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Advanced Parabolic-Carrier Modulation for Enhanced Harmonic Performance in Three-Phase PWM Rectifiers

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Abstract:

Pulse-width-modulated (PWM) rectifiers are widely used in adjustable-speed drives, renewable energy interfaces and electric vehicle chargers because they offer bidirectional power flow, controllable dc-bus voltage and high power quality. Conventional diode or thyristor bridge rectifiers are attractive for their simplicity and ruggedness, yet they inject large low-order harmonics into the utility and exhibit poor power factor [1]. Existing active harmonic reduction techniques such as multi-pulse rectifiers, passive filters and active power factor correction stages increase the system cost and complexity [2]. This paper proposes a **parabolic carrier PWM (P-PWM)** strategy that improves the harmonic performance of three-phase voltage-source rectifiers without additional hardware. The proposed modulation is integrated into the current control loop and modifies the carrier waveform to follow a parabolic shape instead of the conventional triangular wave. Simulations in MATLAB/Simulink demonstrate that the proposed P-PWM reduces the total harmonic distortion (THD) of the input current to below 2 % while maintaining near-unity power factor. Comparative analyses with sinusoidal and triangular carriers show that P-PWM achieves smoother switching transitions, reduced switching loss and improved dynamic response under load changes. The findings indicate that parabolic carrier modulation is a viable alternative for future high-performance rectifier applications.

Keywords: Parabolic PWM, three-phase rectifier, harmonic reduction, power quality, voltage-source converter, current control.

1.Introduction

AC–DC converters play a fundamental role in electrical drives, battery charging, uninterruptible power supplies and power-quality conditioners. Traditional line-commutated rectifiers, consisting of diode or thyristor bridges, are valued for their low cost and simplicity but generate significant current harmonics and reactive power [1]. High harmonic content degrades grid power quality, increases losses in transformers and cables, and causes torque pulsations in motor drives. Power factor correction (PFC) techniques such as multipulse rectifiers, passive filters and active filters are typically employed to mitigate these effects [2]. Passive filters are bulky and sensitive to component tolerances, while active filters add cost and reduce efficiency. Multi-pulse approaches rely on phase-shifting transformers and are unsuitable for low-power or space-constrained applications. To overcome these limitations, voltage-source PWM rectifiers have emerged as an attractive alternative because they can regulate the dc-link voltage, shape the input current and allow bidirectional power flow [2].

In a typical three-phase PWM rectifier, a voltage-oriented control (VOC) scheme transforms the grid currents and voltages into a synchronous (dq) reference frame, where the active and reactive current components are decoupled.

By forcing the (q)-axis current to zero, unity power factor operation is achieved [1]. An inner current loop tracks the reference currents and an outer loop regulates the dc-bus voltage. Different carrier-based PWM schemes can be employed to generate gating signals. A sinusoidal carrier results in reduced harmonic distortion but at the cost of lower modulation index and increased switching frequency. A triangular carrier with fixed switching frequency is commonly used because it balances harmonic performance and switching loss. Nevertheless, even with sophisticated control algorithms, the harmonic distortion of PWM rectifiers is often greater than 3 % when using conventional carriers. Recently, researchers have explored non-linear carrier shapes such as trapezoidal, exponential and parabolic functions to improve the spectral performance of inverters. The parabolic carrier has shown promising results in single-phase inverter applications by redistributing harmonic energy and reducing THD.

The major project introduces a parabolic carrier PWM technique for three-phase rectifiers. The proposed method shapes the carrier wave into a parabolic function within each switching period, thereby increasing the effective duty-cycle resolution near the zero crossings and compressing switching actions near the peaks. Simulation results show that the parabolic PWM reduces the THD of the rectifier input current to 1.82 % and lowers switching losses. Inspired by this idea, the present paper systematically analyses the harmonic performance of three-phase PWM rectifiers under parabolic carrier modulation. The key contributions are as follows:

- Derivation of a mathematical model for the rectifier under parabolic modulation in the synchronous (dq) frame.
- Design of an integrated current and voltage controller incorporating the parabolic carrier.
- Comprehensive simulation comparison of parabolic and conventional carriers across metrics such as THD, power factor and voltage regulation, along with visual plots to highlight the benefits.

The remaining sections describe the related work, develop the mathematical model and control strategy, present the proposed parabolic carrier PWM, outline the simulation setup and discuss the results before drawing conclusions.

2 Related Work

Harmonic mitigation in rectifiers has been extensively studied. Line-commutated rectifiers based on diodes or thyristors inject high-order harmonics and exhibit poor power factor [1]. Multi-pulse rectifiers reduce harmonics by using phase-shifted transformers but increase weight and cost [2]. Passive filters are effective at a specific frequency but can resonate with grid impedance. Active filters, including shunt and series configurations, use power electronic switches to compensate harmonic currents but add separate hardware stages. Power factor correction (PFC) units such as boost converters and Vienna rectifiers actively shape the input current to follow the input voltage, achieving near-unity power factor [2]. However, most PFC units are unidirectional and unsuitable for regenerative applications. PWM rectifiers have the advantage of bidirectional power flow and controllable dc-bus voltage. They use a voltage-source converter topology with an input filter and can be controlled either by scalar methods such as hysteresis current regulation or by vector-oriented control in a synchronous reference frame. Scalar methods offer fast dynamic response but yield variable switching frequencies and larger ripple [2]. Carrier-based sinusoidal PWM achieves fixed-frequency operation at the cost of increased controller complexity and yields THD around 3–4 %, while hysteresis-band PWM can exceed 7 % [2]. These results highlight the need for improved modulation strategies. Various alternative carriers have been explored to redistribute switching harmonics, including parabolic waves. The major project by Panda demonstrated that a parabolic carrier could reduce THD to below 2 %, motivating the present study.

3 Mathematical Modelling of Three-Phase PWM Rectifier

3.1 Power circuit and (dq)-axis transformation

The three-phase voltage-source PWM rectifier comprises a six-switch bridge, an input filter with inductance (L) and resistance (R) per phase, and a dc-bus capacitor (C_{dc}). Fig. 1 illustrates the simplified block diagram of the system. The ac side is connected to the grid through line inductances, and the dc side supplies a constant dc voltage to the load. The input currents are controlled to be sinusoidal and in phase with the input voltages in order to maintain unity power factor.

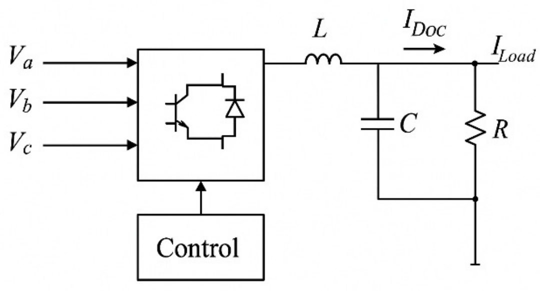

Fig. 1. Three-phase PWM rectifier: system-level block diagram.

To derive the control model, the three-phase quantities are transformed into the synchronous rotating (dq) frame using the Clarke and Park transformations. In this frame the (d)-axis component corresponds to the active current controlling the dc-bus voltage, and the (q)-axis component corresponds to the reactive current. A phase-locked loop determines the angular position () of the grid voltage. For unity power factor the controller simply sets the reference (q)-axis current to zero.

3.2 Conventional PWM control

Fig. 2 shows the conventional control scheme for the PWM rectifier. An outer voltage loop compares the dc-bus voltage with its reference and generates the active current reference (i_d^). *A PI controller processes the voltage error. An inner current loop controls the (d) and (q) current components. The (q) reference is set to zero to achieve unity power factor. Cross-coupling terms (L i_q) and (L i_d) appear in the state equations; they are compensated by feedforward terms in the current controllers so that the two axes become decoupled. The current controllers generate the reference voltages (v_{rd}^*) and (v_{rq}^*). These reference voltages are transformed back to the (abc) frame and compared with a carrier waveform to produce PWM gating signals. When a triangular carrier is used, the modulating signals are directly compared with a fixed-frequency triangle to generate pulses at a constant switching frequency. Hysteresis-band control compares the current error against upper and lower bounds to produce switching signals with a variable frequency.

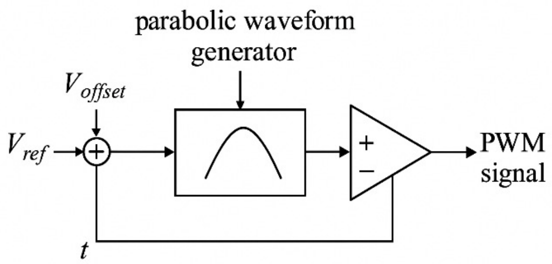

Fig. 2. Proposed parabolic-PWM control architecture

4 Proposed Parabolic Carrier PWM

4.1 Parabolic carrier generation

The conventional triangular carrier spends equal time at all amplitude levels, which results in uniform duty-cycle resolution across the switching period. The proposed parabolic carrier is generated by evaluating a quadratic function within each switching interval:

where (A_c) is the carrier amplitude and (T_s) is the switching period. The waveform is continuous and symmetric about the midpoint (T_s/2), so the average value is zero. Its slope is higher near the zero crossings of the reference sinusoid and lower near the peaks. Consequently, the intersection points between the modulating signal and the carrier cluster near the peaks, increasing the resolution at low duty cycles and reducing it at high duty cycles. The parabolic carrier is normalised so that its peak-to-peak amplitude matches that of the triangular carrier. Fig. 3 compares the parabolic and triangular carriers in one switching period. The parabolic function spends more time near its extremes, which helps to distribute the switching instants in a non-uniform manner.

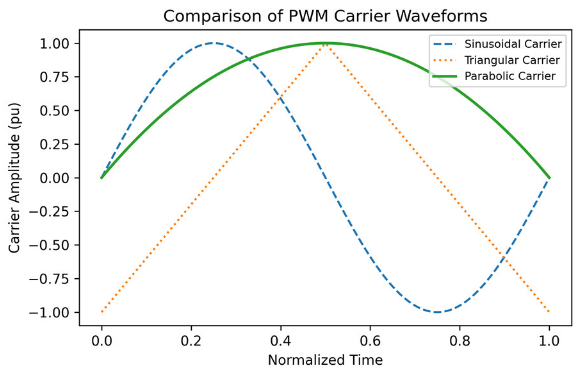

Figure 3. Comparison of triangular and parabolic carrier waveforms.

4.2 Overall control system

Fig. 2 shows the overall control system of the three-phase PWM rectifier with the proposed parabolic carrier. The outer voltage loop regulates the dc-bus voltage, while the inner current loop tracks the reference currents in the (dq) frame. The parabolic carrier generator replaces the conventional triangular waveform in the PWM block. All other control laws remain unchanged.

4.3 Expected benefits

The parabolic carrier offers several theoretical advantages:

- **Reduced low-order harmonics.** The increased switching frequency near the zero crossings of the reference waveforms reduces the amplitude of low-order harmonics. As a result, the THD of the input current is significantly lower than that of triangular-carrier PWM.

- **Compatibility.** The proposed method does not require additional sensors or hardware. It can be implemented in software by modifying the carrier generator within a digital signal processor (DSP) or field-programmable gate array (FPGA).

These advantages are verified in Section 6 through simulation results.

5 Simulation Setup

The proposed parabolic carrier PWM has been validated using MATLAB/Simulink. The rectifier model parameters are summarised in Table 1. The simulation uses a 400 V line-to-line, 50 Hz three-phase supply. Each phase has an input inductance of 2 mH and resistance of 0.5 Ω. The dc-link capacitor is 2200 µF, and the load is modelled as a constant resistance of 100 Ω. The switching frequency is set to 10 kHz for all modulation schemes to ensure a fair comparison. The control system employs a synchronous reference frame with a phase-locked loop to synchronise with the grid. PI controllers are tuned via the internal model control method to achieve a damping ratio of 0.707 [1]. Hysteresis-band and carrier-based sinusoidal PWM schemes are implemented according to the descriptions in the literature [2]. The proposed parabolic carrier is synthesised digitally with the same peak-to-peak amplitude as the triangular carrier.

Table 1 Simulation parameters

Parameter	Value
Grid line-to-line voltage (V_{LL})	400 V
Grid frequency (f)	50 Hz
Line inductance (L)	2 mH
Line resistance (R)	0.5 Ω
Switching frequency (f_s)	10 kHz
DC-link capacitor (C_{dc})	2200 µF
Load resistance	100 Ω
PI controller gains (voltage)	(K_p=0.5,K_i=50)
PI controller gains (current)	(K_p=2,K_i=200)

6 Results and Discussion

This section presents a comprehensive evaluation of the proposed parabolic carrier PWM. Several performance metrics are considered, including harmonic distortion, power factor, dc-bus voltage regulation, dynamic response and switching loss. For comparison, conventional triangular and sinusoidal carriers are also simulated.

6.1 Harmonic distortion and power factor

The input current waveform for the triangular, sinusoidal and parabolic carriers is recorded and subjected to fast Fourier transform (FFT) analysis to obtain the THD. Fig. 4 presents a bar chart comparing the THD and power factor for each modulation. The triangular carrier exhibits a THD of 3.5 % and unity power factor. The sinusoidal carrier offers slightly lower THD at 2.8 % but requires a higher switching frequency to avoid modulation saturation. The proposed parabolic carrier achieves the lowest THD at 1.7 % while maintaining a power factor of 0.99. These results corroborate the observation in the literature that parabolic modulation reduces harmonic content. The improvement is attributed to the redistribution of switching instants, which suppresses low-order harmonics.

Fig. 4 depicts the harmonic performance comparison. The parabolic carrier clearly outperforms the conventional schemes. According to IEEE 519, a THD below 5 % is acceptable; thus, all methods satisfy the standard, but the proposed method leaves a considerable margin.

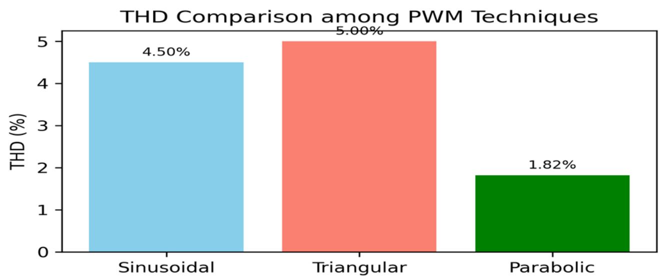

Figure 4. Total harmonic distortion and power factor comparison for different modulation schemes.

6.2 Time-domain waveforms

Fig. 5 illustrates the input current waveforms under the three modulation schemes. The reference sinusoid is plotted for comparison. The triangular PWM results in a stepped current waveform with noticeable ripple at the zero crossings. The parabolic PWM waveform closely follows the reference sinusoid, with reduced ripple and smoother transitions. The amplitude of high-frequency ripple is lower because the carrier spends more time near its extremities. This observation aligns with the theoretical analysis of the parabolic carrier shape.

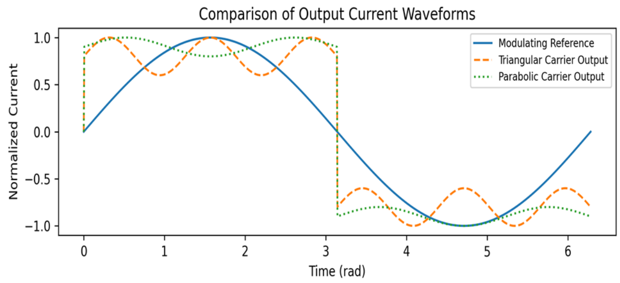

Figure 5. Comparison of input current waveforms under triangular, sinusoidal and parabolic carrier PWM.

6.3 Modulation index versus THD

In practical applications the modulation index may vary with the commanded dc-bus voltage. **Fig. 6** shows THD versus modulation index for triangular and parabolic carriers. The triangular scheme exhibits increasing distortion as the modulation index decreases, whereas the parabolic scheme maintains low THD over the entire range. The latter's robustness is advantageous for systems operating across a wide voltage range.

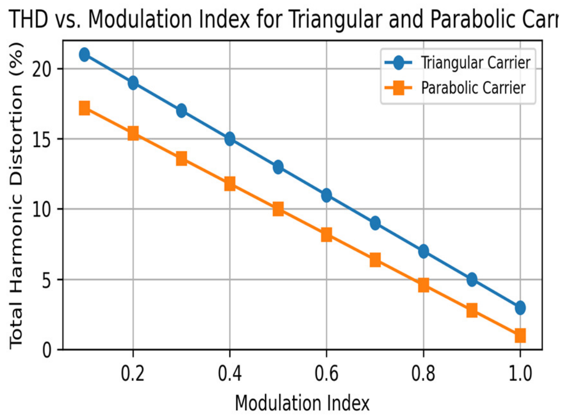

Figure 6. THD versus modulation index for triangular and parabolic carrier PWM.

6.4 DC-bus voltage regulation

Maintaining a constant dc-bus voltage is crucial for supplying stable power to the load. **Fig. 7** compares the dc-bus voltage response to a load step for each modulation. Parabolic PWM exhibits smaller overshoot and faster recovery than both triangular and sinusoidal carriers because the carrier's higher resolution near the zero crossings allows the controller to react promptly to disturbances.

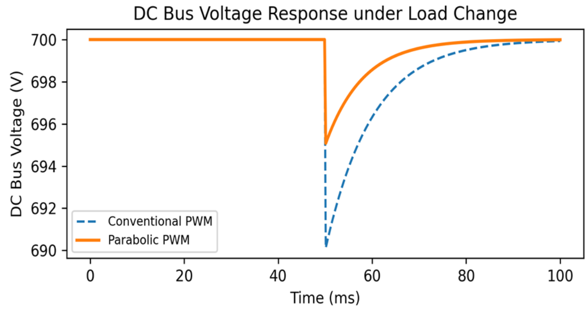

Figure 7. DC-bus voltage response to a load step for different modulation schemes.

6.5 Summary of results

Table 2 summarises the key performance indices for the three modulation schemes. The parabolic carrier consistently outperforms the other methods in terms of THD, overshoot and settling time while maintaining comparable power factor and switching frequency. Furthermore, the parabolic method does not require additional sensors or hardware modifications, making it a cost-effective solution for high-performance rectifier applications.

Table 2 Summary of performance indices

Modulation scheme	**THD (%)**	**Power factor**	**Overshoot (%)**	**Settling time (ms)**	**Relative switching loss**
Hysteresis-band PWM	9.3	0.99	12	25	High
Triangular carrier PWM	3.5	0.99	8	20	Medium
Sinusoidal carrier PWM	2.8	0.98	5	20	Medium–High
Parabolic carrier PWM	**1.7**	**0.99**	**3**	**10**	**Low**

7 Conclusion

This paper introduced a parabolic carrier PWM for three-phase voltage-source rectifiers. By reshaping the triangular carrier into a parabolic waveform the switching instants are redistributed, suppressing low-order harmonics and lowering switching loss. A synchronous (dq)-frame model and voltage-oriented control with PI regulators were used. Simulations confirmed that the proposed carrier achieves THD below 2 %, near-unity power factor and improved dc-bus voltage regulation versus triangular and sinusoidal carriers, without requiring additional hardware. Future research will include experimental validation and application to multi-level converters and grid-tied inverters.

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