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A Review on Inverter Technologies for Solar PV Power Generation

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A B S T R A C T

Overall efficiency plays a huge role in current power systems hence the importance of understanding the conversion of energy, this is especially important in renewable energy systems such as the solar photovoltaic (PV) system. At the center of this process are inverters, which take direct current (DC), produced by solar panels and transform it into the alternating current (AC) used within homes and for connection to the grid. In this paper, a literature review of numerous inverter topologies is presented, examining the foundation and pros and cons of inverter topologies as they apply to a PV system. Some reviewed inverter topologies comprise six-switch controlled converters, Z-source inverters, multilevel inverters, and five-level active neutral point clamped (ANPC) inverters. Each topology is tailored for certain issues such as; AC line current harmonic distortion, voltage regulation and synchronization to the grid while providing certain advantages in different applications. Six-switch converters are simple and reliable; Z-source inverters created a new impedance network for simplifying single-stage buck-boost conversion; multilevel inverters yield high power quality with low THD; the ANPC inverter enhances multilevel inverters further to have higher efficiency and reliability. The paper also describes several developments including the modular design, modern control techniques, and multifunctional structure that improves the inverters efficiency, flexibility, and compatibility with smart grid. They are useful for prolonging the performance and optimizing the costs of PV-based energy systems supporting the occurrence of renewable energy. This review has revealed the increasing importance of inverters in meeting these challenges and enabling the transition to a prosumer dominated green energy paradigm for solar PV systems and the electricity grid.

Keywords: ANPC inverters, DC-AC converters, Energy conversion, Inverters, Multilevel inverters, Photovoltaic systems, Power efficiency, Renewable energy, Solar power generation, Z-source inverters.

1. Introduction

Energy conversion is imperative to current practices, especially in renewable energy incorporation to power systems like the solar PV systems [1]. Although, DC-DC converters are very important in controlling and transmitting maximum power from PV panels the DC-AC inverters are significant in converting the DC power generated by the panels to AC form in order to interface with the AC power poles and home appliances [2]. Inverters form a critical link in the process of integration of renewable power systems into the currently existing energy systems hence forming an important actor for innovation of sustainable solar systems.

Inverters are used not for the conversion of DC to AC only, but also for controlling power quality, synchronization with the grid and, of course, to meet the efficiency standard of energy [3]. Superior inverter topologies have been designed to deal with issues such as harmonics, voltage control, and energy loss, which are important factors for the generation of steady and efficient power supply [4]. Holed at inverter topology has a significant effect on characteristics, availability, and stability of the PV systems some important aspects include efficiency and thermal control of the inverter system, its capability to operate under variable load and input voltage.

Several types of inverters are widely used in solar PV system [5] and they differ in operating features and utilization. These include central inverters mostly used in utility scale applications; string inverters used in mid-scale applications; multi-string inverters which are more modular and have better fault tolerance than string inverters; and micro inverters used at the scale of a single module to provide best conversion efficiency for the module, and scalability of the system. Moreover, new generation technologies including hybrid inverters and bi-directional inverters are widening their utility in connecting energy storage systems and interactiveness with the grid.

With the adoption of renewable energy, particularly photovoltaic systems, increasing, inverters have become objects of research and development. Essentially, the advancement in the inverter technology has given rise to different multiple configurations of the single inverter [6]: One of these are the conventional six-switch controlled converters which offer a reliable and simple solution to DC-AC conversion. New ideas can be proposed as Z-source inverters, applicable for single-phase and different types of three-phase systems, with single-stage buck-boost feature and robustness to grid perturbation. Alternatively, multilevel inverters are for high power applications that provide better quality power and low levels of electromagnetic interferences due to multiple voltage levels. Recent innovations have targeted complex topologies such as the ANPC loaded into the five-level H-bridge grid tied inverter for PV systems with high power densities and Grid Code compliance. Electric-drive systems in these applications incorporate complex control schemes and modularity for increased power-to-volume ratios, better thermal management, and better resiliency to failures. Innovations such as solar electricity are key to fulfilling the expanding need to attain larger and more dependable renewable energy systems. Also, intelligent grid features and sophisticated control systems are allowing inverters to ensure grid voltage control and follow the changing energy requirements.

This paper is a review of some of the inverter topologies suitable for solar PV application, the way the selected topologies work, their merits, demerits and the areas of their suitability. Thus, presenting this review of the current developments in inverter systems, the article is designed to benefit researchers and engineers, as well as professionals from the solar PV field, with useful insights into the improvements of the systems and the solutions to contemporary energy conversion issues.

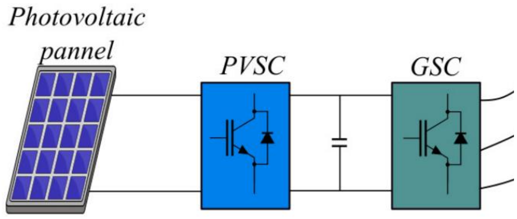

Fig. 1 – General overview of the solar PV system.

2. Six-Switch Controlled Inverter

The six-switch controlled converter topology (Fig. 2) is one of the most typical used in the power energy conversion systems, where it represents an essential heterogeneous converter in the Multi-Source Converter – Grid Side Converter (MSC-GSC) systems [7][8]. This ubiquitous topology works as either a controlled rectifier or voltage inverter, making it a building block for efficient energy conversion in many applications. Indeed the fact that it is widely employed in renewable energy systems especially those in PV applications puts it as being crucial in today's power systems.

An essential characteristic of the six-switch converter is isolation between the generator side and the grid side due to the use of a DC bus. This separation is useful in excluding the transients or disturbances resulting from the generator side to the rest of the grid and therefore improving on the stability and quality of power supplied. The DC bus is placed in between the two sides to maintain operational isolation and enable a low impedance path for energy transfer.

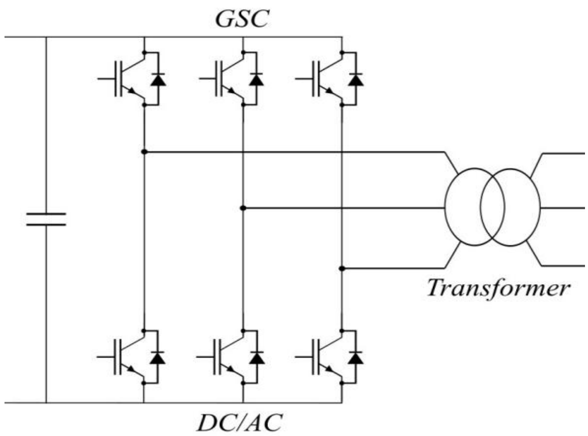

Fig. 2 – Six-switch controlled inverter.

This paper identifies several control techniques aimed at regulating the DC bus voltage at a value higher than the peak line-to-line voltage of the grid in order to realize the best performance. This requirement provides assurance to grid-side converter and also ensures energy transfer and phasor synchronization with the grid. Further, the topology offers diverse modulation techniques, which include the space vector pulse-width modulation (SVPWM), that optimizes the converter and minimizes harmonic distortion.

Thus, six-switch controlled converter is an indispensable part of renewable energy systems because of its reliability, versatility and performances. This is true however the system is quite simple and still is replete with options for further improvement, key among them being improved control algorithm, better thermal system and incorporation in smart grid. Such refinements also strengthen its position as the premier option for usage in PV based energy conversion applications.

3. Z-Source Converter

The Z-source inverter presented in Fig. 3 is a unique power conversion topological structure well-suited for energy exchange between dual voltage levels, free of the conventional inverter drawbacks [9][10]. Unlike the typical full-bridge inverters, the Z-source inverter employs an impedance network to extend freedom in the conversion process. The structure of the Z-source inverter is based upon the Z-network which is formed by the inductor and two capacitors connected in "Z" shape. The inductor is in series with the input voltage and the capacitors are resonating both in series and shunt to the load resistor. To achieve full energy conversion, this network is connected with standard inverter bridge. This means that by utilizing the Z-source network the inverter can perform the voltage boosting and bucking steps in one conversion stage thereby foregoing other conversion stages such as the DC-DC converter.

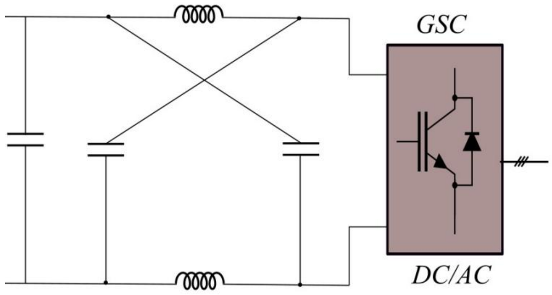

Fig. 3 – Z-source converter.

The major strength of the Z-source inverter is the flexibility in the processing of varying input voltages, and compared to conventional inverters, the Z-source inverter offers a higher level of output voltage. This makes it very ideal for use in renewable energy sources like PV systems and Wind energy systems which the input voltage may vary at times. Moreover, the impedance network enhances electromagnetic immunity, thereby enhancing performance and reliability of the different components in the system. The inherent feature of the Z-source inverter is its suitability for wide input voltage variations which make it suitable especially for use with renewable power sources where reliability and versatility are key factors, enhances its compatibility with renewable energy sources, making it a preferred choice in scenarios where reliability and adaptability are critical.

However, the use of the Z-source inverter has some disadvantages such as higher order levels of the inverter system, higher cost of the initial investment, and lower level of utility control at high power levels. These may create some instability and unreliability in high power application of organic solar cell. Moreover, the topology demands proper engineering and management in order to avoid some drawbacks, such as over-voltage stress.

In order to meet these challenges, improved control strategies, which include SVPWM with angle modification [11] and MPC [12] have been used. These methods seek to improve performance stability and power density as well as minimize voltage stress and switching losses. Further research has also considered diode-clamped converter topologies of Z-source in addition to impedance network improvement in renewable energy systems especially in grid integration [13]. Due to the concept of the special impedance network and variable operation, the Z-source inverter remains as a viable solution for advanced energy conversion requirements while capturing the emerging sustainable power systems requirements.

4. Multilevel Inverter

The multilevel converter (shown in Fig. 4) is elaborative power electronics that produce multiple levels of output voltage leading to enhanced power quality and enable the incorporation of compact output filters. This feature has made multilevel converters particularly ideal for highly-powered applications and large-scale energy solutions, where power density, efficiency and energy handling capabilities are paramount [14][15].

Another distinguished innovation in this context is known as Modular Multilevel Converter (MMC) which has become preferable choice for high power and high voltage needed application in the industry and renewable energy field. The MMC eliminates the requirement for large line-frequency transformers by essentially building the MMC at a higher voltage level using a multiplicity of half-bridge converter sub-modules. This modularity also increases system dependability through redundancy whereby if some of the sub modules are defective in the system, the system still works.

Another major benefit of the MMC is that it is able to function at lesser average switching frequencies for the conversion stages compared to traditional inverters and rectifiers, still demonstrating good quality of the output waveform. This characteristic lowers the switching losses and electromagnetic tendency that decreases the total energy usage. Versatility could also be derived from the fact that modular design means scalability and therefore the product can easily be used inisions that are varied.

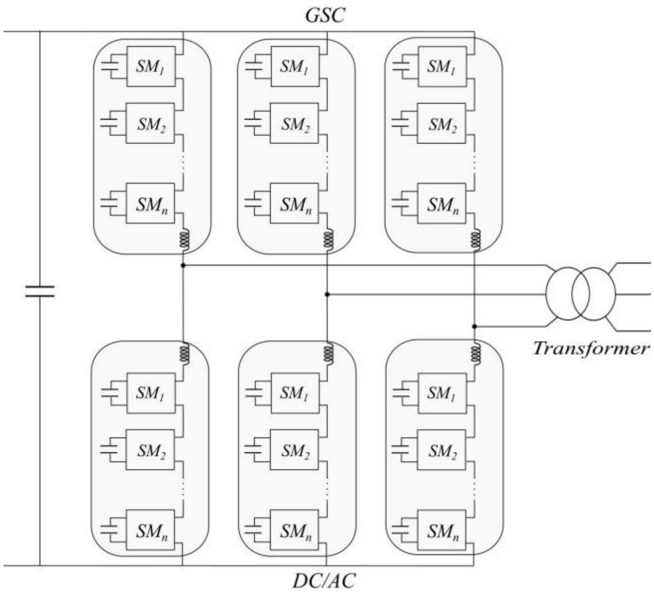

Fig. 4 – Cascaded MMC.

The earlier discussion shows that multilevel converters' advantages are not limited to modularity. This architecture is inherently less stressful on power electronic components which, in turn, provides longer service life and greater reliability. Also, the possibility to generate waveforms with a shape close to sinusoidal and smaller total harmonic distortion (THD) reduces the requirements for filtering, which enhances the overall system efficiency. Multilevel converters also offer flexibility in terms of their control schemes and maintain stability in application and their components for fault tolerance in challenging circumstances.

However, multilevel converters have certain problems themselves. A major issue with them is the depth of their control strategies, which entails, for instance, the use of model predictive control (MPC) [16][17] or complicated pulse-width modulation (PWM) [18] to balance voltage and guarantee overall stability of the grid. Furthermore, in order to sustain the stability of the multilevel converters, a large number of real time measurements are required, which leads to more complexity and cost. These challenges along with thinning of the top of the liquid layer due to higher initial investment for additional components or the complicated controls show where future research and development can be directed.

In spite of the challenges that come with the integration of multilevel converters, they have been shown to be a revolutionizing technology in power electronics. Thanks to the modularity and the high-performance/reliability ratio, they are essential in the current power system, especially in the integration of renewable energy sources [19]. While the development research goes on in order to solve their problems, these types of converters will be able to occupy even more important position in the further evolution of power-saving, innovative technologies of utilizing renewable energy sources.

5. Five-Level ANPC Inverter

The five-level active neutral point clamped (ANPC) inverter shown in Fig. 5 is a big step forward in medium-high voltage power electronics. With the primary purpose of improving the performance and efficiency of multilevel inverters the five level ANPC topology is ideal for systems that require high quality of output voltage waveform and low dv/dt stress. The proposed topology belongs to the family of multilevel inverters, known for their capability of generating stepped output voltage waveforms with considerably less harmonic content of the voltage and with higher voltage capabilities as compared to conventional two-level inverters.

Conventionally, neutral point clamped (NPC) five-level inverters have been preferred for the medium voltage industrial applications. With lower total harmonic distortion (THD) and lower voltage stress they have become an ideal solution in many industries. However, these conventional NPC inverters possess some inherent problems including the need for a large number of DC-link capacitors and the problem of voltage balance of capacitor. These problems can create serious problems during the design of the systems and slow the performance in some operating conditions.

However, NPC designs do not meet these requirements, and the development of ANPC inverter as an improved solution has been reported in this article. This topology combines aspects of the NPC and FC designs and provides reasonable price, compactness, and design simplicity [21]. The ANPC inverter introduces similar number of switches to that of conventional NPC configuration, however, offers enhancements that help to alleviate the DC-link capacitors, and voltage regulation issues. Thus, reducing the number of active and passive components, the ANPC inverter obtains higher efficacy and reliability with no disturbance of the system complicacy.

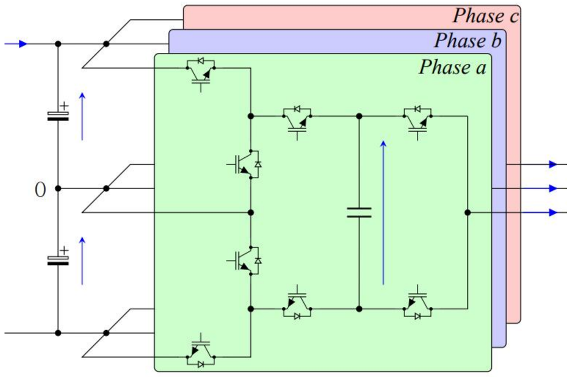

Fig. 5 – ANPC inverter.

Subsequent extensions in this paradigm include several novel switched capacitor multilevel inverter configurations [22]. These innovations expect to minimize the number of power electronics components and passive elements needed to make the system operate, thus enhancing the layout and the efficiency of the overall system. These improvements make the ANPC inverter a tempting proposition for grid interfaced PV systems where quality of power and efficiency are of very high importance.

The five level ANPC inverter is particularly advantageous in renewable energy applications such as photovoltaic PV systems where the nature of solar generation exhibit high degree of variability [23]. The fact that the developed signal is of high quality voltage waveform with low harmonics makes it suitable for today's grid requirements; with simple and compact design translates to low cost of installation and servicing.

Finally, the five-level ANPC inverter system is an important technology that offers efficiency in medium to high voltage power conversion in industrial and renewable energy systems. Through objective elimination of basic structurally-deficient NPC inverters and subsequent effective utilization of components, this topology not only improves the effectiveness, longevity, and profitability of multilevel inverter systems for a grid interfaced PV system and much more.

6. Conclusion

In this paper, the various inverter topologies necessary for the optimum performance of PV systems operating in renewable energy fields have been described in detail. The part played by inverters in transferring power from PV modules from DC to AC which is well compatible with grid systems is very important in realizing the efficiency, reliability and compatibility of the systems. All the topologies which have been presented: six-switch controlled converters, Z-source converters, multilevel converters and the five-level ANPC inverter have advantages that fit certain application needs and provides solutions to various operation and design issues.

The six-switch converter is widely used topology because of these features and remains a popular choice in many applications such as grid integration. The Z-source inverter has an additional impedance network which makes it suitable for renewable energy systems in spite of its complexities mainly because of its ability to vary in accordance with changes in input conditions. MMC are categorized under multilevel converters that provide a better profile of voltage waveform in addition to being highly reliable for high-power and medium voltage applications. Last but not least, the five-level ANPC inverter improves the multilevel inverter system; some challenges include the capacitor balancing problems, component count; nonetheless, the advanced ANPC inverter promotes energy conversion affordability and efficiency.

The analysis highlights how these inverter topologies are evolving to meet the demands of modern PV systems, focusing on improving energy efficiency, reducing harmonics, and optimizing system design. Innovations like modularity, soft-switching techniques, and hybrid designs are pushing the boundaries of performance and scalability, ensuring that PV-based energy systems can reliably meet global energy needs.

In conclusion, the selection and application of the appropriate inverter topology depend on the specific requirements of the PV system, such as power level, voltage range, and grid compatibility. Advancements in inverter design and control strategies are paving the way for more sustainable and efficient energy systems, contributing significantly to the adoption of renewable energy sources and the transition to a cleaner energy future. This ongoing research and development in inverter technologies underscore their vital role in the growth and optimization of solar PV power generation.

References

1. Pourasl, H. H., Barenji, R. V., & Khojastehnezhad, V. M. (2023). Solar energy status in the world: A comprehensive review. *Energy Reports, 10*, 3474–3493.

2. Zidane, T. E. K., et al. (2023). Grid-Connected Solar PV Power Plants Optimization: A Review. *IEEE Access, 11*, 79588–79608.

3. Blaabjerg, F., Yang, Y., Kim, K. A., & Rodriguez, J. (2023). Power Electronics Technology for Large-Scale Renewable Energy Generation. *Proceedings of the IEEE, 111*(4), 335–355.

4. Morey, M., Gupta, N., Garg, M. M., & Kumar, A. (2023). A comprehensive review of grid-connected solar photovoltaic system: Architecture, control, and ancillary services. *Renewable Energy Focus, 45*, 307–330.

5. Zeb, K., Uddin, W., Khan, M. A., Ali, Z., Ali, M. U., Christofides, N., & Kim, H. J. (2018). A comprehensive review on inverter topologies and control strategies for grid-connected photovoltaic system. *Renewable and Sustainable Energy Reviews, 94*, 1120–1141.

6. Kolantla, D., Mikkili, S., Pendem, S. R., & Desai, A. A. (2020). Critical review on various inverter topologies for PV system architectures. *IET Renewable Power Generation, 14*, 3418–3438.

7. Bhaskar, M. S., Padmanaban, S., Almakhles, D. J., Gupta, N., & Subramaniam, U. (2022). Double-switch switched-inductor converter with minimal switch voltage stress for renewable energy conversion. *Computers & Electrical Engineering, 98*, 107682.

8. Singh, S., Saini, S., Gupta, S. K., et al. (2023). Solar-PV inverter for the overall stability of power systems with intelligent MPPT control of DC-link capacitor voltage. *Protection and Control of Modern Power Systems, 8*(15).

9. Liu, Y., Abu-Rub, H., Ge, B., Blaabjerg, F., Ellabban, O. S., & Loh, P. C. (2016). *Impedance Source Power Electronic Converters* (1st ed.). IEEE Press.

10. Kshirsagar, N., Debre, P. D., Kadu, A., & Juneja, R. (2017). Design of three phase Z-source inverter for solar photovoltaic application. *2017 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, 1–6.

11. Manoj, P., Annamalai, K., Dhara, S., & Somasekhar, V. T. (2022). A Quasi-Z-Source-Based Space-Vector-Modulated Cascaded Four-Level Inverter for Photovoltaic Applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 10*(4), 4749–4762.

12. Liu, Y., Liu, X., Li, X., Yuan, H., & Xue, Y. (2023). Model Predictive Control-Based Dual-Mode Operation of an Energy-Stored Quasi-Z-Source Photovoltaic Power System. *IEEE Transactions on Industrial Electronics, 70*(9), 9169–9180.

13. Das, C. K., Annamalai, K., & Veeramraju Tirumala, S. (2022). A Quasi-Z-Source-Based Five-Level PV Inverter With Leakage Current Reduction. *IEEE Transactions on Industry Applications, 58*(1), 400–412.

14. Paneti, A. V. P., & Dhanamjayulu, C. (2023). An overview on multi-level inverter topologies for grid-tied PV system. *International Transactions on Electrical Energy Systems*, 9690344.

15. Padmanaban, S., Dhanamjayulu, C., & Khan, B. (2021). Artificial Neural Network and Newton Raphson (ANN-NR) Algorithm Based Selective Harmonic Elimination in Cascaded Multilevel Inverter for PV Applications. *IEEE Access, 9*, 75058–75070.

16. Garcia, C., et al. (2024). Model Predictive Control in Multilevel Inverters Part I: Basic Strategy and Performance Improvement. *IEEE Open Journal of Industry Applications, 5*, 428–441.

17. Norambuena, M., et al. (2024). Model Predictive Control in Multilevel Inverters Part II: Renewable Energies and Grid Applications. *IEEE Open Journal of Industry Applications, 5*, 414–427.

18. Lashab, A., Sera, D., Hahn, F., Camurca, L. J., Liserre, M., & Guerrero, J. M. (2021). A Reduced Power Switches Count Multilevel Converter-Based Photovoltaic System With Integrated Energy Storage. *IEEE Transactions on Industrial Electronics, 68*(9), 8231–8240.

19. Bana, P. R., Panda, K. P., & Panda, G. (2020). Power Quality Performance Evaluation of Multilevel Inverter With Reduced Switching Devices and Minimum Standing Voltage. *IEEE Transactions on Industrial Informatics, 16*(8), 5009–5022.

20. Liu, C., et al. (2022). Leakage Current Suppression of Transformerless 5L-ANPC Inverter With Lower Ripple Model Predictive Control. *IEEE Transactions on Industry Applications, 58*(5), 6297–6309.

21. Agarwal, R., Gupta, K. K., & Singh, S. (2022). A novel self-boosting 5-level inverter for grid-connected photovoltaic system. *Electric Power Systems Research, 211*, 108201.

22. Baksi, S. K., & Behera, R. K. (2023). A Reduced Switch Count Seven-Level Boost ANPC Based Grid Following Inverter Topology With Photovoltaic Integration. *IEEE Transactions on Industry Applications, 59*(4), 4238–4251.

23. Wang, H., Kou, L., Liu, Y.-F., & Sen, P. C. (2017). A New Six-Switch Five-Level Active Neutral Point Clamped Inverter for PV Applications. *IEEE Transactions on Power Electronics, 32*(9), 6700–6715.