International Journal of Applied Power Engineering (IJAPE)
Vol. 13, No. 2, June 2024, pp. 499∼507
ISSN: 2252-8792, DOI: 10.11591/ijape.v13.i2.pp499-507

Comprehensive review and analysis of photovoltaic energy conversion topologies

Adil Mansouri[1], Abdelmounime El Magri[1], El Khlifi Younes[1], Rachid Lajouad[1], Mohamed Said Adouairi[2]
[1]EEIS Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Casablanca, Morocco
[2]LIMAS Laboratory, Faculty of Sciences Dhar El Mahraz, Sidi Mohammed Ben Abdellah University, Fez, Morocco

Article Info

Article history:

Received Jun 10, 2023
Revised Oct 29, 2023
Accepted Nov 15, 2023

Keywords:

Energy conversion
Multi-level converters
Photovoltaic
Power converters
Renewable energy systems

ABSTRACT

Energy conversion is a pivotal process with widespread applications, spanning renewable energy systems, electric vehicles, and industrial power grids. Selecting the right energy conversion topology is critical for optimizing system performance, efficiency, and reliability. This comprehensive review paper provides a thorough overview of energy conversion topologies used in photovoltaic (PV) panel systems, as well as their applicability in diverse domains. Furthermore, the paper conducts a detailed analysis of commonly employed energy conversion topologies. Each topology is meticulously examined based on its operating principles, advantages, drawbacks, and typical use cases. This comprehensive review serves as an invaluable resource for researchers, engineers, and practitioners engaged in the dynamic field of energy conversion, offering insights into both wind energy and photovoltaic panel systems.

Corresponding Author:

Adil Mansouri
EEIS Laboratory, ENSET Mohammedia, Hassan II University of Casablanca
Casablanca, Morocco
Email: mansouri_adil@yahoo.com

1. INTRODUCTION

The electrical energy conversion process involves phases like generation, transmission, distribution, and consumption. Energy sources are categorized into fossil fuels (coal, oil, natural gas) and renewables (solar, wind, hydro, geothermal) [1]. There's a shift toward renewables due to their sustainability and positive environmental impacts [2]. Various renewable energy systems have different strengths and weaknesses. Photovoltaic (PV) systems use solar panels, wind systems employ turbines, and hydroelectric plants utilize water force for electricity [3]-[5]. Each technology varies in energy efficiency, costs, maintenance, longevity, and dependability. Choosing the right technology is crucial, considering local conditions, and objectives in renewable energy utilization.

The escalating global energy shortage has prompted a growing reliance on photovoltaic (PV) systems, but their output power remains constrained. To address this limitation, boost converters have gained prominence by stepping up the low input voltage to a higher output level, particularly in renewable energy applications. Researchers have prioritized boost converter design to encompass key considerations such as low cost and high reliability. Challenges persist, however, in achieving optimal output while minimizing maintenance requirements. Consequently, these demands and constraints have led to the classification of boost converters based on factors like efficiency, voltage gain, and diverse DC-DC converter configurations [6]-[8]. Furthermore, operational parameters such as elevated temperature ranges and low electromagnetic compatibility emissions must be upheld. This comprehensive review delves into various step-up converter topologies, shedding light on their high efficiency, voltage conversion ratios, and soft-switching techniques. It focuses specifically on PV systems, encompassing the installation and design of photovoltaic power systems, while exploring advancements in power converter technologies to meet the demands of modern solar PV power plants.

2. PHOTOVOLTAIC POWER CONVERTER TOPOLOGIES

Solar energy, abundant and continually advancing technologically, has become a leading contender in power generation. Solar photovoltaic (PV) systems, converting solar energy into electricity, are gaining popularity for various scales [9]. Technological progress in semiconductors and power electronics has reduced PV system costs, enabling efficient electricity generation and direct grid integration. Connecting to the grid enhances PV power utilization, reduces reliance on batteries, and optimizes cost-effectiveness, while minimizing maintenance.

Figure 1 illustrates a typical grid-connected PV system's block diagram. In grid-connected PV systems, inverters play a crucial role. Three main inverter types exist: central inverters for large-scale setups, string/multi-string inverters for simpler configurations, and module-integrated microinverters for enhanced performance and fault tolerance [10]. These innovations ensure better efficiency, reliability, and grid integration, paving the way for the future of solar energy.

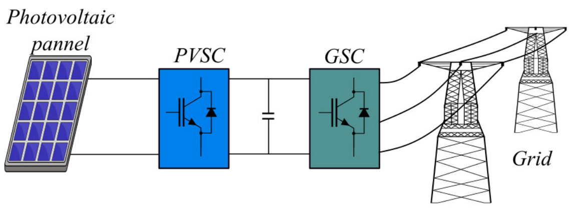

Figure 1. Grid-connected PV system

3. DC/DC POWER CONVERTERS TOPOLOGY

3.1. Buck converter

The buck converter Figure 2 is known for its simplicity and high efficiency. Its main purpose is to efficiently charge batteries, especially when dealing with unpredictable power outputs from PV systems, and it also helps regulate voltage, current, and power for the connected solar panels. However, the converter's operation can become more intricate when it switches between continuous and discontinuous modes, largely influenced by environmental conditions, which can impact the performance of the connected loads. To address these challenges, researchers have explored various modifications and configurations for buck converters [11], [12].

A reconfigurable switched capacitor circuit [13] adjusts to changing input and output voltages, reducing energy loss but potentially increasing switching losses due to extra components. Modulation techniques like hybrid pulse width modulation can minimize these losses. Multiphase DC-DC interleaved buck converters [14] divide output current among phases, lowering stress on switches and conduction losses. Despite increasing complexity in PV systems, these advances aim to ensure continuous operation and enhance conversion efficiency, optimizing power generation and usage.

3.2. Boost converter

Solar PV power generation faces challenges like weather fluctuations and shading, affecting efficiency. Integrating a DC-DC boost converter (Figure 3) addresses variable PV panel voltages, ensuring optimal output regardless of conditions [15]. By elevating voltages from 12-60 V to over 380 V, this converter is essential for energy conversion. Through techniques like pulse-width modulation, it generates higher output DC voltages. Ongoing research aims to enhance boost converter performance [16] for consistent and efficient solar PV power production.

Various boost converter topologies have been developed. Conventional boost converters achieve high voltage gains but face increased losses with higher duty cycles. Soft-switching step-up converters, utilizing techniques like zero current transition (ZCT), eliminate reverse recovery issues. Coupled inductors and zero voltage transition-pulse width modulation (ZVT-PWM) converters reduce losses and ensure voltage regulation. Some topologies achieve zero voltage switching (ZVS) and zero current switching (ZCS), reducing losses [17]. Non-inductive converters provide high voltage ratios, while switched capacitor converters offer efficiency at light loads. Inductance-less and multi-level converters enhance potential density. Multiplier/divider and modular capacitor coupled boost converters improve efficiency and control.

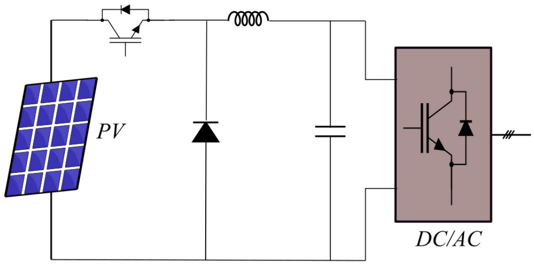

Figure 2. Buck converter

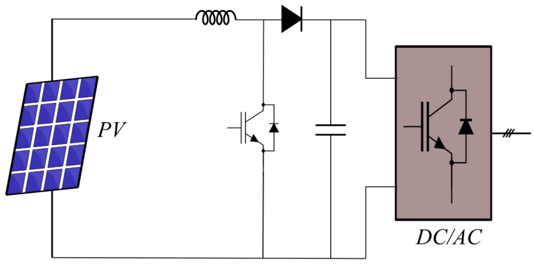

Figure 3. Boost converter

3.3. Buck-boost converter

The buck-boost converter Figure 4 presents a solution in comparison to boost converters, encompassing the entire (I-V) characteristics and minimizing input current ripple during continuous conduction mode [18]. Two-switch buck-boost variations offer reduced stress on components relative to single-switch configurations. An innovative approach involves the two-switch non-inverting buck-boost converter, integrating potential for extra current storage and leveraging the MPPT algorithms for enhanced efficiency during heavy loads [19]. However, challenges like increased inductor currents and switching losses resulting from buffer region introduction can impact operational regions.

Exploring cascade, interleaved, and super-imposed configurations through an AC-DC equivalent circuit synthesis method demonstrates improved efficiency, although comprehensive parameter design insights may be lacking. Despite challenges, advancements within the buck-boost converter realm continue [20], utilizing techniques like high-frequency transformers and integration of converter types to enhance efficiency, dynamics, and power density across various applications, notably in photovoltaic systems.

3.4. Cuk converter

The cuk converter in Figure 5, another prominent topology, offers unique advantages in comparison to traditional boost converters [21]. It provides continuous input and output currents, resulting in reduced current ripple and electromagnetic interference. This converter can achieve voltage inversion with a single switch, facilitating bidirectional power flow. Additionally, its inherent voltage step-down and step-up capabilities make it suitable for a wide range of applications [22], [23], including energy storage systems and renewable energy sources. However, the cuk converter also comes with challenges, including increased complexity due to its unique topology, potential for higher voltage stresses on components, and the need for careful design to ensure proper operation and control. Despite these challenges, its versatile performance characteristics continue to drive research into optimizing and applying the cuk converter for various power conversion needs.

3.5. Zeta converter

The PV zeta converter in Figure 6, a critical component in a stand-alone wind energy conversion system. This converter employs a nonlinear control strategy with three regulators [24]. To simplify the control system and enhance efficiency, an uncontrolled rectifier is employed alongside the DC-DC zeta converter, which acts as the controlled interface between the wind turbine and the battery. The zeta converter is chosen for its advantages, including uninterrupted output current, a wide MPPT region, and minimal ripple in both input and output currents. It operates in both continuous and discontinuous modes, with the continuous mode being the most common. Mathematical formulas governing the design of zeta parameters, highlighting its potential in continuous conduction mode and discontinuous conduction mode. Additionally, the modified zeta inverter (MZI) topology, a PV-based system using the zeta converter in DCM, capable of stepping up DC input voltage and injecting active current into the grid with reduced total harmonic distortion.

3.6. SEPIC converter

SEPIC converters (Figure 7) are designed to minimize voltage ripple. Researchers optimize equivalent inductance and capacitance to reduce maximum voltage ripple due to input voltage and load resistance [25]. Continuous conduction mode is explored, differentiating between complete-inductor-supply and incomplete-inductor-supply modes. Output voltage ripple waveforms, analyzed against equivalent inductance, offer efficiency insights [26]. Enhanced designs, like modified SEPIC with extra diode and capacitor, reduce input current ripple and act as a preregulator.

Addressing input current distortion challenges, techniques include harmonic balance to predict device resilience against switching stress. Soft switching methods like zero voltage switching (ZVS) and zero current switching (ZCS) effectively reduce input current ripple and switching losses. Modifications like quasi-resonant circuits maintain zero voltage switching across a wide input-output range. The design integrates resonant components, synchronizing inductor voltage with PV output current. Coupled with a gate driver circuit for complementary MOSFET inverters, this enhances overall performance.

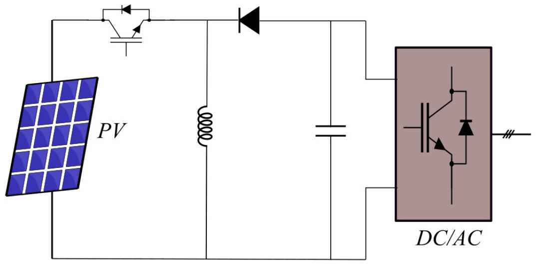

Figure 4. Buck-boost converter

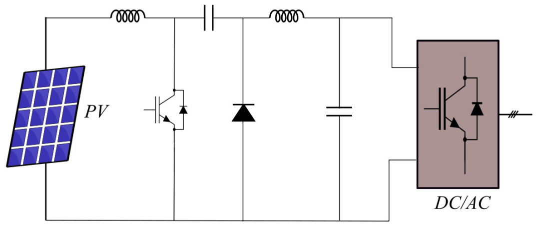

Figure 5. Cuk converter

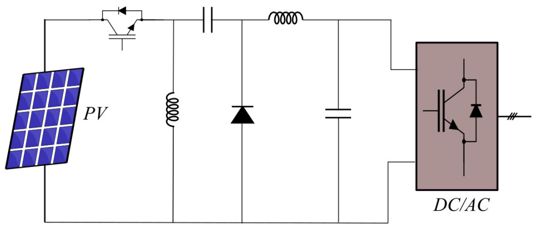

Figure 6. Zeta converter

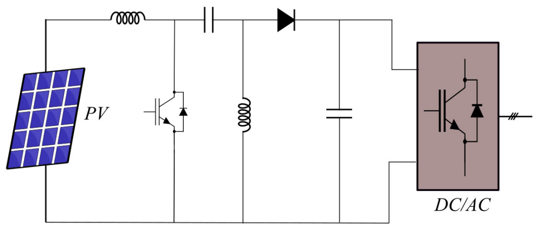

Figure 7. SEPIC converter

3.7. Flyback converter

The design of flyback converters Figure 8 entails a focus on optimizing their performance across multiple dimensions [27]. Researchers have explored methods to manage input and output voltage ripples, critical for achieving high efficiency [28]. Strategies involve adjusting key parameters like duty cycle, switching frequency, and transformer turns ratio to achieve the desired output voltage and minimize voltage ripple.

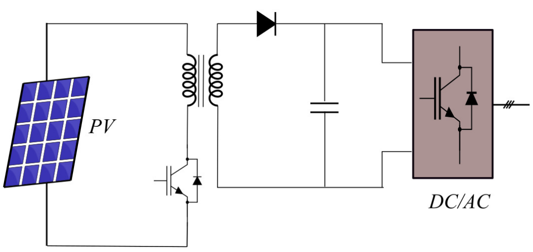

Figure 8. Flyback converter

The operational modes, continuous conduction mode and discontinuous conduction mode, have been analyzed to understand their impact on efficiency, voltage ripple, and system stability. The trade-offs between these modes guide design decisions to ensure optimal converter performance. Additionally, investigations into the influence of parameters like transformer inductance, load resistance, and control mechanisms have offered insights into balancing efficiency and stability [29]. By delving into these aspects, researchers are advancing the design of flyback converters to meet the demands of diverse power electronics applications.

4. INVERTER DC/AC TOPOLOGIES

4.1. Six-switch controlled converter

The dominant topology employed as a multi-source converter-grid-side converter (MSC-GSC) in power energy conversion applications is the six-switch converter Figure 9. This topology functions as a controlled rectifier or voltage inverter and has been extensively utilized, as noted in references [30], [31]. The presence of a DC bus creates a clear separation between the generator and the grid, effectively insulating the grid side from any transients occurring on the generator side. Additionally, In order to guarantee the optimal functioning of the grid-side converter, it is essential to sustain a net DC bus voltage that exceeds the peak line-to-line voltage of the grid [32].

4.2. Z-source inverter

Z-source inverters Figure 10 are unique power inverters designed for electrical energy conversion between two voltage sources. Unlike conventional inverters using full-bridge topologies, Z-source inverters incorporate a distinctive impedance network, adding extra control to the conversion process [33], [34]. This topology includes an inductor and two capacitors arranged in a specific ”Z” shape. The inductor is in series with the DC input voltage, while the two capacitors are in parallel and series with the load. The Z-source network is connected to a standard inverter bridge [35] to complete the energy conversion.

The Z-source inverter offers benefits such as enhanced output voltage and adaptability to variable input levels, making it suitable for renewable energy systems. It also shows better resistance to electromagnetic interference than conventional inverters, leading to improved efficiency. However, challenges include increased complexity, higher costs, reduced controllability at high power levels, and concerns about stability and reliability [36]. To overcome these limitations, especially in applications like wind energy systems, advanced control techniques may be required.

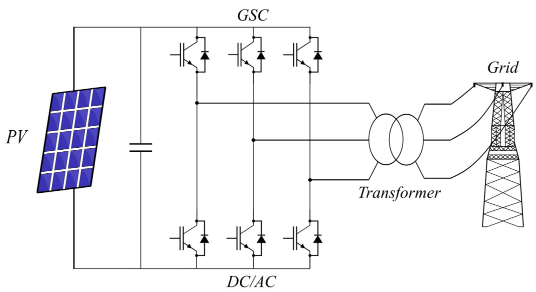

Figure 9. Converter with six switches

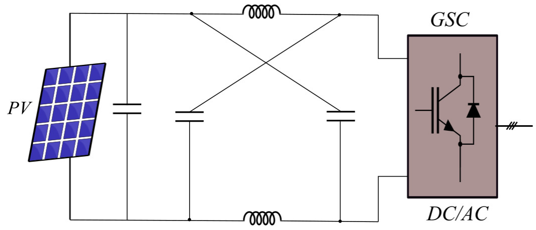

Figure 10. Z-source inverter

4.3. Multilevel converters

Multilevel converters Figure 11 represent an advanced technology for generating multi-level output voltages, enabling the use of smaller output filters. These converters find particular relevance in high-power applications and large-scale power energy systems, as highlighted in references [37]. In recent times, modular multilevel converters (MMC) have attracted considerable research interest due to their ability to cater to the requirements of high power and high voltage in various industrial domains [38]. The MMC operates at elevated voltage levels and stands out by obviating the need for line frequency transformers. Instead, it comprises multiple half-bridge converter sub-modules, ensuring enhanced reliability through redundancy. The presence of numerous modules within the MMC enables a significant reduction in the average switching frequency, all while maintaining the quality of electrical energy. This modular framework positions the MMC as an appealing choice for applications such as medium-voltage drives, high-voltage direct current (HVDC) transmission, and flexible electric power transmission systems. The advantages of multilevel converters encompass their modular design, increased reliability, reduced switch stress, fault-tolerant operation, generation of quasi-sinusoidal output waveforms, and high efficiency. However, it's important to acknowledge their drawbacks, including the complexity associated with control strategies and the requirement for a significant number of measurements to ensure the stability of the power conversion system.

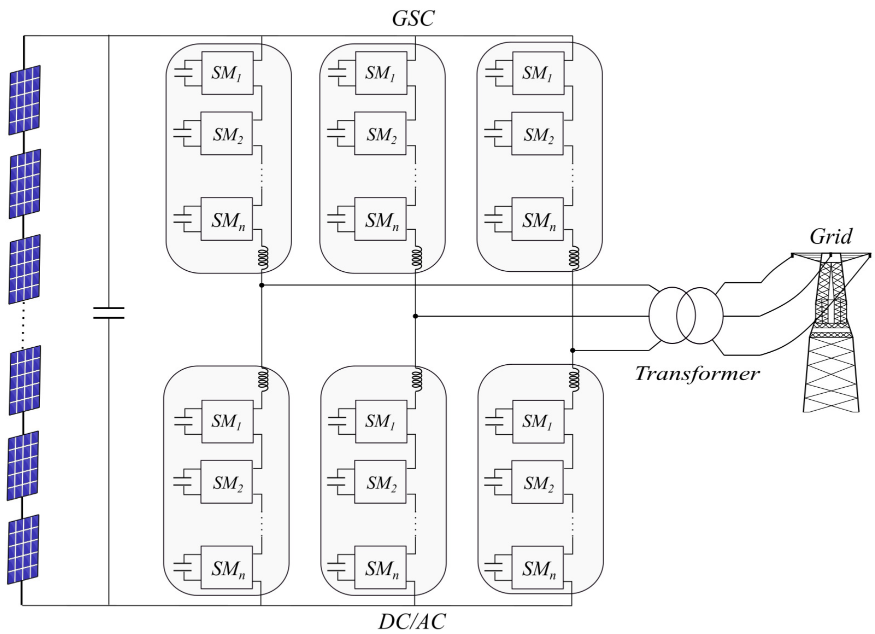

Figure 11. Modular cascaded level converter (MMC)

4.4. Grid-connected PV based 5-level ANPC inverter

The 5-level active neutral point clamped (ANPC) inverter Figure 12 represents a significant advancement in medium-high voltage power electronics conversion technology. In the world of multilevel inverters, which provide high-quality stepped output voltage waveforms and low dv/dt stresses, conventional topologies like the neutral point clamped (NPC) 5-level inverter have been popular for medium voltage industrial applications due to their lower total harmonic distortion and reduced voltage stress compared to 2-level inverters. However, these conventional NPC 5L inverters have drawbacks, including the need for multiple DC-link capacitors and voltage balancing challenges.

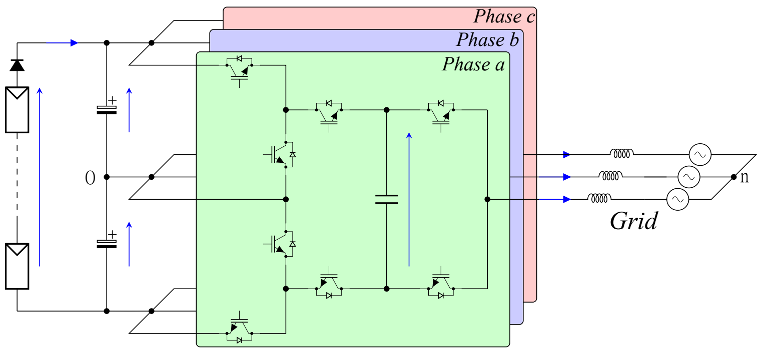

Figure 12. Photovoltaic energy conversion system based on an active neutral-point clamped (ANPC) inverter

To address these issues, the ANPC topology, which combines elements of NPC and flying capacitor

(FC) designs, has gained attention for its cost-effectiveness, compact size, and simpler design [39]. ANPC overcomes the limitations of conventional NPC inverters while maintaining the same number of switches and minimizing the number of active and passive components. Various alternative switched capacitor multilevel inverter topologies have been proposed to further reduce power electronics and passive components.

5. CONCLUSION

The careful selection and integration of photovoltaic (PV) converter topologies are essential for efficiently and reliably converting solar energy into electricity. This attention to detail in considering the unique attributes and performance parameters of PV converters not only enhances the reliability and sustainability of our energy systems but also plays a crucial role in the broader context of renewable energy technologies. The judicious selection of renewable technologies like solar, wind, and hydroelectric power, based on their distinct characteristics, cost-effectiveness, and durability, is fundamental to achieving optimal system performance across varying environmental conditions. Together, these efforts contribute significantly to our pursuit of a cleaner and greener energy future.

REFERENCES

[1] O. Krishan and S. Suhag, "An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources," *International Journal of Energy Research*, vol. 43, no. 12, pp. 6171–6210, Oct. 2019, doi: 10.1002/er.4285.

[2] T. Adefarati and R. C. Bansal, "Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources," *Applied Energy*, vol. 236, pp. 1089–1114, Feb. 2019, doi: 10.1016/j.apenergy.2018.12.050.

[3] V. Khare, P. Chaturvedi, and M. Mishra, "Solar energy system concept change from trending technology: A comprehensive review," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 4, p. 100183, Jun. 2023, doi: 10.1016/j.prime.2023.100183.

[4] A. Mansouri, A. El Magri, R. Lajouad, F. Giri, and A. Watil, "Nonlinear control strategies with maximum power point tracking for hybrid renewable energy conversion systems," *Asian Journal of Control*, Sep. 2023, doi: 10.1002/asjc.3233.

[5] A. A. Abbood, "Harmonic spectra of BLDC motor supplied by a solar PV multilevel inverter," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 20, no. 3, pp. 1693–1702, Dec. 2020, doi: 10.11591/ijeecs.v20.i3.pp1693-1702.

[6] A. Mansouri, A. El Magri, I. El Myasse, R. Lajouad, and N. Elaadouli, "Backstepping nonlinear control of a five-phase PMSG aerogenerator linked to a Vienna rectifier," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 32, no. 2, pp. 734–741, Nov. 2023, doi: 10.11591/ijeecs.v32.i2.pp734-741.

[7] T. Sutikno, A. S. Samosir, R. A. Aprilianto, H. S. Purnama, W. Arsadiando, and S. Padmanaban, "Advanced DC–DC converter topologies for solar energy harvesting applications: a review," *Clean Energy*, vol. 7, no. 3, pp. 555–570, Jun. 2023, doi: 10.1093/ce/zkad003.

[8] A. Mansouri, A. El Magri, R. Lajouad, F. Giri, M. S. Adouairi, and B. Bossoufi, "Nonlinear observer with reduced sensors for WECS involving Vienna rectifiers – Theoretical design and experimental evaluation," *Electric Power Systems Research*, vol. 225, p. 109847, Dec. 2023, doi: 10.1016/j.epsr.2023.109847.

[9] N. Khaldi, Y. Barradi, K. Zazi, and M. Zazi, "Controller design for PV experimental bench with ADRC strategy supervised by Labview created interface," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 2, pp. 1162–1176, Jun. 2021, doi: 10.11591/ijpeds.v12.i2.pp1162-1176.

[10] A. Mansouri, A. El Magri, R. Lajouad, F. Giri, and A. Watil, "Optimization Strategies and Nonlinear Control for Hybrid Renewable Energy Conversion System," *International Journal of Control, Automation and Systems*, vol. 21, no. 11, pp. 3796–3803, Nov. 2023, doi: 10.1007/s12555-023-0058-7.

[11] P. Azer and A. Emadi, "Generalized State Space Average Model for Multi-Phase Interleaved Buck, Boost and Buck-Boost DC-DC Converters: Transient, Steady-State and Switching Dynamics," *IEEE Access*, vol. 8, pp. 77735–77745, 2020, doi: 10.1109/ACCESS.2020.2987277.

[12] S. Kapat, "Sampling-Induced Border Collision Bifurcation in a Voltage-Mode DPWM Synchronous Buck Converter," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 6, pp. 1048–1052, Jun. 2019, doi: 10.1109/TCSII.2018.2866520.

[13] Y. Li, B. L. Dobbins, and J. T. Stauth, "An Optically Powered, High-Voltage, Switched- Capacitor Drive Circuit for Microrobotics," *IEEE Journal of Solid-State Circuits*, vol. 56, no. 3, pp. 866–875, Mar. 2021, doi: 10.1109/JSSC.2020.3032076.

[14] E. Ibarra, A. Arias, I. M. de Alegría, A. Otero, and L. de Mallac, "Digital Control of Multiphase Series Capacitor Buck Converter Prototype for the Powering of HL-LHC Inner Triplet Magnets," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 10, pp. 10014–10024, Oct. 2022, doi: 10.1109/TIE.2021.3120489.

[15] F. H. Aghdam and M. Abapour, "Reliability and Cost Analysis of Multistage Boost Converters Connected to PV Panels," *IEEE Journal of Photovoltaics*, vol. 6, no. 4, pp. 981–989, Jul. 2016, doi: 10.1109/JPHOTOV.2016.2566885.

[16] Q. Huang, A. Q. Huang, R. Yu, P. Liu, and W. Yu, "High-Efficiency and High-Density Single-Phase Dual-Mode Cascaded Buck–Boost Multilevel Transformerless PV Inverter With GaN AC Switches," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 7474–7488, Aug. 2019, doi: 10.1109/TPEL.2018.2878586.

[17] T.-J. Liang, M.-H. Cheng, W.-Y. Huang, and W.-J. Tseng, "Interleaved Half-Bridge Flyback Converter With Zero-Current Switching," *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3370–3383, Apr. 2019, doi: 10.1109/TPEL.2018.2852332.

[18] M. R. Banaei and H. A. F. Bonab, "A Novel Structure for Single-Switch Nonisolated Transformerless Buck–Boost DC–DC Converter," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 198–205, Jan. 2017, doi: 10.1109/TIE.2016.2608321.

[19] H. Wu, T. Mu, H. Ge, and Y. Xing, "Full-Range Soft-Switching-Isolated Buck-Boost Converters With Integrated Interleaved Boost

Converter and Phase-Shifted Control," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 987–999, Feb. 2016, doi: 10.1109/TPEL.2015.2425956.

[20] H.-S. Son, J.-K. Kim, J.-B. Lee, S.-S. Moon, J.-H. Park, and S.-H. Lee, "A New Buck–Boost Converter With Low-Voltage Stress and Reduced Conducting Components," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 7030–7038, Sep. 2017, doi: 10.1109/TIE.2017.2686300.

[21] W. Ma *et al.*, "Hopf Bifurcation and Its Control in the One-Cycle Controlled Cuk Converter," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 8, pp. 1411–1415, Aug. 2019, doi: 10.1109/TCSII.2018.2880868.

[22] C. A. Ramos-Paja, D. Gonzalez-Motoya, J. P. Villegas-Seballos, S. I. Serna-Garces, and R. Giral, "Sliding-mode controller for a photovoltaic system based on a Cuk converter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 3, p. 2027–2044, Jun. 2021, doi: 10.11591/ijece.v11i3.pp2027-2044.

[23] R. Pandey and B. Singh, "A Power-Factor-Corrected LLC Resonant Converter for Electric Vehicle Charger Using Cuk Converter," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6278–6286, Nov. 2019, doi: 10.1109/TIA.2019.2934059.

[24] M. R. Banaei and H. A. F. Bonab, "A High Efficiency Nonisolated Buck–Boost Converter Based on ZETA Converter," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 3, pp. 1991–1998, Mar. 2020, doi: 10.1109/TIE.2019.2902785.

[25] S.-W. Lee and H.-L. Do, "Zero-Ripple Input-Current High-Step-Up Boost–SEPIC DC–DC Converter With Reduced Switch-Voltage Stress," *IEEE Transactions on Power Electronics*, vol. 32, no. 8, pp. 6170–6177, Aug. 2017, doi: 10.1109/TPEL.2016.2615303.

[26] H. Ardi and A. Ajami, "Study on a high voltage gain SEPIC-based DC–DC converter with continuous input current for sustainable energy applications," *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10403–10409, Dec. 2018, doi: 10.1109/TPEL.2018.2811123.

[27] Z. Ma, S. Wang, H. Sheng, and S. Lakshmikanthan, "Modeling, Analysis and Mitigation of Radiated EMI Due to PCB Ground Impedance in a 65 W High-Density Active-Clamp Flyback Converter," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 12, pp. 12267–12277, Dec. 2023, doi: 10.1109/TIE.2023.3239904.

[28] G. Spiazzi and S. Buso, "Extended Analysis of the Asymmetrical Half-Bridge Flyback Converter," *IEEE Transactions on Power Electronics*, vol. 36, no. 7, pp. 7956–7964, Jul. 2021, doi: 10.1109/TPEL.2020.3044840.

[29] Y. Cao, K. Li, and M. Lu, "Balancing Method Based on Flyback Converter for Series-Connected Cells," *IEEE Access*, vol. 9, pp. 52393–52403, 2021, doi: 10.1109/ACCESS.2021.3070047.

[30] M. S. Bhaskar, S. Padmanaban, D. J. Almakhles, N. Gupta, and U. Subramaniam, "Double-switch switched-inductor converter with minimal switch voltage stress for renewable energy conversion," *Computers & Electrical Engineering*, vol. 98, p. 107682, Mar. 2022, doi: 10.1016/j.compeleceng.2022.107682.

[31] M. Nabatirad, R. Razzaghi, and B. Bahrani, "Autonomous power balance in hybrid AC/DC microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 146, p. 108752, Mar. 2023, doi: 10.1016/j.ijepes.2022.108752.

[32] A. Mansouri, A. El Magri, R. Lajouad, and F. Giri, "Control design and multimode power management of WECS connected to HVDC transmission line through a Vienna rectifier," *International Journal of Electrical Power & Energy Systems*, vol. 155, p. 109563, Jan. 2024, doi: 10.1016/j.ijepes.2023.109563.

[33] M. Alizadeh and S. S. Kojori, "Small-signal stability analysis, and predictive control of Z-Source Matrix Converter feeding a PMSG-WECS," *International Journal of Electrical Power & Energy Systems*, vol. 95, pp. 601–616, Feb. 2018, doi: 10.1016/j.ijepes.2017.09.018.

[34] A. R. Dehghanzadeh, V. Behjat, and M. R. Banaei, "Double input Z-source inverter applicable in dual-star PMSG based wind turbine," *International Journal of Electrical Power & Energy Systems*, vol. 82, pp. 49–57, Nov. 2016, doi: 10.1016/j.ijepes.2016.02.017.

[35] E. Jaoide, F. El Aamri, M. Outazkrit, A. Radouane, and A. Mouhsen, "PI-based ZSVM Control of Quasi-Z-Source Inverter for Photovoltaic Applications in Standalone Mode," *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, vol. 11, no. 1, Feb. 2023, doi: 10.52549/ijeei.v11i1.4224.

[36] E. Jaoide, F. El Aamri, M. Outazkrit, A. Radouane, and A. Mouhsen, "Characteristics Dynamic Analysis and Modeling of Quasi-Z-Source Inverters for PV Applications," *The Proceedings of the International Conference on Electrical Systems & Automation, Singapore: Springer Singapore*, 2022, pp. 91–102. doi: 10.1007/978-981-19-0039-6_8.

[37] F. Eroğlu, M. Kurtoğlu, A. Eren, and A. M. Vural, "A novel adaptive state-of-charge balancing control scheme for cascaded H-bridge multilevel converter based battery storage systems," *ISA Transactions*, vol. 135, pp. 339–354, Apr. 2023, doi: 10.1016/j.isatra.2022.09.044.

[38] F. Deng, Y. Chen, J. Dou, C. Liu, Z. Chen, and F. Blaabjerg, "Isolation Forest Based Submodule Open-Circuit Fault Localization Method for Modular Multilevel Converters," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 3, pp. 3090–3102, Mar. 2023, doi: 10.1109/TIE.2022.3167138.

[39] R. Agarwal, K. K. Gupta, and S. Singh, "A novel self-boosting 5-level inverter for grid-connected photovoltaic system," *Electric Power Systems Research*, vol. 211, p. 108201, Oct. 2022, doi: 10.1016/j.epsr.2022.108201.

BIOGRAPHIES OF AUTHORS

Adil Mansouri received his Ph.D. in Electrical Engineering - Automatic from Hassan II University, Casablanca, Morocco, in 2023. Currently an Electrical Engineering professor in preparatory Engineering classes. His research interests include optimization, observation and nonlinear control of AC machines and renewable energy. He can be contacted at email: mansouri_adil@yahoo.com.

Abdelmounime El Magri received his Ph.D. in Electrical Engineering - Automatic Control from Mohammed V University, Rabat, Morocco, in 2011. He is currently a professor at the Hassan II University, Casablanca Morocco. His research interests include optimization, observation and nonlinear control of AC machines and energy conversion systems. He has coauthored several papers on these topics. He can be contacted at email: magri_mounaim@yahoo.fr.

El Khlifi Younes is a Ph.D. student in Université Hassan II de Casablanca Department of Electrical Engineering. Currently an Electrical Engineering professor in preparatory Engineering classes. His research interests include optimization, observation and nonlinear control of AC machines and renewable energy. He can be contacted at email: younes.elkhlifi5@gmail.com.

Rachid Lajouad was born in 1974. He received Ph.D. degree in Electrical Engineering from Mohammed V University, Rabat, Morocco, in 2016. Currently, he is a Professor at the Hassan II University, Casablanca, Morocco. His research interests include optimization, observation and nonlinear control of AC machines and renewable energy. He has published several journal/conference papers on these topics. He can be contacted at email: dsa.lajouad@gmail.com.

Mohamed Said Adouairi is a Ph.D. student in LIMAS Laboratory, Faculty of Sciences Dhar El Mahraz, Sidi Mohammed Ben Abdellah University, Fez, Morocco. His research interests include optimization, observation and nonlinear control of AC machines and renewable energy. He can be contacted at email: adouairi.said@gmail.com.