Iin (A)	Pout (W)	Pin (W)	Efficiency (%)
60%	No-load	11.50	5.57	2.36	111.44	113.28	98.37
60%	Loaded	10.71	12.55	5.12	233.73	245.76	95.22
70%	No-load	21.02	10.49	8.59	381.91	412.31	92.62
70%	Loaded	18.50	24.30	17.99	785.05	863.52	90.09
90%	No-load	34.63	17.36	24.26	1041.56	1164.48	89.44
90%	Loaded	29.85	40.28	48.82	2085.49	2343.36	88.99

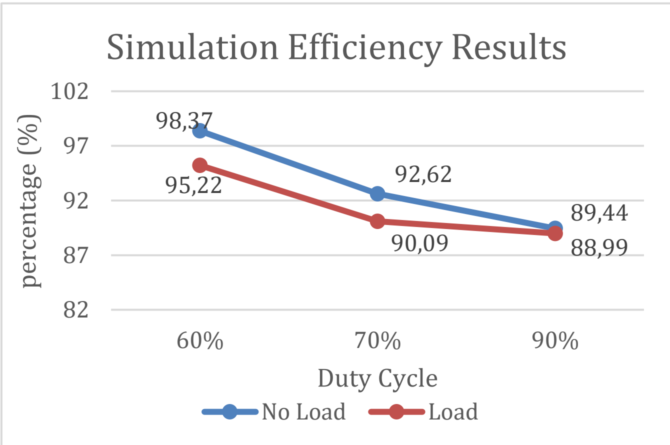

Figure 3. Efficiency graph of Six-Step PWM simulation at various duty cycles

Total Harmonic Distortion (THD) Analysis

THD analysis revealed a significant improvement with increasing duty cycle, Figure 4 showed a 46.12% reduction from 60% to 90% under no-load conditions (107.82% to 61.70%). The BLDC motor provided a natural filtering effect that attenuated harmonics, particularly noticeable at lower duty cycles where loaded conditions consistently produced lower THD than no-load conditions.

However, THD levels above 60% are considered very high. This is inherent to the Six-Step PWM method, as the trapezoidal waveform produced by six-step commutation introduces strong low-order harmonics, particularly the 5th, 7th, and 11th orders, which dominate the harmonic spectrum. These harmonics cannot be eliminated without additional filtering, explaining why the measured THD far exceeds the IEEE 519 recommended limit of <5%.

The best THD performance was achieved at 90% duty cycle under no-load conditions (61.70%), which approaches the theoretical limit for six-step methods reported in literature (~62%). To make Six-Step PWM suitable for stricter industrial or regulatory environments, mitigation strategies such as LC filters, third-harmonic injections, or hybrid PWM techniques should be considered.

Table 4. THD Results of Six-Step PWM Simulation

Duty Cycle	Condition	THD Vab (%)	THD Vbc (%)	THD Vca (%)	Avg. THD (%)
60%	No-load	108	108	106	107.82
60%	Loaded	96	100	97	97.67
70%	No-load	93	90	93	92.58
70%	Loaded	78	78	79	78.33
90%	No-load	61	63	60	61.70
90%	Loaded	80	80	80	80.00

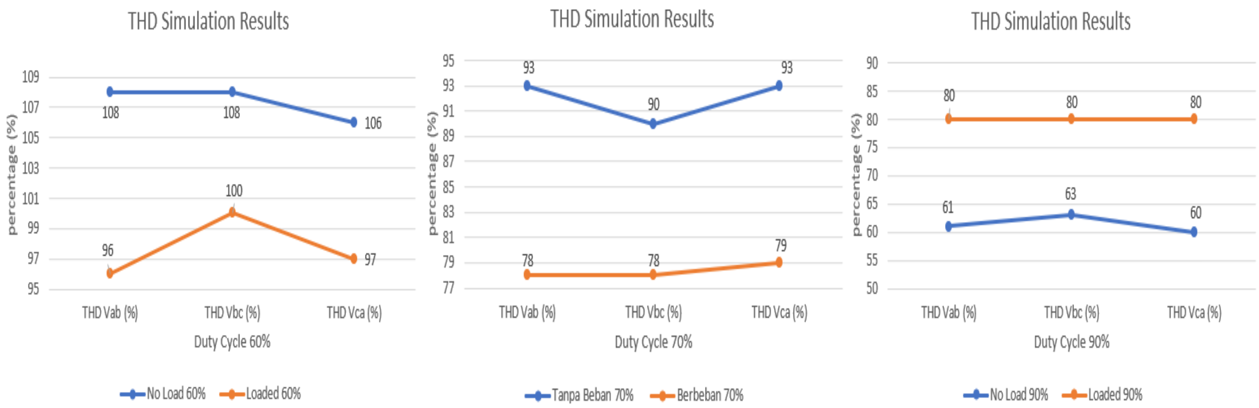

Figure 4. THD graph of Six-Step PWM simulation at various duty cycles

Commercial Controller Validation Results

The Votol EM-50S controller, which employs the SPWM method with a switching frequency of 13–14 kHz, was tested as a commercial technology benchmark. The testing conditions matched those used in the Six-Step PWM simulations.

1. SPWM Voltage and Current Characteristics

The line-to-neutral voltages were well-balanced: no-load 21.50 V (60%), 24.20 V (70%), 24.53 V (90%); loaded 20.80 V (60%), 22.57 V (70%), 23.57 V (90%).

The line-to-line voltages were: no-load 29.80 V (60%), 36.73 V (70%), 40.63 V (90%); loaded 27.17 V (60%), 32.20 V (70%), 38.80 V (90%).

Current measurements showed a nonlinear trend with a sharp increase at the 90% duty cycle: no-load 1.8 A (60%), 2.96 A (70%), 16.73 A (90%); loaded 7.53 A (60%), 14.06 A (70%), 18.46 A (90%).

2. Efficiency and THD of Votol Controller

Table 5. Votol EM-50S controller test results

Duty Cycle	Condition	Pin (W)	Pout (W)	Efficiency (%)	Avg. THD (%)
60%	No-load	110.4	79.5	72.01	31.9
60%	Loaded	408.0	330.7	81.05	36.0
70%	No-load	153.6	129.9	84.57	36.6
70%	Loaded	811.2	617.5	76.11	32.1
90%	No-load	888.0	734.7	82.73	44.4
90%	Loaded	1065.6	810.7	76.07	43.8

The SPWM method achieved its best efficiency at a 70% duty cycle under no-load conditions (84.57%), with THD remaining stable between 31.9% and 44.4%.

Comparison Between Six-Step PWM and SPWM

The efficiency comparison chart (Figure 5) shows that Six-Step PWM consistently outperforms SPWM in all operating conditions, with the largest gap at 60% duty cycle under no-load (26.36%) and the smallest at 90% duty cycle under no-load (6.71%). Conversely, the THD comparison chart (Figure 6) indicates that SPWM excels in signal quality, maintaining much lower and more stable THD levels. These results highlight a clear trade-off between high efficiency in Six-Step PWM and superior signal quality in SPWM. This confirms the fundamental trade-off between efficiency and signal quality: Six-Step PWM offers an average efficiency advantage of 13.60% but produces THD that is 48.88% higher than SPWM.

Table 6. Performance comparison of both methods

Parameter	Six-Step PWM	SPWM Votol	Difference
Average Efficiency	92.46%	78.86%	+13.60%
Average THD	86.35%	37.47%	+48.88%
Highest Efficiency	98.37%	84.57%	+13.80%
Lowest THD	61.70%	31.90%	+29.80%

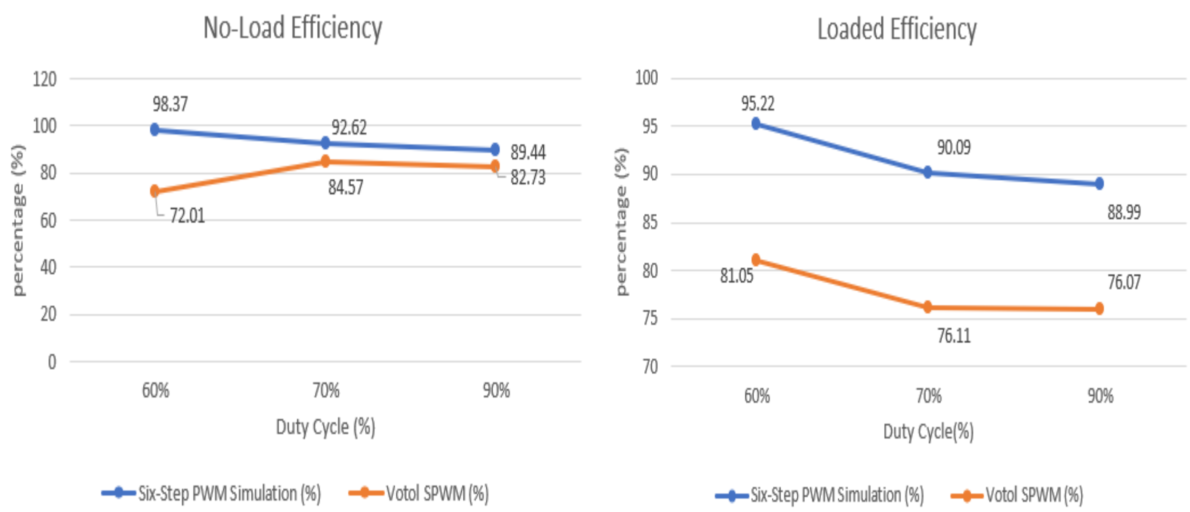

Figure 5. Efficiency comparison: Six-Step PWM vs. SPWM Votol

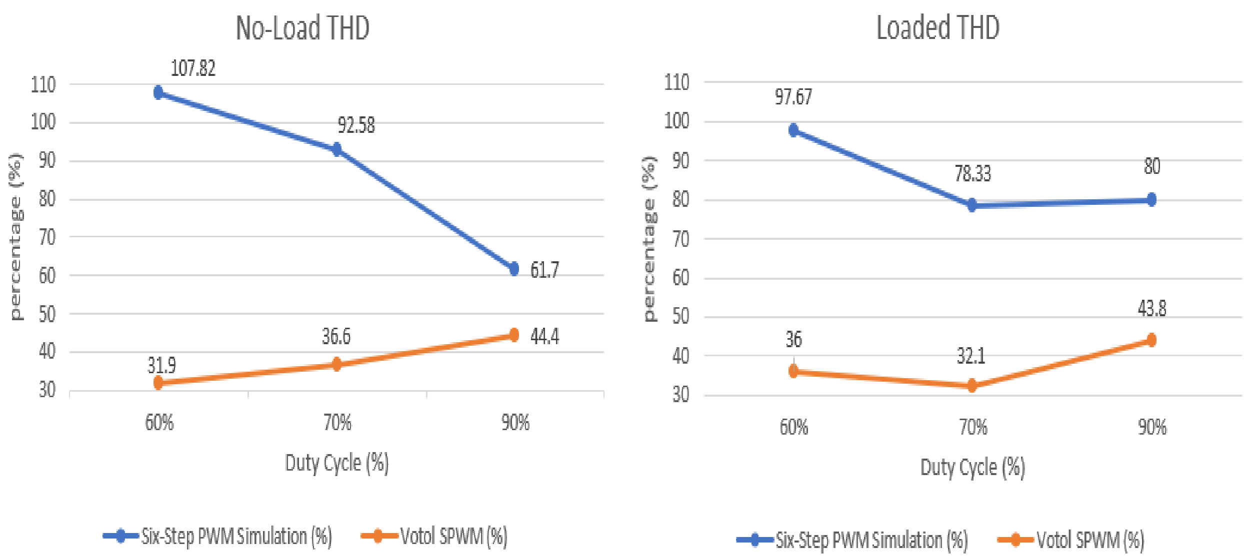

Figure 6. THD comparison: Six-Step PWM vs. SPWM Votol

Performance Optimization Analysis

The results indicate that duty cycle selection significantly impacts both efficiency and THD characteristics. For Six-Step PWM, 60% duty cycle provides maximum efficiency but highest THD, while 90% duty cycle offers the best THD performance with acceptable efficiency. This suggests that optimal operating points exist for different application requirements. For applications prioritizing energy efficiency and extended driving range, Six-Step PWM at 60–70% duty cycle provides substantial advantages. The 13.60% average efficiency improvement over commercial SPWM could translate to 15–20% increased driving range in electric vehicles, a significant advantage for consumer acceptance and practical utility.

However, for applications requiring compliance with strict harmonic standards or minimal electromagnetic interference, SPWM remains preferable despite lower efficiency. The consistent THD performance of SPWM makes it more suitable for sensitive electronic environments or where regulatory compliance is mandatory. The observed THD values at higher duty cycles are consistent with theoretical predictions of six-step commutation, where harmonic content approaches 62% under ideal no-load conditions. This shows that the simulation results are in line with established theory. Furthermore, the efficiency improvement of up to 13.6% compared to conventional SPWM confirms that Six-Step PWM offers tangible performance benefits under certain operating points. Despite these advantages, the reliance on duty cycle tuning highlights a limitation of Six-Step PWM. While efficiency peaks around 60–70%, the associated THD levels may exceed acceptable limits for grid-connected or sensitive electronic applications. This trade-off emphasizes the need for additional filtering methods to achieve both high efficiency and acceptable waveform quality. In particular, mitigation strategies such as LC filters, third-harmonic injection, and hybrid PWM techniques may be considered to reduce THD while maintaining efficiency [9], [14], [18].

System Balance and Stability

Phase balance analysis revealed that Six-Step PWM maintains excellent balance under no-load conditions but experiences increased imbalance under load, particularly at higher duty cycles. This characteristic suggests that practical implementations may require additional balancing circuits or control methods to ensure stable operation under varying load conditions. The loaded condition testing demonstrated that the method can handle significant power levels (up to 2.3 kW input power) while maintaining efficiency above 88%, indicating robust performance for electric vehicle applications. The current handling capability of up to 40 A output current confirms suitability for high-power motor drive applications. The phase imbalance observed under loaded conditions reflects a common limitation of six-step control, particularly at higher duty cycles where commutation overlaps become more pronounced. This suggests that practical implementations may require balancing circuits or simpler control improvements to maintain stability under dynamic loading conditions. Another limitation lies in the absence of active filtering, which contributes to higher current distortion. Future research can be directed toward the application of LC filters to reduce THD and the development of more optimized control methods, so that both system efficiency and stability can be further improved.

4. Conclusions

The Six-Step PWM method successfully converted a 48 V DC input into AC output with an efficiency range of 88.99%–98.37% across all test conditions, consistently surpassing the 70% efficiency benchmark and outperforming the Votol EM-50S SPWM controller (72.01%–84.57%). On average, Six-Step PWM delivered a 13.60% efficiency advantage, which could translate into a 15–20% increase in driving range for EV applications. Increasing the duty cycle from 60% to 90% produced opposite effects on efficiency and THD. Efficiency decreased from 98.37% to 88.99% due to increased switching losses, while THD improved from 107.82% to 61.70%. However, the THD values remained far above the <5% target recommended by IEEE 519 [19], demonstrating that Six-Step PWM requires additional harmonic mitigation measures for compliance with strict standards. This work quantifies the efficiency vs. THD trade-off of Six-Step PWM compared with SPWM in EV BLDC drives: Six-Step PWM is optimal for applications prioritizing energy efficiency and extended driving range, while SPWM remains superior for applications demanding low harmonic distortion. The main limitation of this study is that it relied on simulation and comparison with a single commercial controller benchmark, without hardware prototype validation. Future work should focus on experimental implementation, hardware testing, and the integration of harmonic mitigation methods such as LC filters, hybrid PWM, or advanced modulation schemes to balance efficiency and power quality.

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