Cascaded PI-Controlled Multistage Boost Converter for Low-Voltage Renewable Sources

Thanh-Lam Le
Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Vietnam
lamlethanh@hcmute.edu.vn (corresponding author)

Le Van Truc
Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Vietnam
2430613@student.hcmute.edu.vn

Thinh Nguyen Tien
Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Vietnam
2390612@student.hcmute.edu.vn

Received: 25 June 2025 | Revised: 21 August 2025 | Accepted: 2 September 2025

DOI: https://doi.org/10.48084/etasr.12941

ABSTRACT

High step-up DC-DC converters are essential for interfacing low-output renewable energy sources with higher-voltage power systems. Traditional boost converters, despite their simplicity and wide adoption, face significant limitations in achieving large voltage amplification with high efficiency and stability under dynamic operating conditions. This paper presents a Multistage Capacitor-Assisted Boost Converter (MCABC) that attains high voltage gain at moderate duty ratios, thereby reducing the switching stress and improving the energy transfer efficiency. To address the challenges of voltage regulation in such high-gain systems, a cascaded dual-loop Proportional–Integral (PI) control strategy is implemented, comprising an outer voltage loop for accurate reference tracking and an inner current loop to suppress the inrush and limit the peak current. This control-oriented approach ensures robust dynamic performance and minimal output ripple under varying operating conditions. The experimental validation confirmed both the feasibility of the proposed converter and the effectiveness of the control scheme, demonstrating stable regulation and a fast transient response. The results highlight the suitability of the proposed MCABC for practical deployment in photovoltaic systems, fuel cell applications, and other low-voltage energy platforms that require efficient and reliable voltage elevation.

Keywords-converter system; step-up converter; cascaded control; digital control; voltage regulation

I. INTRODUCTION

The global pursuit of clean and sustainable energy has led to a significant increase in the deployment of renewable energy sources, including Photovoltaic (PV) systems, fuel cells, and wind power [1-3]. This trend is further accelerated by the rapid growth of the electric vehicles, onboard charging systems, and distributed energy applications [4]. However, the intrinsic intermittency and low-voltage characteristics of most renewable sources pose a serious challenge in ensuring stable and efficient energy conversion and utilization [5]. As a result, high-efficiency power conversion systems, particularly DC-DC converters, have become indispensable for stepping up or conditioning the output voltages from these sources [6].

Conventional power converters are typically designed based on fixed circuit topologies, without considering dynamic control strategies. These systems often rely on hardware-centric solutions with fixed duty ratios or predefined structures that lack adaptability under varying load and input conditions [7]. Consequently, they suffer from issues, such as poor voltage regulation, limited dynamic performance and suboptimal efficiency. In particular, modifying the output characteristics of such converters often requires redesigning the hardware, leading to increased cost, complexity, and time-to-market, especially in systems that demand high reliability and compact integration [8, 9].

Boost converters have become essential in renewable energy and low-voltage applications due to their ability to step up the voltage levels from inherently weak sources, such as PV panels or fuel cells [10]. However, ensuring that these converters consistently deliver a stable and regulated output voltage remains technically challenging, especially under dynamic conditions, where the input voltage, load demand, and component parameters vary significantly [11, 12]. These challenges are further exacerbated in open-loop configurations with fixed duty cycles, where the nonlinear characteristics of the boost topology often result in poor voltage regulation and degraded system stability [13-15]. To address these limitations, closed-loop control strategies have been widely adopted, allowing the system to dynamically adjust the switching behavior in real time [16].

Advancements in the control theory have enabled the integration of intelligent and adaptive techniques, such as fuzzy logic [17], neural networks [18, 19], and model-free adaptive control [20], into the regulation of nonlinear dynamic systems. These approaches are capable of learning or adapting to variations and disturbances, offering improved robustness and dynamic performance. However, such benefits come at the cost of increased system complexity, requiring high-speed processors, fast sampling rates, and reliable sensing infrastructure [21]. This added complexity may hinder the commercial scalability, particularly in cost-sensitive applications, such as residential PV systems or electric mobility. Consequently, ongoing research focuses on designing control-oriented boost converter systems that strike an optimal balance between performance, implementation simplicity, and economic viability, ultimately facilitating the broader adoption in practical energy conversion scenarios.

To address these challenges, this study presents a novel boost converter topology, the MCABC, which achieves a high voltage gain through a modular transformerless structure. By leveraging cascaded capacitor-diode stages, the converter enables efficient step-up conversion at moderate duty ratios, thereby reducing the switching stress and improving the energy transfer efficiency. In parallel with the hardware innovation, a closed-loop control strategy based on cascaded PI regulators is employed to ensure stable output voltage under varying input and load conditions. This integration of topology and control enhances the dynamic performance, suppresses the overcurrent risks, and ensures reliable regulation. The main novelty of this work lies in the synergy between the MCABC topology and the cascaded PI control strategy, which together provide a high-gain, a well-regulated and experimentally validated solution. With its compact design, the high gain capability, and robust control, the proposed MCABC offers a practical and cost-effective solution for modern power applications, such as PV systems, fuel cells, and electric drives. The following sections detail the converter architecture, control implementation and experimental validation.

II. SYSTEM ANALYSIS AND PROBLEM FORMULATION

A. *Classical Boost Converter Overview*

The classical boost converter is a widely adopted DC-DC step-up topology due to its structural simplicity and ease of control. It consists of an inductor *L*, a power switch S_0, a diode *D*, a filter capacitor *C*, and a resistive load *R*. The converter operates by storing energy in the inductor when the switch is turned on and transferring that energy to the output during the off period. This energy transfer mechanism results in a higher output voltage compared to the input. During the ON state (i.e., S_0 is closed), the input voltage V_{in} is applied across the inductor, causing a linear increase in the inductor current. At this stage, the diode *D* is reverse-biased and isolates the output stage, so the load is supplied solely by the output capacitor. The inductor voltage in this mode is given by:

$$V_L^{ON} = V_{in} \tag{1}$$

When the switch is turned OFF, the inductor current is forced to continue flowing owing to its stored energy. As a result, the diode *D* becomes forward-biased and the inductor transfers its energy to both the output capacitor and the load. The voltage across the inductor during this period is:

$$V_L^{OFF} = V_{in} - V_o \tag{2}$$

By applying the principle of volt-second balance on the inductor over one switching period TT, one obtains:

$$V_L^{\mathrm{ON}} \cdot DT + V_L^{\mathrm{OFF}} \cdot (1 - D)T = 0 \tag{3}$$

Substituting (1) and (2) into (3) leads to the well-known voltage gain expression for the ideal boost converter:

$$\frac{V_o}{V_{\mathrm{in}}} = \frac{1}{1-D} \tag{4}$$

where $D \in (0,1)$ is the duty cycle of the switch, defined as the fraction of the switching period during which S_0 remains ON.

Equation (4) shows that the output voltage increases as the duty ratio *D* increases. However, when *D*→1, the gain tends toward infinity, which is not feasible in practical implementations due to several limitations. As *D* approaches higher values, the stress on the switch and diode becomes excessive, and the efficiency drops due to higher conduction losses, increased current ripple, and non-ideal switching effects. In addition, the classical boost converter lacks flexibility for high step-up gain applications. It cannot efficiently accommodate low-voltage sources, such as PV panels or fuel cells, in systems where a high output voltage is required. These drawbacks underline the need for enhanced converter topologies that can achieve higher voltage gain with improved efficiency and reduced stress on the components. Thus, in the current work, a modified boost converter architecture based on the switched-capacitor approach is introduced to address these issues.

B. *Proposed Multistage Capacitor-Assisted Boost Converter*

To address the inherent limitations of the classical boost converter, this study proposes a novel topology, the MCABC. The circuit diagram of the proposed MCABC is illustrated in Figure 1. The architecture consists of a single controlled switch S_0, one inductor *L*, five diodes (D_a, D_b, D_1, D_2, and D_3), and five capacitors (C_a, C_b, C_1, C_2, and C_3), organized into three cascaded voltage-boosting stages.

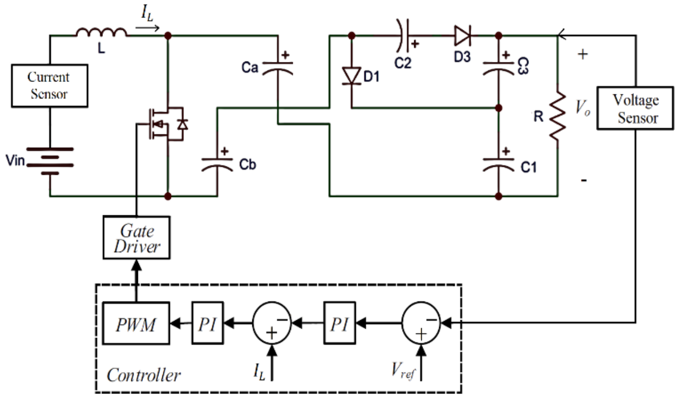

Fig. 1. Block diagram of the proposed MCABC with cascaded PI control.

The MCABC enhances the voltage gain by leveraging a capacitor-assisted energy transfer mechanism. During the ON period of the switch S_0, the inductor stores energy from the input source V_{in}, while the capacitors in the intermediate stages are isolated or redirected through diodes. When the switch is turned OFF, the energy stored in the inductor is released through a sequence of charge redistribution across the capacitors, resulting in an accumulative voltage at the output.

Under the assumption of continuous conduction mode, ideal components, and negligible switching loss, the overall output voltage can be approximated as:

$$V_o \approx \frac{n \cdot V_{\text{in}}}{1-D} \tag{5}$$

where n is the number of effective voltage-boosting stages, which is equal to 3 in the present configuration.

The voltage gain of the MCABC can also be interpreted from the steady-state voltages of the capacitors involved in each stage. Specifically, the first-stage capacitors C_a and C_b are charged to the same level V_C, which approximates to $V_C = \frac{V_{\text{in}}}{1-D}$. The intermediate capacitor C_1 formed through the combination of C_a and C_b, holds a voltage of roughly $2V_C$. The final output is the sum of this voltage and that of capacitor C_3, which also maintains a level near V_C. Hence, the total output voltage approaches:

$$V_o \approx V_{C_1} + V_{C_3} \approx 3V_C = \frac{3}{1-D} V_{\text{in}}$$

This cumulative behavior demonstrates the high step-up gain potential of the proposed MCABC topology while avoiding extreme duty ratios.

The proposed converter offers several key advantages over classical boost converters. It achieves higher voltage gain at relatively low duty ratios, thereby reducing the stress on the switching device and diodes. Its stage-based structure is inherently modular and scalable, which allows further voltage gain enhancement by adding additional capacitor-diode stages. Moreover, the system operates without the need for transformers or magnetic coupling, resulting in a compact, lightweight, and cost-effective implementation. Efficiency is also improved due to the distributed energy transfer, reduced peak currents, and gradual voltage build-up across the stages. With these features, the MCABC is a promising candidate for modern power conversion applications that require high step-up ratios, including low-voltage PV systems, fuel cell stacks, and battery-powered electric drives.

C. Experimental Setup

An experimental study was conducted to validate the effectiveness of the proposed solution. The experimental setup is shown in Figure 2. As depicted in Figure 2, the experimental setup consisted of the MCABC prototype mounted on a test rack, including the inductor and capacitor modules on the upper layer, the DSP control and driver boards on the middle layer, and the DC supply and measurement instruments (oscilloscope and PC) connected externally for data acquisition. The system was implemented using the Texas Instruments DSP TMS320F28379D, with the control algorithm designed in MATLAB/Simulink and subsequently deployed onto the development board. The experimental parameters were: the capacitors C_a, C_b, C_2, and C_3 were rated at 220 μF and C_1 at 470 μF. The inductor L was 420 μH. The power switches used (IRFB4115PBF MOSFETs) were rated at 150 V–104 A. The diodes (RHRP3060) were rated at 600 V–30 A and the resistive load was set at 100 Ω. The input voltage was maintained constant at 12 V_{dc} throughout the experiments. The experimental waveforms in Figures 3 and 4 were acquired in real time via the DSP's SCI interface, where the output voltage was sampled through the Analog-to-Digital Converter (ADC) channels at a 20 kHz control rate and logged in MATLAB/Simulink for visualization. The ripple percentages were computed from the recorded steady-state voltage data following the reference changes.

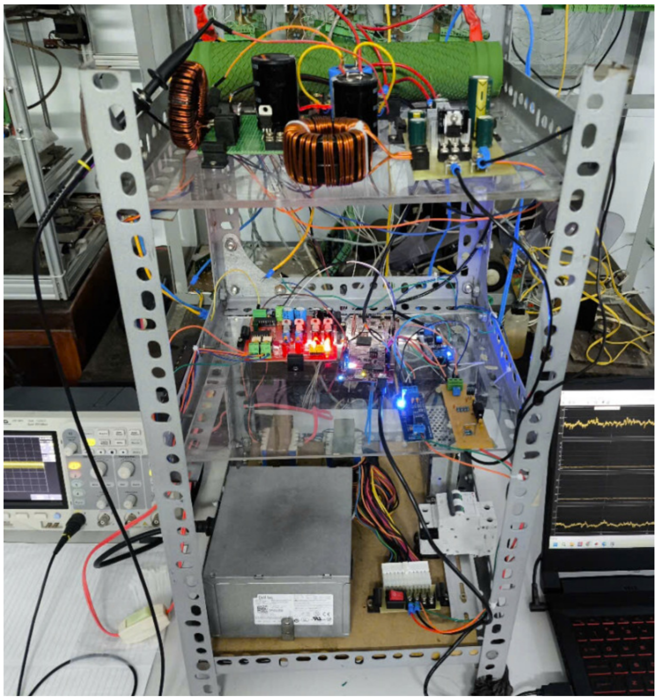

Fig. 2. Experimental setup of the proposed MCABC prototype: (top) power stage with inductors and capacitors, (middle) DSP control and driver boards, (bottom) DC source and interface. An oscilloscope and PC are used for measurement and data logging.

III. VOLTAGE REGULATION TECHNIQUE FOR THE PROPOSED MCABC

Maintaining a stable output voltage is a fundamental requirement in high step-up DC-DC converters, particularly in applications where the input sources are low-voltage and dynamically varying. In such scenarios, including the proposed MCABC, any disturbance in the load or input supply can lead to significant voltage deviations that compromise the system stability, efficiency, or safety. This issue is especially pronounced in open-loop configurations, where the fixed duty ratios are unable to accommodate real-time fluctuations, thereby increasing the risk of overvoltage or overcurrent events. To address these challenges, a robust and adaptive voltage regulation strategy is imperative.

This study adopts a cascade control architecture comprising two nested PI loops to regulate the output voltage while simultaneously preventing the excessive current through the inductor. The outer voltage loop generates the reference signal for the inner current control loop. The voltage feedback is sensed via a precision voltage divider and digitized through an ADC interfacing with the DSP controller. The outer PI controller compares the measured output voltage V_o with the reference setpoint V_{ref}, producing a current reference I_{ref} that reflects the necessary correction. This reference current is then used in the inner loop to regulate the actual inductor current I_L. A fast-acting current sensor continuously monitors I_L, and its error with respect to I_{ref} is minimized using another PI controller. The output of this current controller modulates the duty ratio of the Pulse-Width Modulation (PWM) signal, which in turn governs the switching of the main power transistor. The dual-loop PI control law can be expressed as:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e\,(\tau) d\tau \qquad (6)$$

where $e(t)$ denotes the tracking error of either the voltage loop or the current loop, $u(t)$ is the control signal for the PWM generator, and K_p, K_i are the proportional and integral gains, respectively. The outer loop operates with slower dynamics to ensure accurate voltage tracking, whereas the inner loop provides rapid current regulation to suppress the inrush and limit the peak current during transient events. In high step-up converters, such as MCABC, the inductor current may experience large variations due to the rapid load changes or multi-stage charge redistribution. A single-loop voltage control is often insufficient to react quickly to such disturbances, leading to overshoot or instability. Therefore, the cascaded PI structure is adopted: the fast inner current loop ensures immediate response and current limiting, while the slower outer voltage loop maintains accurate voltage tracking without inducing oscillations. This separation of time scales enhances the overall stability, simplifies gain tuning, and provides a more robust solution for complex multi-stage converter dynamics.

This cascaded structure not only enhances the output voltage accuracy, but also adds a layer of protection against overcurrent scenarios, which are a common risk in multistage boost converters. Moreover, separating the control objectives into distinct loops simplifies the tuning process and improves the robustness across varying operating conditions. The entire control algorithm was implemented digitally using the TI DSP TMS320F28379D, enabling flexible parameter tuning, real-time control updates, and seamless integration with high-speed data acquisition systems. This digitally controlled PI-based cascade regulation strategy ensures high-quality voltage regulation, superior transient response, and improved reliability of the MCABC topology under practical deployment scenarios.

IV. ANALYSIS RESULTS

Figure 3 presents the measured output voltage under step changes in the reference voltage from 30 V to 60 V. Despite these abrupt changes, the output voltage closely tracks the reference with negligible overshoot or undershoot, demonstrating the fast dynamic response of the system. To further evaluate the quality of the output, the steady-state ripple was analyzed immediately after each transition. Figure 4 displays the ripple percentages computed based on the method described in [22, 23]. In particular, the ripple is quantified as the Root-Mean-Square (RMS) deviation of the sampled output voltage from its steady-state average value, normalized to the average, expressed as $V_{\text{ripple}} = \frac{V_{\text{ripple}}}{V^*} \times 100\%$, where $V_{\text{ripple}} = \sqrt{\frac{1}{m}\sum_{k=1}^{m}(V(k) - V^*)^2}$. Here, $V(k)$ denotes the sampled output voltage at instant k, V^* is the steady-state average voltage, and m is the number of samples considered in the calculation. This calculation was performed using the logged waveforms in MATLAB/Simulink after each reference transition. The maximum and minimum ripple were 12.8% and 8.5%, respectively, with variations remaining within acceptable limits.

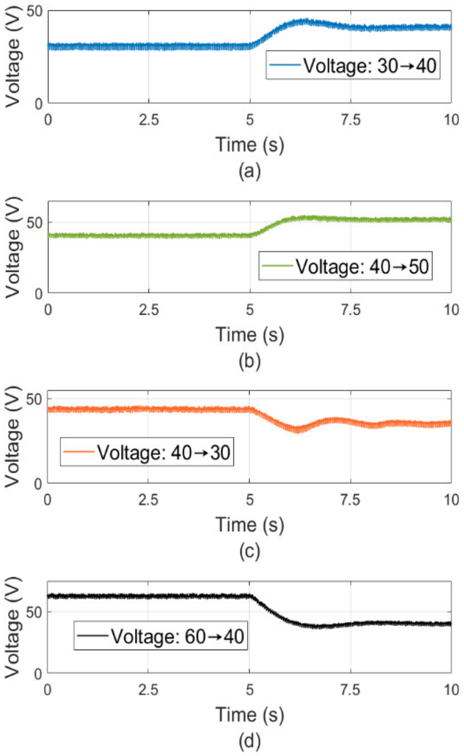

Fig. 3. Experimental analysis under varying applied voltage conditions.

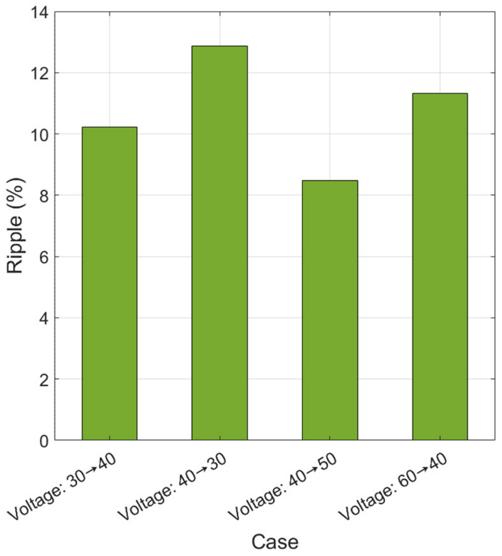

Fig. 4. Experimental evaluation of ripple variation.

Overall, the experimental results confirm that the proposed system maintains a fast and stable voltage response, accurately following reference commands under various operating conditions, even when the input voltage remains constant at 12 V.

V. CONCLUSIONS

The proposed Multistage Capacitor-Assisted Boost Converter (MCABC) demonstrates a structurally simple yet highly effective approach to achieving high voltage gain in DC-DC conversion without relying on magnetic coupling or extreme control efforts. By orchestrating staged charge transfer via capacitors and diodes, the converter delivers improved voltage boosting capability while mitigating the losses and reducing the component stress. Coupled with a digitally implemented cascaded Proportional–Integral (PI) controller, the system ensures tight voltage regulation and robust dynamic performance under varying load and input conditions. The experimental validation confirmed the practicality and efficiency of the design, making the MCABC a strong candidate for integration into modern power electronics applications, such as renewable energy systems and electric transportation.

REFERENCES

[1] A. Q. Al-Shetwi, "Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges," *Science of The Total Environment*, vol. 822, May 2022, Art. no. 153645, https://doi.org/10.1016/j.scitotenv.2022.153645.

[2] A. Yadav, N. Pal, J. Patra, and M. Yadav, "Strategic planning and challenges to the deployment of renewable energy technologies in the world scenario: its impact on global sustainable development," *Environment, Development and Sustainability*, vol. 22, no. 1, pp. 297–315, Jan. 2020, https://doi.org/10.1007/s10668-018-0202-3.

[3] D. Hidouri, R. Marouani, and A. Cherif, "Modeling and Simulation of a Renewable Energy PV/PEM with Green Hydrogen Storage," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12543–12548, Feb. 2024, https://doi.org/10.48084/etasr.6492.

[4] A. B. Ahmad *et al.*, "Renewable integration and energy storage management and conversion in grid systems: A comprehensive review," *Energy Reports*, vol. 13, pp. 2583–2602, Jun. 2025, https://doi.org/10.1016/j.egyr.2025.02.008.

[5] N. Hosseinzadeh, A. Aziz, A. Mahmud, A. Gargoom, and M. Rabbani, "Voltage Stability of Power Systems with Renewable-Energy Inverter-Based Generators: A Review," *Electronics*, vol. 10, no. 2, Jan. 2021, Art. no. 115, https://doi.org/10.3390/electronics10020115.

[6] Z. R. Labidi, H. Schulte, and A. Mami, "A Model-Based Approach of DC-DC Converters Dedicated to Controller Design Applications for Photovoltaic Generators," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4371–4376, Aug. 2019, https://doi.org/10.48084/etasr.2829.

[7] W. Lei, W. Qinghua, M. Wei, and T. Wenhu, "Stability Improvement for One Cycle Controlled Boost Converters Based on Energy Balance Principle," *Chinese Journal of Electronics*, vol. 32, no. 6, pp. 1293–1303, Nov. 2023, https://doi.org/10.23919/cje.2021.00.204.

[8] Y. Wang, Y. Wang, X. Song, and Z. Liang, "Finite-Time Adaptive Neural Network Observer-Based Output Voltage-Tracking Control for DC–DC Boost Converters," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 70, no. 7, pp. 3005–3016, Jul. 2023, https://doi.org/10.1109/TCSI.2023.3264536.

[9] H.-J. Ko, H.-G. Koh, and Y.-J. Choi, "A Model Predictive Current Control Method for Achieving a High Efficiency and High Robustness Boost PFC Converter Operation," *IEEE Access*, vol. 11, pp. 142754–142763, 2023, https://doi.org/10.1109/ACCESS.2023.3343124.

[10] M. R. S. de Carvalho, R. C. Neto, E. J. Barbosa, L. R. Limongi, F. Bradaschia, and M. C. Cavalcanti, "An Overview of Voltage Boosting Techniques and Step-Up DC-DC Converters Topologies for PV Applications," *Energies*, vol. 14, no. 24, Jan. 2021, Art. no. 8230, https://doi.org/10.3390/en14248230.

[11] K. V. G. Raghavendra *et al.*, "A Comprehensive Review of DC–DC Converter Topologies and Modulation Strategies with Recent Advances in Solar Photovoltaic Systems," *Electronics*, vol. 9, no. 1, Jan. 2020, Art. no. 31, https://doi.org/10.3390/electronics9010031.

[12] Q. Nguyen-Vinh and T.-L. Le, "Optimal frequency modulation of carrier waves and its application to induction motor drive systems," *Electrical Engineering*, vol. 107, no. 6, pp. 6791–6803, Jun. 2025, https://doi.org/10.1007/s00202-024-02887-7.

[13] F. Yi and F. Wang, "Review of Voltage-Bucking/Boosting Techniques, Topologies, and Applications," *Energies*, vol. 16, no. 2, Jan. 2023, Art. no. 842, https://doi.org/10.3390/en16020842.

[14] L. F. Lai *et al.*, "Design Trends and Perspectives of Digital Low Dropout Voltage Regulators for Low Voltage Mobile Applications: A Review," *IEEE Access*, vol. 11, pp. 85237–85258, 2023, https://doi.org/10.1109/ACCESS.2023.3303809.

[15] H. Aliamooei-Lakeh, S. Aliamooei-Lakeh, M. Toulabi, and T. Amraee, "Enhancement in Robust Performance of Boost Converter-Based Distributed Generations Utilizing Active Disturbance Rejection Controller," *IEEE Transactions on Automation Science and Engineering*, vol. 21, no. 4, pp. 6094–6108, Oct. 2024, https://doi.org/10.1109/TASE.2023.3322043.

[16] W. E. Aouni and L.-A. Dessaint, "Real-Time Implementation of Input-State Linearization and Model Predictive Control for Robust Voltage Regulation of a DC-DC Boost Converter," *IEEE Access*, vol. 8, pp. 192101–192108, 2020, https://doi.org/10.1109/ACCESS.2020.3032327.

[17] H. Li, B. Song, T. Chen, Y. Xie, and X. Zhou, "Adaptive fuzzy PI controller for permanent magnet synchronous motor drive based on predictive functional control," *Journal of the Franklin Institute*, vol. 358, no. 15, pp. 7333–7364, Oct. 2021, https://doi.org/10.1016/j.jfranklin.2021.07.024.

[18] T. K. Nizami and A. Chakravarty, "Neural Network Integrated Adaptive Backstepping Control of DC-DC Boost Converter," *IFAC-PapersOnLine*, vol. 53, no. 1, pp. 549–554, Jan. 2020, https://doi.org/10.1016/j.ifacol.2020.06.092.

[19] D. Wang *et al.*, "Model Predictive Control Using Artificial Neural Network for Power Converters," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 4, pp. 3689–3699, Apr. 2022, https://doi.org/10.1109/TIE.2021.3076721.

[20] X. Liu, L. Qiu, Y. Fang, and J. Rodríguez, "Predictor-Based Data-Driven Model-Free Adaptive Predictive Control of Power Converters Using Machine Learning," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 8, pp. 7591–7603, Aug. 2023, https://doi.org/10.1109/TIE.2022.3208594.

[21] M. Capra, B. Bussolino, A. Marchisio, G. Masera, M. Martina, and M. Shafique, "Hardware and Software Optimizations for Accelerating Deep Neural Networks: Survey of Current Trends, Challenges, and the Road Ahead," *IEEE Access*, vol. 8, pp. 225134–225180, 2020, https://doi.org/10.1109/ACCESS.2020.3039858.

[22] T.-L. Le and M.-F. Hsieh, "An enhanced direct torque control strategy with composite controller for permanent magnet synchronous motor," *Asian Journal of Control*, vol. 26, no. 4, pp. 1683–1702, 2024, https://doi.org/10.1002/asjc.3306.

[23] A. Nasr, C. Gu, X. Wang, G. Buticchi, S. Bozhko, and C. Gerada, "Torque-Performance Improvement for Direct Torque-Controlled PMSM Drives Based on Duty-Ratio Regulation," *IEEE Transactions on Power Electronics*, vol. 37, no. 1, pp. 749–760, Jan. 2022, https://doi.org/10.1109/TPEL.2021.3093344.