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INPUT PERFORMANCE ENHANCED BASED PREDICTIVE CONCEPT AND SPACE VECTOR FOR MATRIX RECTIFIER

Hoang-Long Dang[1], Nguyen Thanh Hai[2], Tan Luong Van[1]*

[1]Faculty of Electrical and Electronics Engineering Technology,

Ho Chi Minh City University of Industry and Trade, Ho Chi Minh City, Viet Nam

[2]Binh Duong University, Ho Chi Minh City, Vietnam

*Email: *luongvt@huit.edu.vn*

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ABSTRACT

To address the simultaneous challenges of grid-side power quality in AC-DC matrix converters, this study proposes a predictive strategy founded on the space vector modulation (SVM) framework. The salient and defining contribution of this research is the rigorous enforcement of unity power factor (UPF) operation across the entire modulation range, particularly addressing the phase displacement issues often observed at low modulation depths. In conventional control schemes, maintaining precise phase synchronization between the current input and grid voltage presents a significant hurdle; however, this proposal overcomes that limitation through a physics-based approach. Specifically, the predictive control (PC) algorithm is utilized to mathematically derive the input current dynamics. By processing the instantaneous system states, the PC algorithm analytically computes an optimal input current reference vector that is perfectly phase-locked with the source voltage vector. This process effectively nullifies the displacement angle, thereby eliminating reactive power injection into the utility grid. This optimized reference trajectory is subsequently synthesized by the SVM stage, which provides high-resolution vector placement to enhance waveform fidelity. The resulting synergy guarantees a near-zero displacement power factor on the AC side while concurrently maintaining high-quality current on the DC side. The efficacy of this approach in maximizing active power transfer efficiency and ensuring high-quality waveform generation at both input and output ports is substantiated through extensive simulation analysis.

Keywords: Power factor, input performance, predictive concept, space vector, matrix rectifier.

1. INTRODUCTION

In the rapidly evolving landscape of modern power electronics, the three-phase AC-DC matrix converter (MC) has established itself as a superior topological solution, commanding substantial attention across a spectrum of rigorous industrial applications. Functioning as a direct topological derivative of the indirect matrix converter family, this converter architecture inherits a suite of intrinsic merits, most notably its capacity for bidirectional power flow, the inherent synthesis of high-quality sinusoidal input currents, controllable input power factor regulation, and the facilitation of high-power-density designs due to the absence of bulky DC-link storage elements [1]. Such favorable characteristics have precipitated the widespread adoption of these converters in critical infrastructure and advanced systems, ranging from electric vehicle propulsion trains and photovoltaic energy harvesting to grid-interface subsystems, microgrid architectures, fuel cell power conditioning units, and sophisticated battery charging stations [2]. From a fundamental operational perspective, the AC-DC MC functions as a single-stage current-source rectifier, uniquely capable of executing direct AC-to-DC energy conversion while managing power transfer in both directions.

To orchestrate the complex switching sequences required for the efficient operation of AC-DC MCs, the research community has cultivated a diverse array of control methodologies. The spectrum of these strategies extends from foundational classical techniques, such as analog-based pulse-width modulation (PWM) [3] and the mathematically rigorous Alesina-Venturini transfer function approach [4], to more sophisticated, high-performance paradigms like space vector modulation (SVM) [5] and model predictive control (MPC) [6]. The MPC framework, in particular, distinguishes itself by utilizing a discrete-time model to exhaustively evaluate all permissible switching states within a sampling interval, predicting the future trajectory of system variables. It subsequently selects the optimal switching state that minimizes a pre-designed cost function, thereby enforcing desired system behavior in the subsequent control horizon [7]. In parallel, SVM has been canonically regarded as the industry standard for modulation in AC-DC MCs, with extensive literature dedicated to its implementation for direct power factor enforcement and its integration into battery energy storage systems [8].

Despite these significant technological strides, the practical deployment of AC-DC MCs remains hindered by persistent operational challenges, primarily concerning the output power quality and grid-side synchronization. A predominant issue is the mitigation of low-frequency current ripple on the DC side. Conventional remediation techniques often necessitate increasing the switching frequency, which inevitably incurs a penalty of elevated switching losses or physically enlarging the output filter inductance, a solution that detrimentally impacts the converter’s gravimetric density and economic feasibility. Furthermore, ensuring rigorous grid compatibility presents a simultaneous hurdle; specifically, maintaining unity power factor (UPF) and eliminating phase displacement between the input current and grid voltage is notoriously difficult, particularly at low modulation depths where traditional linear controllers struggle. While advanced modulation schemes have been explored to alleviate these issues, such as the optimized zero-vector placement within an SVM framework described in [9], their efficacy is often non-uniform. Such methods typically demonstrate utility only at low modulation indices; at higher modulation depths, the vanishing duration of the zero vector renders these optimization attempts futile, failing to provide consistent ripple attenuation or phase alignment across the full operational envelope.

To surmount these multifaceted challenges, this paper proposes a novel, physics-based hierarchical control architecture that synergistically integrates the predictive capabilities of predictive control (PC) with the high-resolution synthesis of the space vector (SV) concept. The proposed strategy is explicitly engineered to address the dual objectives of rigorous UPF enforcement and superior DC current ripple attenuation across the entire modulation range. The control philosophy operates on a two-stage process: firstly, a physics-based PC algorithm is deployed to analytically derive the input current dynamics and compute a precise input current reference vector that is phase-locked to the grid voltage. This effectively nullifies displacement angles and eliminates reactive power injection. Secondly, the SV concept is utilized to synthesize this optimized reference. By mathematically constructing "space vectors" from linear combinations of adjacent active switching vectors, this stage significantly enhances the control resolution. Within each switching period, the reference vector is synthesized using a sequence of two active vectors and one zero vector, affording granular control over the input power factor quality.

The performance, robustness, and theoretical validity of this proposed methodology are comprehensively corroborated through extensive simulation analysis. This hybrid control paradigm successfully merges the rapid dynamic response inherent to predictive control with the superior steady-state harmonic performance and fixed switching frequency characteristics of SVM. The result is a robust control solution that guarantees near-zero displacement power factor on the AC side while concurrently stabilizing the DC output current. The remainder of this manuscript is organized as follows: Section II elucidates the AC-DC MC topology and its mathematical modeling. Section III details the theoretical principles and implementation of the proposed PC-SV control scheme. Section IV provides the simulation evidence to verify the proposed strategy, followed by concluding remarks in Section V.

2. TOPOLOGY AND MATHEMATICAL MODELING

The circuit architecture of the AC-DC MC investigated in this study is schematically illustrated in Figure 1. Physically, this topology is synthesized using a matrix of six bidirectional power switches. Each switching cell is typically constructed by coupling two discrete insulated-gate bipolar transistors (IGBTs) in a common-emitter anti-serial configuration to block voltage in both directions. To attenuate high-order harmonic content arising from high-frequency switching events and grid interactions, a three-phase LC filter network is installed at the grid interface. Simultaneously, a passive output filter stage is integrated to smooth the rectified current, thereby ensuring the spectral integrity and quality of the delivered DC waveform.

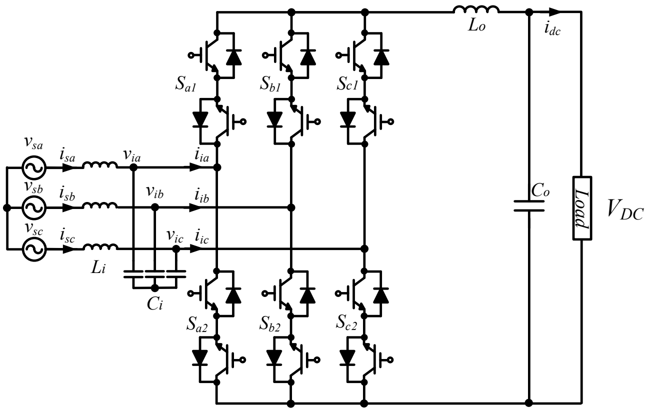


Fig. 1. AC-DC matrix converter.

The modulation and control logic of this converter are strictly dictated by two intrinsic physical constraints derived from the source and load characteristics. First, given the voltage-stiff nature of the three-phase grid supply, the switching sequence must absolutely prevent any inter-phase short-circuits at the input terminals. Second, owing to the inherent inductive properties of the DC load, the continuity of the output current path must be preserved at all times to avoid destructive open-circuit conditions. Compliance with these mandatory conditions imposes a rigid switching protocol: at any specific instant, only one switch within the upper arm group and one switch within the lower arm group are permitted to conduct. This operational requirement consequently restricts the converter to a discrete set of nine permissible switching state combinations.

The operational dynamics of the matrix converter are mathematically governed by two intrinsic relationships. Primarily, the instantaneous three-phase input currents are synthesized as a function of the active switching state combinations and the DC load current amplitude. Conversely, the instantaneous DC output voltage is generated through the modulation of the three-phase grid voltages by the specific switching sequences of the power semiconductor array.

$$i_i = \mathrm{S}\, i_{dc} \tag{1}$$

$$V_{dc} = S^T\, v_i \tag{2}$$

$$S = \begin{bmatrix} S_{a1} - S_{a2} \\ S_{b1} - S_{b2} \\ S_{c1} - S_{c2} \end{bmatrix} \tag{3}$$

where

i_i Input currents $[i_{ia}\ i_{ib}\ i_{ic}]^T$

v_i Input voltages $[v_{ia}\ v_{ib}\ v_{ic}]^T$

S Switches matrix

The model of input filter of the MC is extracted as

$$v_s = R_i i_s + L_i \frac{di_s}{dt} + v_i \tag{4}$$

$$i_s = C_i \frac{dv_i}{dt} + i_i \tag{5}$$

where

v_s Source voltages $[v_{sa}\ v_{sb}\ v_{sc}]^T$

i_s Source currents $[i_{sa}\ i_{sb}\ i_{sc}]^T$

Given that the PC paradigm is inherently formulated within the discrete-time domain, establishing a discrete-time mathematical model of the AC-DC MC is a prerequisite for controller implementation. Consequently, the transient behavior of the input filter stage is modeled using a state-space formulation derived from equations (4) and (5). Utilizing this discretized state-space model in conjunction with the system coefficients detailed in [10], the prediction of the source current is computed as follows:

$$i_s(k+1) = c_1 v_s(k) + c_2 v_i(k) + c_3 i_s(k) + c_4 i_i(k) \tag{6}$$

3. THEORETICAL PRINCIPLE OF PROPOSED STRATEGY

The proposed control framework employs the predictive control (PC) algorithm to mathematically derive the required input current reference trajectory, utilizing the system's discrete-time state-space dynamics defined in (6). Subsequently, the actual modulation of the converter is executed via a space vector synthesis technique. Fundamentally, the identification of the optimal switching vector for the subsequent sampling interval is predicated upon the minimization of a specific cost function. The primary role of this function is to quantify the magnitude of the deviation between the predicted evolution of system variables and their corresponding target reference signals. Within the specific context of the AC-DC matrix converter, this optimization criterion is mathematically formulated as

$$g = |i_{s^*} - i_s(k+1)|^2 \tag{7}$$

where i_{s^*} is the source current reference.

The objective function systematically evaluates the entire set of available switching vectors to identify the single optimal state for implementation in the subsequent sampling interval. Theoretically, the ideal switching vector is one that forces the predicted current trajectory to perfectly converge with the reference signal. Consequently, under these ideal conditions, the global minimum of the cost function would be zero. By synthesizing equations (6) and (7), the cost function formulation can be algebraically restructured as follows:

$$i_{s^*} = i_s(k+1) = c_1 v_s(k) + c_2 v_i(k) + c_3 i_s(k) + c_4 i_i(k) \tag{8}$$

The parametric coefficients utilized within the predictive control algorithm are synthesized by establishing a discrete-time equivalent of the input LC filter's continuous dynamics. To achieve this, the continuous-time differential expressions describing the evolution of the input voltage and current vectors, as defined in (Eq. 4) and (Eq. 5), are mapped into the discrete domain via the application of the Forward Euler discretization scheme over the fundamental sampling interval.

The input current is obtained as

$$i_i(k) = (i_{s^*} - (c_1 v_s(k) + c_2 v_i(k) + c_3 i_s(k)))/c_4 \tag{9}$$

To ensure the accuracy and reproducibility of the predictive model, the discrete-time coefficients utilized in Equations (6), (8), and (9) must be explicitly defined. These coefficients are analytically derived by applying the Forward Euler discretization approximation to the continuous-time differential equations of the input LC filter described in (4) and (5).

$$c_1 = \sqrt{\frac{C_i}{L_i}} \sin\left(\frac{T_s}{\sqrt{C_i L_i}}\right) \tag{10}$$

$$c_2 = -c_1 \tag{11}$$

$$c_3 = \cos\left(\frac{T_s}{\sqrt{C_i L_i}}\right) \tag{12}$$

$$c_4 = 1 - c_3 \tag{13}$$

The fundamental principles governing sector identification and reference vector synthesis within the conventional SV paradigm are depicted in Figure 2. In this standard framework, the hexagonal control space is partitioned into six distinct sectors. When the target input current reference vector, $\vec{I}_{ref}$, traverses a specific region such as Sector I its synthesis is mathematically realized by linearly combining the two adjacent active switching vectors alongside a selected zero vector. This process ensures the precise reconstruction of the reference amplitude and phase angle through the time-averaged application of these fundamental physical vectors.

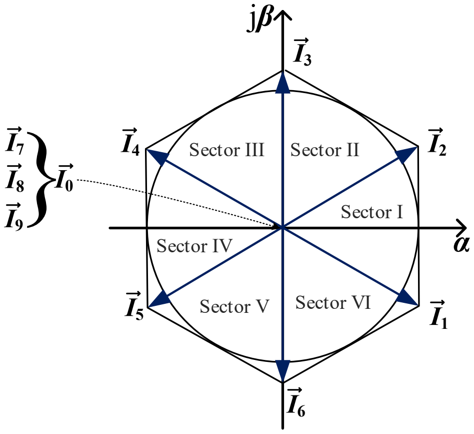


Fig. 2. The sector division for AC-DC MC.

The comprehensive architecture of the control strategy is schematically detailed in Figure 3. The system employs a cascaded control structure, initiated by an outer voltage regulation loop. Here, the error signal derived from the sensed load voltage relative to its reference is compensated by a PI controller to formulate the magnitude command for the DC link current. On the grid side, the core predictive algorithm necessitates a comprehensive set of instantaneous feedback variables: the measured three-phase source voltages, converter input node voltages, and line currents are continuously monitored to model and forecast the system's dynamic trajectory. Furthermore, the source voltage signals are utilized to extract the precise grid synchronization angle. This angle is then integrated with the DC current command to generate the instantaneous sinusoidal source current references. Finally, the required input currents are computed, and the converter is modulated using the established standard SVM scheme.

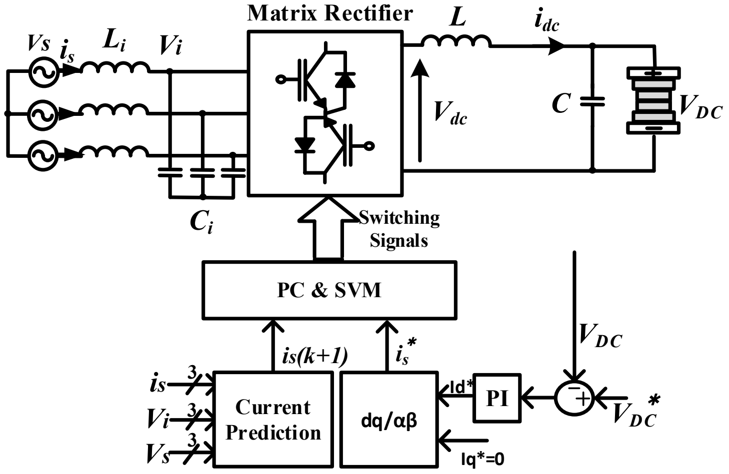


Fig. 3. Control scheme of proposed strategy.

4. PERFORMANCE AND DISCUSSION

To rigorously validate the efficacy of the proposed control framework, a comprehensive numerical simulation was conducted within the PSIM environment, benchmarking the method against the conventional strategy detailed in [11] with a primary focus on quantifying power factor operation. The modeled AC-DC matrix converter system is energized by a 100 V, 60 Hz three-phase source and features an input LC filter stage characterized by an inductance of 2.5 mH and a capacitance of 60 µF to suppress grid-side harmonics. On the output side, the rectified power is delivered to a 10 Ω resistive load via a smoothing filter consisting of a 1 mH inductor and a 40 µF capacitor. To emulate a realistic digital control implementation, the algorithms are executed with a sampling frequency set to 10 kHz.

The steady-state input characteristics of the AC-DC matrix converter under the 10 A load condition are comprehensively evaluated through the time-domain waveforms in Figure 4 and the frequency-domain spectral analysis in Figure 5. Figure 4 provides a comparative illustration of the steady-state three-phase source currents and the scaled A-phase source voltage under a 10 A load condition. This comparison serves to benchmark the proposed control strategy (Fig. 4b) against the conventional technique referenced in [11] (Fig. 4a). A salient feature observed in subplot (b) is the precise phase alignment between the A-phase source current, and its corresponding phase voltage. This strict in-phase synchronization confirms that proposed methodologies successfully enforce unity power factor operation, effectively eliminating reactive power injection into the grid.

Contrary to the typical trade-offs observed in some modulation schemes, the proposed control strategy demonstrates a tangible improvement in input current quality. As evidenced by the fast Fourier transform (FFT) analysis in Figure 5, the proposed method achieves a total harmonic distortion (THD) of 3.6% (Fig. 5b). This represents a notable enhancement over the conventional strategy referenced in [11], which exhibits a higher THD of 4.3% (Fig. 5a). The spectral plots indicate that the proposed algorithm effectively attenuates low-order harmonics, resulting in a cleaner sinusoidal profile that is more compliant with stringent grid standards.

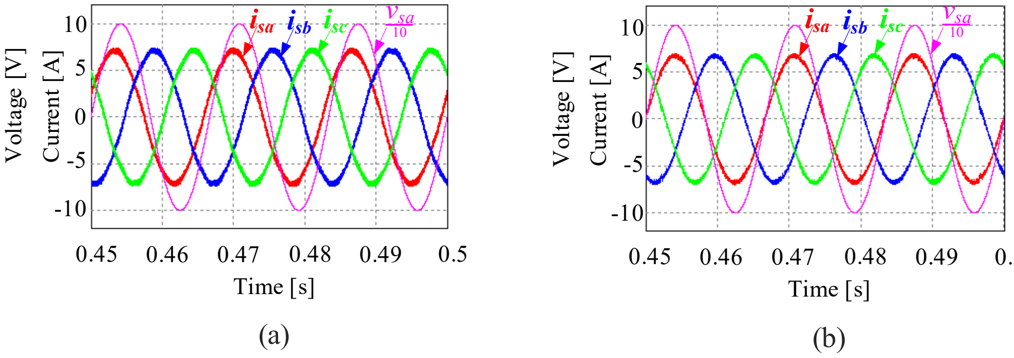


Fig. 4. A comparison of the three-phase source current and A-phase source voltage stability under different control strategies at a 10 A load condition.
(a) Control strategy [11]. (b) Proposed control strategy.

Figures 6 and 7 extend the comparative evaluation to a low-load operating condition (4 A), a critical regime where conventional modulation schemes often suffer from degraded waveform fidelity due to limited duty cycle resolution. Figure 6 illustrates the steady-state three-phase source currents superimposed on the scaled A-phase voltage. Even at this reduced current magnitude, the proposed control strategy (Fig. 6b) maintains exceptional phase alignment between the source current and the grid voltage. The proposed algorithm successfully enforces unity power factor operation compared with the technique [11]. The strict synchronization observed in Fig. 6(b) confirms that the predictive algorithm effectively compensates for the phase displacement typically associated with input filters at light loads, ensuring that reactive power injection remains negligible.

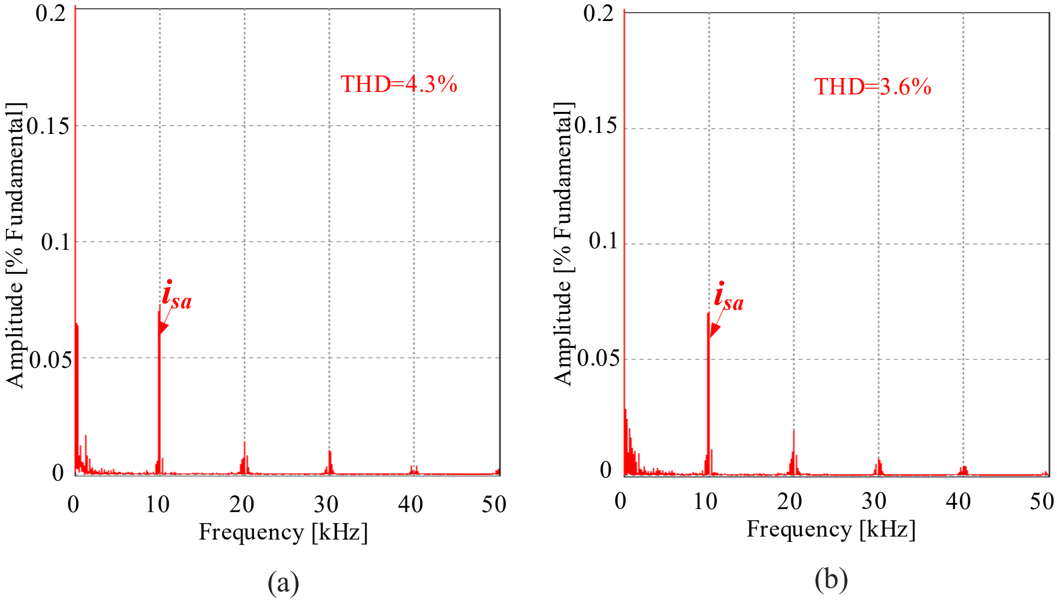
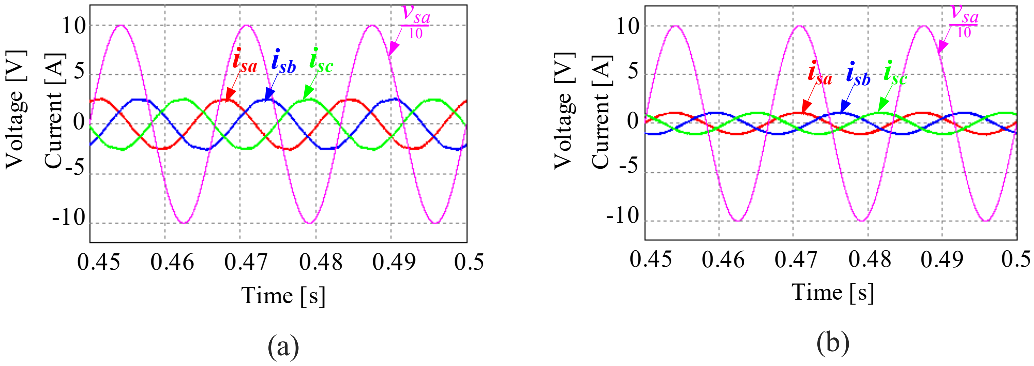


Fig. 5. Resulting THD A-phase current analysis for the AC-DC converter at 10 A, the performance of the different control strategies.
(a) Control strategy [11]. (b) Proposed control strategy.



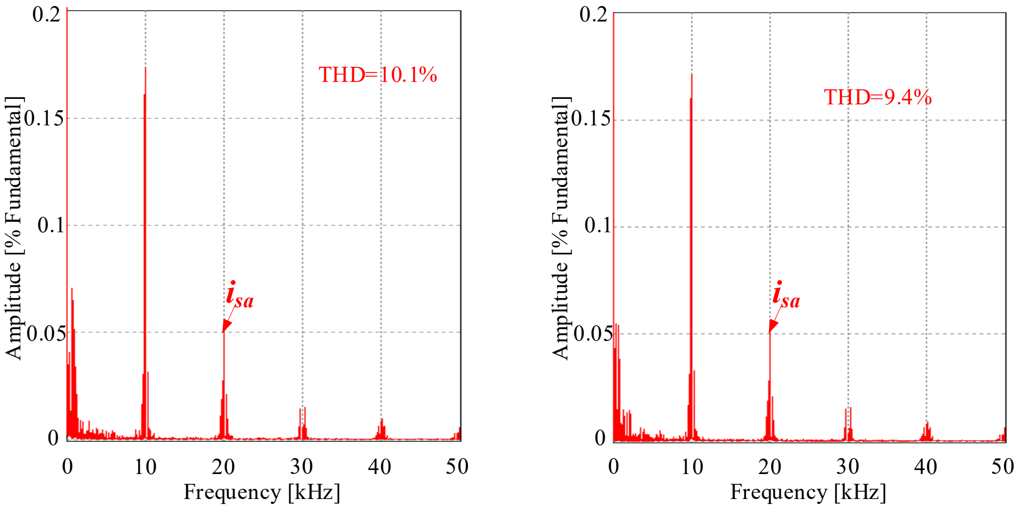
(a)

(b)

Fig. 6. A comparison of the three-phase source current and A-phase source voltage stability under different control strategies at a 4 A load condition.
(a) Control strategy [11]. (b) Proposed control strategy.

The superior performance of the proposed strategy at low modulation indices is quantitatively highlighted in the harmonic spectrum analysis presented in Figure 7. The benchmark strategy exhibits a THD of 10.1%. At low modulation depths, the reduced duration of active vectors often leads to increased distortion in space vector schemes. However, the proposed strategy achieves a noticeably improved THD of 9.4%. This reduction in harmonic content suggests that the enhanced spatial resolution provided by the proposed technique is particularly advantageous in low-current regions. The controller achieves finer granularity, thereby mitigating the harmonic distortion that plagues standard modulation techniques under light-load conditions.

In summary, while the proposed method is primarily designed for unity power factor operation, these results indicate that it offers superior AC-side current quality in the low-power operating range compared to the approach in [11]. The proposed strategy introduces an optimization loop that evaluates the discrete-time prediction models. Consequently, the number of addition and multiplication operations is inherently higher than that of the conventional method. However, unlike exhaustive Finite Control Set Model Predictive Control (FCS-MPC) algorithms that evaluate all possible switching states and suffer from variable switching frequencies, the proposed method analytically computes the optimal reference vector and synthesizes it via SVM. This approach limits the predictive calculations to a single reference generation step per cycle rather than an iterative state-search loop. Therefore, the proposed strategy significantly enhances input performance and unity power factor operation without demanding excessive computational resources.



(a) (b)

Fig. 7. Resulting THD A-phase current analysis for the AC-DC converter at 4 A, the performance of the different control strategies. (a) Control strategy [11]. (b) Proposed control strategy.

5. CONCLUSION

This paper has presented and validated a novel hybrid control strategy for AC-DC matrix converters, effectively synergizing the fast dynamic response of PC with the spectral determinism of SV. A defining contribution of this work is the physics-based derivation of input current references, which ensures the rigorous enforcement of UPF and the elimination of phase displacement across the entire modulation range. Unlike classical predictive approaches that suffer from variable switching frequencies, the proposed integration with standard SV guarantees a fixed switching frequency, facilitating straightforward filter design and predictable harmonic performance. Simulation results have conclusively demonstrated that the strategy maintains high-fidelity sinusoidal input currents. In conclusion, the proposed PC-SV framework offers a robust and comprehensive solution.

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