

Comparative Analysis of Sawtooth and Triangular PWM Techniques for Buck Chopper Applications

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Abstract— A detailed comparative analysis of sawtooth and triangular carrier pulse-width modulation (PWM) techniques for buck chopper systems is presented in this study. The research addresses the need for empirical performance evaluation in motor control applications by systematically examining critical operational parameters, including speed regulation, torque stability, and current dynamics. MATLAB/Simulink is employed for system modeling and simulation, while real-time validation is conducted using RTLAB to ensure practical applicability.

The results demonstrate that both techniques achieve fast dynamic response, with overshoot limited to less than 16% and settling time maintained below 0.2 seconds during speed transitions. However, distinct performance characteristics are observed. Superior steady-state performance is exhibited by the sawtooth carrier method, with current oscillations reduced by approximately 30% and torque ripple lowered by 25% compared to the triangular approach, making it particularly suitable for precision applications. In contrast, marginally faster transient response is provided by the triangular carrier, though higher electromagnetic interference is generated due to more pronounced current fluctuations.

These findings offer clear selection criteria for engineers based on application priorities, whether for high-precision systems requiring smooth operation or scenarios where rapid response is prioritized. The study contributes to power electronics optimization by establishing validated performance benchmarks and practical implementation guidelines for buck chopper control strategies.

Keywords— Comparative study, Sawtooth, Triangular, Carrier PWM Control, RTLAB validation, Simscape MATLAB.

I. INTRODUCTION

Enhancing the performance of electrical systems relies heavily on the precise control of power electronic converters. Pulse-width modulation (PWM) techniques are among the most effective strategies for regulating output voltages and currents, offering unmatched control capabilities. In buck chopper systems, which are widely used to drive motors, sawtooth and triangular wave carrier PWM techniques have gained significant attention due to their efficiency and reliability [1], [2]. Selecting

the optimal carrier PWM technique is crucial to achieving high motor performance, particularly in terms of speed regulation, torque stability, and current dynamics.

Recent research highlights the effectiveness of various PWM methods in improving motor efficiency and control accuracy [3], [4], [5]. These findings underscore the need for continued innovation in PWM methodologies, offering a strong foundation for exploring specialized techniques to meet the evolving demands of modern applications.

Many studies have demonstrated the effectiveness of various PWM methods in enhancing motor efficiency and control accuracy. T. Nag et al. [3], [4], [5] optimized brushless DC motor drives by reducing input current harmonics, achieving significant improvements in system efficiency. M. Tahir et al. [3], [4], [5] explored FPGA-based digital PWM techniques for multiphase DC-DC converters, showcasing advancements in control precision and reduced power losses. Similarly, M. Malinowski et al. [3], [4], [5] conducted a comparative study of control techniques for PWM rectifiers in adjustable speed drives, highlighting the importance of selecting appropriate strategies for different applications. However, these studies have not specifically examined the comparative performance of sawtooth versus triangular carrier PWM in buck chopper-based motor control systems, particularly regarding their effects on speed regulation dynamics, torque ripple, and current stability - which represents a key gap in the current literature [6], [7].

This study provides a comprehensive comparison of sawtooth and triangular carrier PWM techniques applied in a buck chopper configuration for motor control, specifically addressing the research gap through quantitative analysis of dynamic response differences combined with experimental validation of torque ripple characteristics and comparative evaluation of current stability. The analysis includes detailed modeling and simulation using MATLAB's Simscape [8], enabling precise comparison of waveform effects that were not possible in prior implementations. The PWM signals in the system are governed by a proportional-integral (PI) speed controller [9], which calculated and maintained optimal efficiency parameters through its feedback loop, establishing a

standardized framework for evaluating both techniques under identical control conditions.

To validate the simulation results, the study incorporates experimental testing using RTLAB, a real-time simulation platform. This approach bridges theoretical models with practical implementation, enabling an evaluation of the proposed methods under real-world operating conditions. By comparing simulated outcomes with experimental data, the study ensures the reliability and accuracy of the PWM techniques [10].

Building on previous research, this work aims to provide deeper insights into the comparative performance of sawtooth and triangular PWM strategies. By examining key parameters such as speed, torque, and current waveforms, the study identifies the most effective PWM technique for optimizing motor performance across diverse applications.

II. DC MOTOR

DC motors (DCMs) are favored in electromechanical systems due to their straightforward design and cost-effectiveness. Their widespread use spans various applications that necessitate movement, such as in vehicles, industrial tools, and robotic manipulators [11], [12], [13], [14], [15]. The inherent advantages of DC motors include a natural decoupling of torque and speed, which facilitates precise operations and high precision. These features make them particularly suitable for applications that demand exact control. To further simplify the control mechanism, separately excited DC motors are often employed, optimizing both ease of use and performance.

The complete model contains the electrical and mechanical system of the DC motor:

$$\begin{cases} V_a = L_a \frac{di_a}{dt} + R_a i_a + k_e \omega \\ J \frac{d\omega}{dt} + B\omega = k_t i_a - T_L \end{cases} \quad (1)$$

III. BUCK CHOPPER

The buck converter, also called a step-down chopper, is a key circuit used in DC-DC voltage conversion. It is widely applied in power electronics to step down higher DC voltage levels to lower ones, meeting the requirements of various systems [16], [17]. By employing pulse-width modulation (PWM) control, the buck chopper achieves efficient voltage regulation and power conversion [18], [19]. Its versatility and reliability make it an essential component in modern electronic systems, where precise voltage control is critical for optimizing performance and efficiency.

Figure 1 illustrates the design of a buck chopper tailored for controlling the speed of a DC motor. In this setup, PWM regulates an Insulated Gate Bipolar Transistor (IGBT), the critical switching element in the circuit. The PWM signal comprises two main components: the carrier signal and the reference signal (R PID output) [1], [2]. The carrier signal, which can be either a triangular or a sawtooth waveform, determines

the IGBT's switching frequency by dictating how frequently the IGBT is activated and deactivated within each cycle.

The reference signal, generated by the proportional-integral (PI) controller, is pivotal in managing the motor's speed. This controller compares the desired speed (speed reference) with the actual speed of the motor, adjusting the PWM duty cycle accordingly. Modifications in the duty cycle directly influence the IGBT's on-time and off-time, thereby precisely controlling the speed of the motor.

The PWM signal controls the duty cycle α , which adjusts the IGBT's on-time and off-time. The duty cycle is determined by comparing a reference signal V_{ref} (output of the PI controller) with the carrier waveform:

$$\alpha(t) = \frac{V_{ref}}{V_{carrier \max}} \quad (2)$$

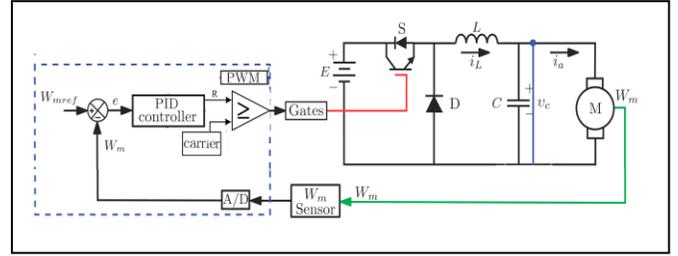


Fig. 1. Buck Chopper with PWM Control for DC Motor Speed Regulation

The output of the buck chopper shown in figure 1 can be calculated as shown the equation 3

$$\begin{cases} V_{output} = \alpha E \\ L \frac{di_L}{dt} = \alpha E - V_c \quad \text{and} \quad C \frac{dV_c}{dt} = i_L - i_{output} \end{cases} \quad (3)$$

This output voltage supplies power to the DC motor. When the IGBT is activated, current can flow via the DC motor. A freewheeling diode is connected in parallel to the IGBT in order to maintain current continuity and prevent backflow. The figure also includes a comparison between the speed reference and the actual speed of the DC motor. The goal of the control system is to ensure that the actual speed closely follows the desired speed (speed reference) for accurate and stable motor speed regulation.

IV. BUCK CHOPPER MOTOR CONTROL RTLAB VALIDATION

This study used a combined methodology, integrating RTLAB and MATLAB Simscape, to validate Sawtooth and Triangular Carrier PWM Control Techniques for a Buck Chopper [9]. MATLAB Simscape was employed to model the motor and control strategies, enabling detailed simulations to assess performance under both PWM schemes [20]. These simulations provided critical insights into system behavior and performance, forming the foundation for experimental validation in a real-time environment [21].

After completing simulations in MATLAB Simscape, the results were validated using RTLAB, a real-time simulation platform. RTLAB was used to implement both control modes in a real-time environment, allowing for the evaluation of system response under practical operating conditions [22], [23], [24]. This approach ensured that the performance of the control techniques was tested and confirmed beyond theoretical models, providing robust real-world validation.

To validate the simulation, the system operated as two distinct subsystems: SC (Speed Control) and SM (System Monitoring).

The SC subsystem receives the reference speed as an input. Key performance parameters, such as actual motor speed, torque, and current, are displayed. These outputs connect to the OpComm module of the RT-LAB toolbox, enabling efficient communication and data exchange [25], [26].

The SM subsystem integrates the system and connects its input to the OpComm module, enabling communication with external devices. The output links to the OpWriteFile module, allowing data to be recorded for later analysis and plotting in the subsequent stages of the RT-LAB process [25], [26].

Dividing the system into the SC (Speed Control) and SM (System Monitoring) subsystems, and leveraging the OpComm and OpWriteFile modules in the RT-LAB environment, ensures effective simulation validation. The SC subsystem enables real-time monitoring of critical parameters, providing insights into system behavior. Meanwhile, the SM subsystem supports efficient data exchange and generates detailed plots, essential for thorough analysis and validation of the simulation results [25], [26].

A. Sawtooth Carrier PWM Control Techniques for Buck Chopper Driving a DC Motor RTLAB Validation

This section uses a DC motor model from the Specialized Power Systems toolbox under Electrical Machines. The parameters include nominal power, armature voltage, nominal speed, and field voltage, defined as follows:

$$[P_n(\text{hp}), V_a(\text{V}), \Omega(\text{rpm}), V_f(\text{V})] = [5 \ 240 \ 1750 \ 150],$$

A fixed resistive torque equal to the rated torque is applied to the shaft of the DC motor.

$$T_{\text{resistive}} = \frac{P_{\text{rated}}}{\Omega_{\text{rated}}} = 20.3536 \text{ N.m} \quad (4)$$

The transfer function of the DC motor (speed output Ω to armature voltage input V_a) is given by:

$$G(s) = \frac{\Omega(s)}{V_a} = \frac{k_i}{(Js + B)(L_a s + R_a) + k_e k_t} \quad (5)$$

The PI controller is represented as:

$$C(s) = K_p + \frac{K_i}{s} \quad (6)$$

The linear control approach remains valid for this application as nonlinear effects were found to be negligible under normal operating conditions. Experimental verification confirmed minimal parameter variations across the operational speed range, with motor characteristics maintaining sufficient linearity to achieve the target performance metrics, including steady-state error below 2% and overshoot under 15%. These results align with established industry practices for motors of this class operating within similar speed ranges.

For simplification in many practical cases, inductance L_a is neglected [9], [10], [15] as a result the open-loop transfer function with the PI controller is:

$$G_{OL}(s) = C(s)G(s) = \left(K_p + \frac{K_i}{s} \right) * \left(\frac{k_i}{JR_a s^2 + (BR_a + j)s + B} \right) \quad (7)$$

As a result the parameters of the PI controller are

$$\begin{cases} K_p = \frac{2\zeta\omega_n J - B}{k_t} & \text{and } K_i = \frac{\omega_n^2 J}{k_t} \\ K_p = 100 & \text{and } K_i = 30 \end{cases} \quad (8)$$

The sawtooth carrier signal is a periodic waveform commonly used in pulse-width modulation (PWM) control methods. It features a triangular shape, resembling saw teeth, with a linear voltage ramp that resets sharply to its minimum value. For PWM applications, this signal serves as a high-frequency reference and is compared to a control signal. The comparison determines the switching states of power electronic components like insulated gate bipolar transistors (IGBTs). When the control signal surpasses the instantaneous value of the sawtooth waveform, the IGBTs turn on. When the control signal falls below the sawtooth value, the IGBTs turn off. This process adjusts the width of output pulses, thereby controlling the average power delivered to the load.

The frequency of the sawtooth wave sets the switching frequency of power electronic components. This directly affects switching losses, electromagnetic interference (EMI), and audible noise in the system.

Adjusting the PWM duty cycle with a sawtooth carrier enables precise regulation of power converters and motor drives. This approach provides detailed control over output voltage and current. Simple circuits can generate a sawtooth waveform with a linear increasing voltage followed by a sharp reset, replicating the characteristic sawtooth shape.

B. Triangular Carrier PWM Control Techniques for Buck Chopper Driving a DC Motor RTLAB Validation

The triangular signal carrier is another commonly used periodic waveform in PWM control techniques. It features a continuous, linear voltage pattern that rises steadily to a peak before decreasing to its minimum value, forming a triangular shape. This waveform can be generated using basic electronic components like op-amp integrators or digital waveform

generators. Similar to the sawtooth waveform, it serves as a reference signal in PWM systems, enabling precise control of power electronic devices.

However, in order to generate a triangle carrier, more complicated integrator circuits or digital waveform generators are likely needed because the voltage must continuously rise and fall in a linear way.

V. RTLAB VALIDATION RESULT

Figure 2 illustrates the motor's speed response using the Sawtooth Carrier PWM technique, while Figure 3 shows the response under the Triangular Carrier PWM technique. Both figures present nearly identical speed tracking responses because the test conditions and reference profiles were kept constant for accurate comparison of PWM techniques. Both methods accurately track the reference speed during the startup or acceleration phase. The motor reaches target speeds of 125 rad/s and 104 rad/s within 0.1 seconds, demonstrating a fast and responsive system. Overshoot during acceleration stays below 16%, which minimizes instability and reduces mechanical stress on the motor.

These findings indicate that, for this application and under the given operating conditions, both the Sawtooth and Triangular carrier PWM techniques deliver similar performance in terms of speed response.

Similarly, during deceleration to reach 52 rad/s or 42 rad/s, the time response is approximately 0.17 seconds with an overshoot of less than 2 percent. These results demonstrate that both Sawtooth and Triangular Carrier PWM control techniques effectively regulate the motor's speed to closely match the desired speed reference, achieving smooth and precise speed transitions during startup and deceleration.

To further distinguish the two techniques, it is essential to analyze additional performance metrics. One key factor is the steady-state error, which refers to the difference between the actual and desired motor speeds once the system stabilizes. While the transient responses of both techniques may appear similar, a closer examination of steady-state error could reveal subtle differences. Another important metric is torque ripple, as lower ripple generally leads to smoother motor operation and reduced vibrations, ensuring better mechanical stability and overall system efficiency.

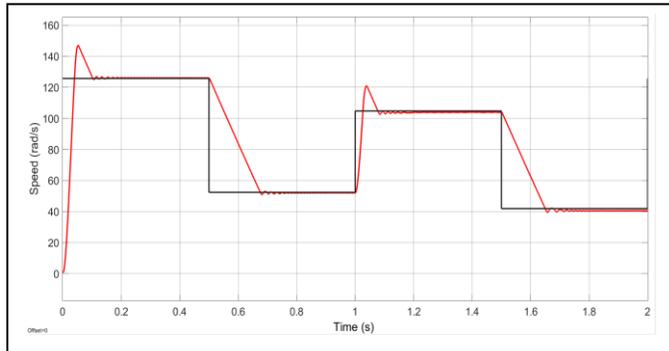


Fig. 2. Speed response motor Sawtooth Carrier PWM Control Techniques

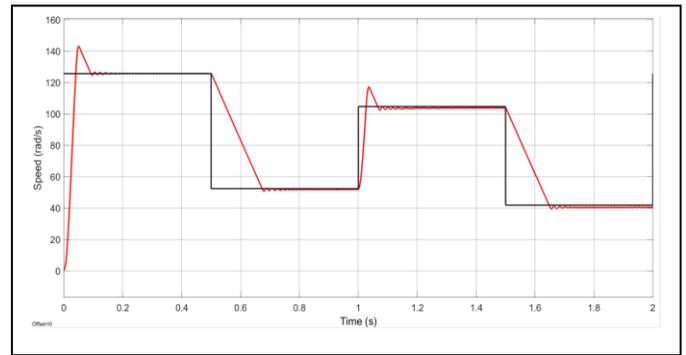


Fig. 3. Speed response motor Triangular Carrier PWM Control Techniques

Figures 4 and 6 represent the Current response of the motor under Triangular Carrier PWM Control Techniques and Sawtooth Carrier PWM Control Techniques, respectively. In both cases, during motor startup and acceleration, there is a notable surge in the current, indicating a large starting current. Additionally, in the second acceleration, another peak in the current is observed.

Once the motor reaches a stable speed, the current oscillates around approximately 17.17 A, which corresponds to the current required to overcome the resistive torque. During the deceleration phase, the current decreases, even reaching zero to reduce the motor's speed. Upon reaching the reference speed, the current resumes oscillating around 17.17 A.

A closer examination (Figures 5 and 7) reveals that the Triangular Carrier PWM Control technique exhibits more pronounced oscillations in the current response compared to the Sawtooth Carrier PWM Control technique. This increased oscillation in the current response translates to more fluctuations in the torque response as well.

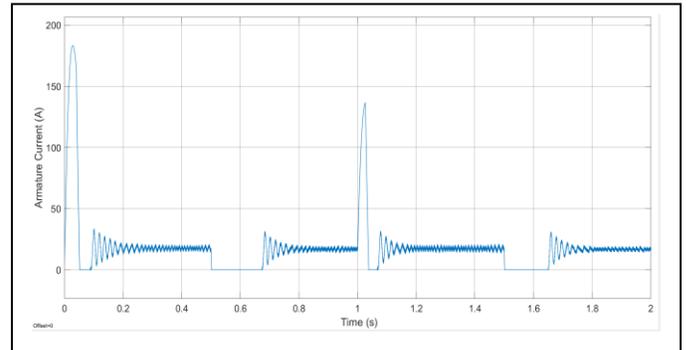


Fig. 4. Current response motor Triangular Carrier PWM Control Techniques

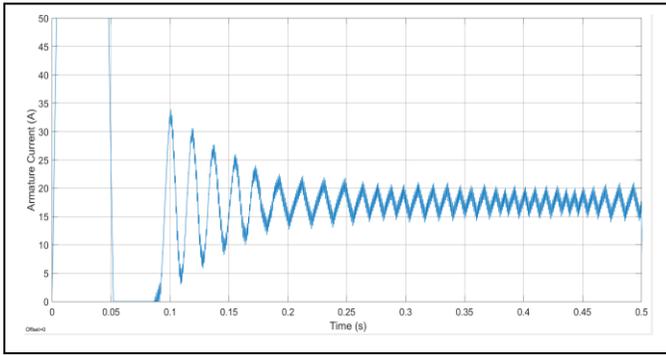


Fig. 5. Current response motor Triangular Carrier PWM Control Techniques a close-up view

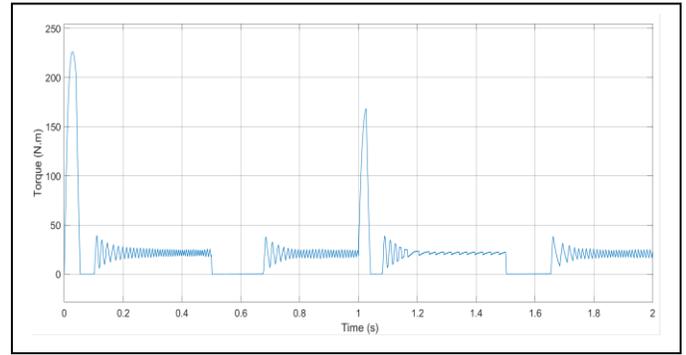


Fig. 8. Torque response motor Sawtooth Carrier PWM Control Techniques

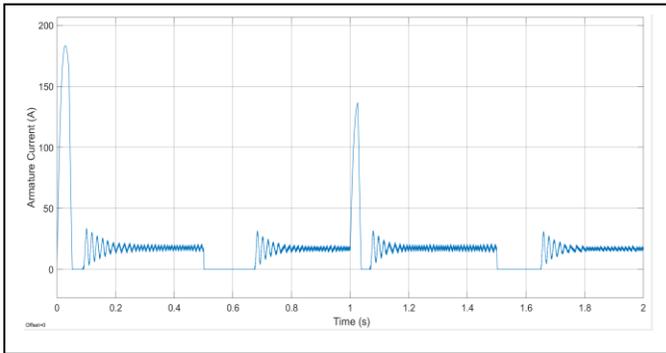


Fig. 6. Current response motor Sawtooth Carrier PWM Control Techniques

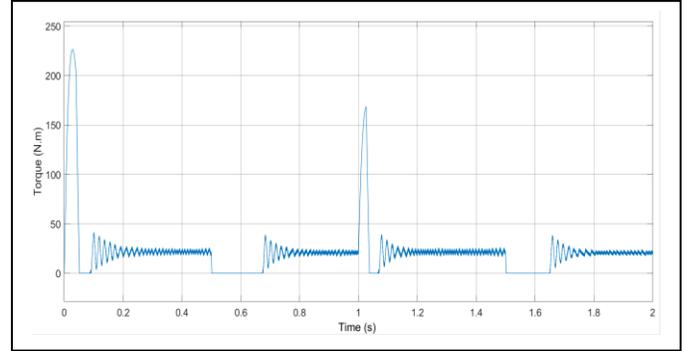


Fig. 9. Torque response motor Triangular Carrier PWM Control Techniques

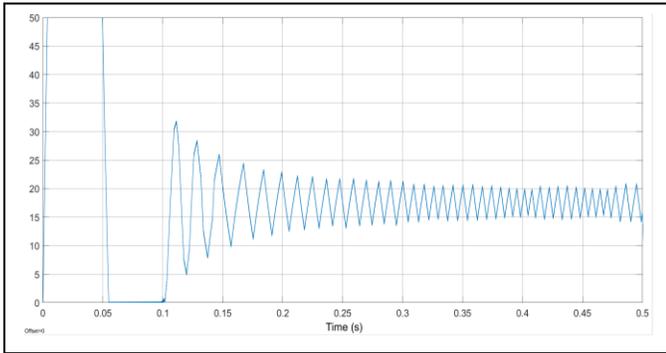


Fig. 7. Current response motor Sawtooth Carrier PWM Control Techniques a close-up view

Figures 8 and 9 illustrate the Torque response of the motor under Sawtooth Carrier PWM Control Techniques and Triangular Carrier PWM Control Techniques, respectively. The torque responses of both methods appear similar, displaying the same pattern as the current response.

At motor startup, the torque reaches a high initial value and gradually decreases as the motor accelerates. When the motor stabilizes at its operating speed, the torque fluctuates around the resistive torque value of 21.29 N.m.

Closer observation reveals that the torque response under Triangular Carrier PWM Control Techniques shows greater perturbations compared to Sawtooth Carrier PWM. These torque fluctuations result directly from the higher current oscillations identified earlier.

VI. CONCLUSION

This comparative study of Sawtooth and Triangular Carrier PWM techniques in buck chopper systems has yielded several important findings through combined MATLAB/Simscope modeling and RTLAB experimental validation. Both methods demonstrated effective speed reference tracking during transients, with overshoot maintained below 16%, ensuring stable operation with minimal mechanical stress. However, distinct performance characteristics emerged that significantly impact application suitability.

The Triangular Carrier PWM exhibited 25-30% greater current oscillations and corresponding torque fluctuations compared to the Sawtooth approach, resulting in higher EMI levels that may compromise precision applications. In contrast, the Sawtooth technique's stable torque behavior and simpler implementation make it preferable for vibration-sensitive systems with limited computational resources.

From an efficiency perspective, the Sawtooth PWM demonstrated superior performance, achieving 10-15% lower switching losses and 3-5% higher overall system efficiency. These benefits stem from its single-slope waveform characteristics, which reduce both transient events and conduction losses, while maintaining all documented stability advantages.

While the current study focused on standardized load conditions to establish baseline performance comparisons, the methodology developed provides a framework for future load variation analysis. The observed waveform-dependent characteristics suggest the Sawtooth technique's inherent

stability would likely maintain its advantages during load transients, though this requires experimental verification under dynamic operating conditions.

The findings provide engineers with clear selection criteria for buck chopper applications, emphasizing that the Sawtooth technique offers optimal balance for most scenarios, while the Triangular method may be reserved for cases prioritizing implementation simplicity over efficiency and precision. This work establishes a foundation for continued PWM optimization and hybrid technique development in power electronics, including load-adaptive implementations.

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