Research Journal of Engineering Technology and Medical Sciences (ISSN: 2582-6212), Volume 08, Issue 02, June-2025
Available at www.rjetm.in/

A Swapping Pattern-Based PWM Technique for Generating Distinct Zero Sequence Sets in Multilevel Inverters

[1]Rajiv Kumar, [2]Chitra Das
[1]M.Tech Scholar, , [2]Associate Professor
[1]Department of Electrical & Electronics Engineering,
[2]Department of Electrical & Electronics Engineering,
Corporate Institute of Science and Technology Bhopal, (M.P.)
Email-: [1]rajivrajpatna2018@gmail.com, [2]thakur.chitra@gmail.com.com ,

*** Corresponding Author: Rajiv Kumar**

Abstract: This paper validates a proposed Swapping Pattern-based PWM (SPS-PWM) for generating distinct Zero Sequence Sets (ZSS) across all inverter levels and compares it with existing PWM techniques. Using triangular waveforms and carrier intersection analysis, the method derives ZSS under a selected switch mode. A systematic search identified optimal carrier pair swaps in a 49-level inverter, addressing challenges in extending SPS-PWM. Matlab simulations confirm that SPS-PWM consistently yields independent, symmetrical switching states. Comparative results illustrate the uniqueness of generated states and highlight voltage-time performance differences between SPS-PWM and traditional PSPWM.

Keywords: *SPS, PWM,ZSS, FACTS,PSPWM*

INTRODUCTION

Multilevel converters have evolved with diverse topologies like cascaded H-bridge, diode clamped, and flying capacitor structures, offering high power and voltage handling—ideal for smart grids and renewable energy systems. These systems eliminate the need for bulky transformers by using modular designs, but as module count grows, so does the risk of faults. Ensuring reliability and fast fault detection is essential. Common failures stem from semiconductor switch issues influenced by operational and environmental factors. While detection methods like adaptive observers and Kalman filters exist, their response times remain a challenge in large-scale systems.

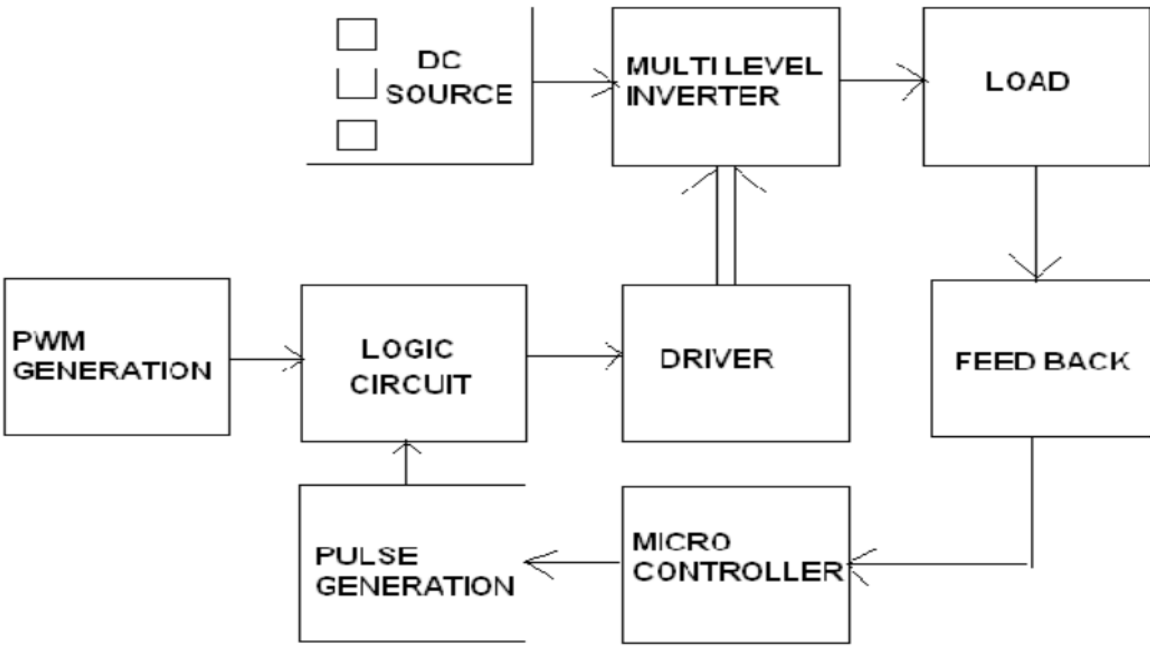

Figure1: Multilevel Inventor

Modern industries demand low-voltage, high-current AC drives for megawatt-level applications, which make direct medium-voltage switching impractical. Multilevel power converters offer an effective solution, enabling high-power, medium-voltage operation compatible with renewable sources like solar, wind, and fuel cells. Widely used in systems like UPCs, AC drives, and FACTS, these converters combine multiple low-voltage DC sources to produce high-quality stepped voltage outputs. Benefits include low harmonic distortion, improved efficiency, and reduced common mode voltage. However, the need for numerous gate drivers adds complexity and cost to the system.

II. Literature Review

Akbari et al. [1] introduced an innovative fault detection method which significantly reduces the time taken to locate faults, specifically focusing on the reliability aspects of components in the proposed fault-resilient switched capacitor cascaded MLI (CSCMLI). The paper's primary achievement is the ability to diminish the count of MLI switches during fault scenarios while maintaining operation at inferior levels. This fault-resilient inverter design needs fewer switches, yet provides heightened reliability. When compared to comparable MLIs, it demonstrates a quicker fault detection dynamic response and a notable reduction in the time needed to pinpoint fault locations. Experimental outcomes vouch for the efficacy of the methods employed in the CSCMLI. Supplementary materials, including processor code, schematics, PCB designs, and videos showcasing the CSCMLI's functionality, are provided.

In research conducted by Wang et al. [2], signals were initially processed using the Fast Fourier Transform (FFT). Following this, Principal Component Analysis (PCA) was deployed for feature extraction from fault signals and minimizing sample dimensions. The study further employed the mRVM model for classifying anomalous samples. Their innovative PCA-mRVM technique surpassed conventional methods, delivering enhanced model sparsity, reduced diagnostic durations, and probabilistic outcomes for each class membership. Their results, underlined by empirical tests, emphasized the potency of the PCA-mRVM diagnostic method.

Mow's et al. [3] detailed the remarkable capabilities of the U.S. electric power infrastructure, commonly known as the grid. This system, featuring an impressive over 1 million megawatts of generating capacity and transmission lines exceeding 300,000 miles in length, reliably serves metropolises like New York City to remote regions in Wyoming. But as electricity consumption surges and adoption of intermittent renewable energy sources becomes more common, the existing grid's ability to consistently transmit and distribute power is being tested [4]–[6].

Author’s offer guidance particularly suited for newcomers to the field, emphasizing the interdisciplinary knowledge required. Traditional electric transmission and distribution networks often face challenges in maintaining robustness and real-time data reliability . Conversely, the smart grid emerges as an adept system capable of restoring stability in the event of disruptions. This is accomplished by harnessing distributed renewable energy generators. Traditional infrastructures often lack the agility needed to assimilate renewable energy generators or microgrids seamlessly. This extensive research is structured to coherently present prior work in the domain, detailing the intricacies, characteristics, and foundational elements to assist those keen on advancing smart grid technology [7]–[14].

In their work, Kamurthy et al. [10] introduce an innovative hybrid bypass methodology to bolster the efficacy of grid-tied inverters in solar energy generation. This technique is demonstrated using the classic H5, oH5, and H6 inverter models. A comparative analysis between the new and existing topologies underscores the viability of the proposed method. Notably, the leakage current for the introduced inverters stands at 9 mA, with a total harmonic distortion hovering around 2%. This suggests that the new inverter design boasts commendable efficiency, along with impressive common mode and differential mode traits.

RESEARCH METHODOLOGY

The research discusses the increasing need for compact and lightweight energy conversion systems, especially in transportation sectors like electric aircraft propulsion and electric vehicles, as well as in stationary applications like PV generators. Wide bandgap (WBG) power semiconductors in multilevel inverter (MLI) topologies are seen as a solution due to their high switching frequency capabilities, which enable significant reductions in component size and weight.

A key concern with such systems, especially when using Gallium Nitride (GaN) devices, is the stability of flying capacitor (FC) voltage, which can drift due to various internal and external factors. This can risk system failure, so maintaining capacitor balance is critical. Existing pulse width modulation (PWM) techniques have limitations in achieving this balance. The study introduces a new generalized PWM strategy called Swapping pattern based PWM (SPS-PWM) for FC MLIs, which can effectively address balancing issues and is scalable to any number of levels. This method combines the benefits of natural and active balancing and is poised to significantly improve the performance of compact energy conversion systems.

RESULTS AND DISCUSSION

This study seeks to verify the proposed swapping pattern by ensuring it produces the appropriate set of distinct ZSS across all levels. This is then contrasted with PWMs documented in academic sources.

The methodology begins with crafting triangular waveforms, and then pinpointing the intersection points between carrier waves. This subsequently leads to the derivation of ZSS for the chosen carrier switch mode. To underscore the intricacies involved in expanding the SPS-PWM without a predefined scheme, we executed a comprehensive search to find the ideal solution when swapping two pairs of carriers in a 49-level inverter.

Running the Matlab script multiple times for a vast array of levels confirms that the SPS-PWM pattern consistently yields an independent equation system characterized by symmetrical states. This observation is visually depicted in Figure 2, where the rank of the equation matrices for the SPS-PWM is contrasted with the ranks for PSPWM.

This study seeks to verify the proposed swapping pattern by ensuring it produces the appropriate set of distinct ZSS across all levels. This is then contrasted with PWMs documented in academic sources.

The methodology begins with crafting triangular waveforms, and then pinpointing the intersection points between carrier waves. This subsequently leads to the derivation of ZSS for the chosen carrier switch mode. To underscore the intricacies involved in expanding the SPS-PWM without a predefined scheme, we executed a comprehensive search to find the ideal solution when swapping two pairs of carriers in a 49-level inverter.

Running the Matlab script multiple times for a vast array of levels confirms that the SPS-PWM pattern consistently yields an independent equation system characterized by symmetrical states. This observation is visually depicted in Figure 2, where the rank of the equation matrices for the SPS-PWM is contrasted with the ranks for PSPWM.

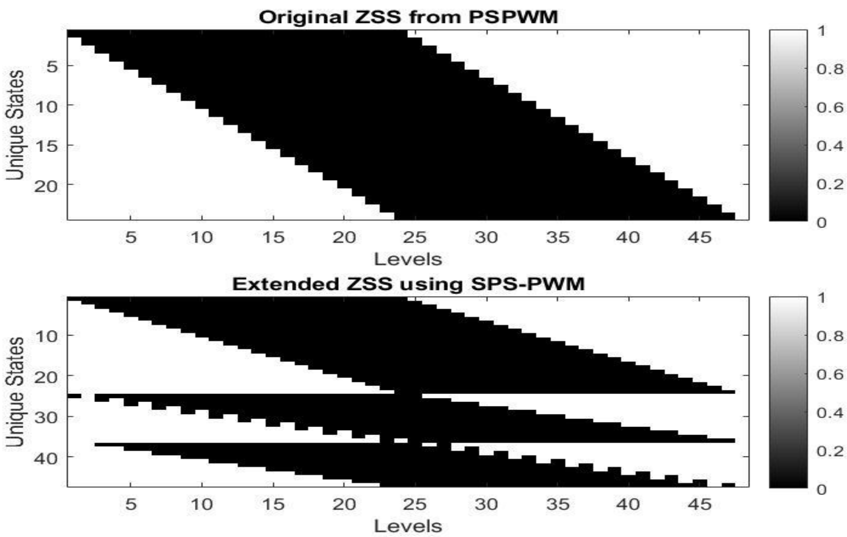

Figure 2 **Number of unique states generated by the SPS-PWM and the PSPWM**

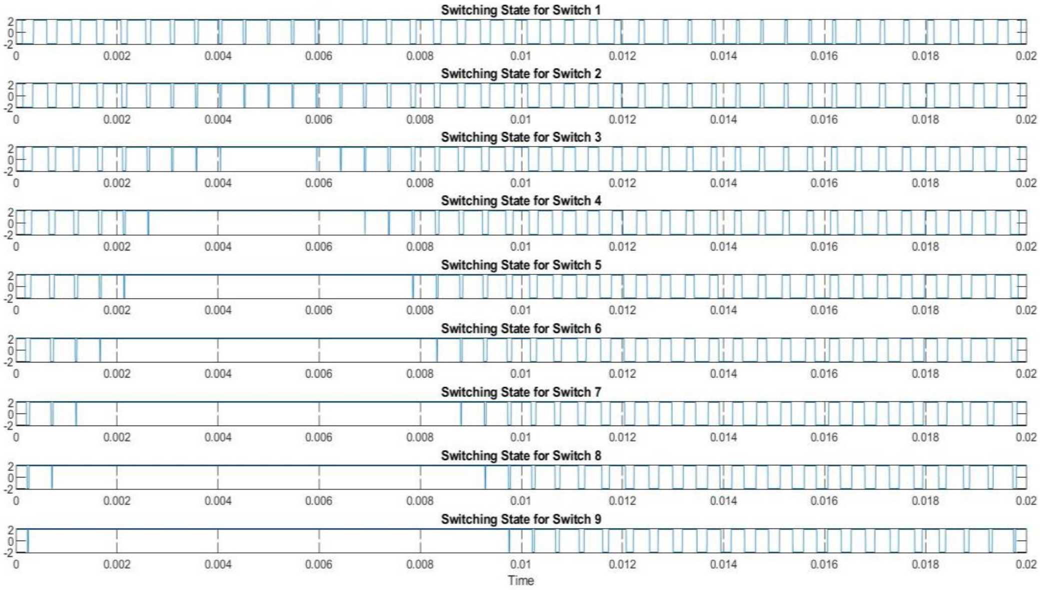

Figure 3: Switching States

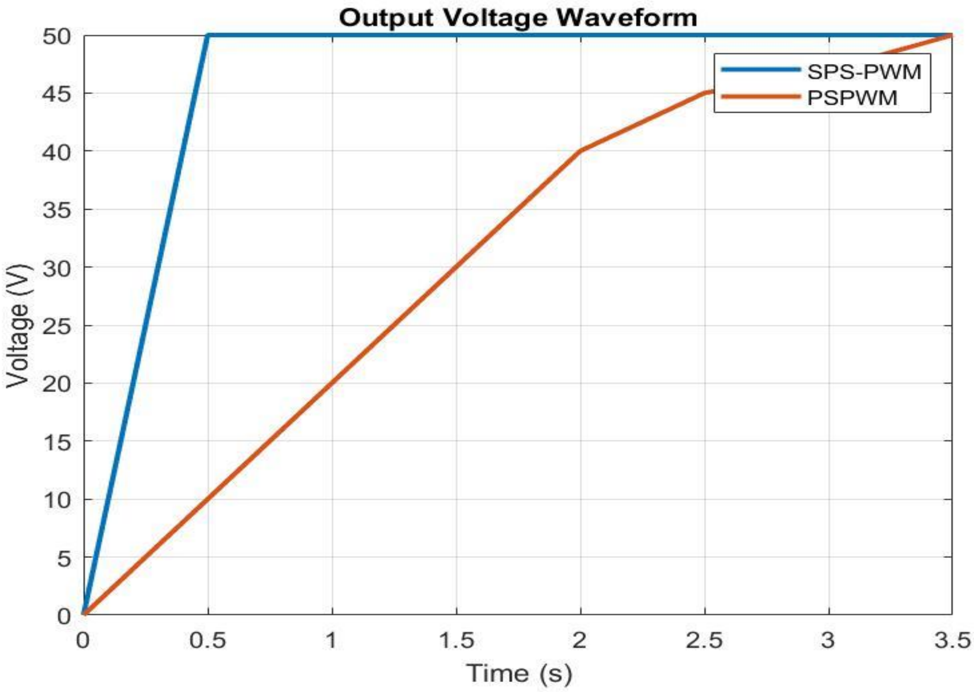

Figure 4: Voltage Time Graph Plotted for SPS-PWM and the PSPWM

In Figure 4, the fluctuations of the FC voltages are depicted when there's a sudden shift in the dc-link voltage. From the data, it's clear that the SPS-PWM method provides the most rapid equilibrium among all FCs in contrast to the traditional PSPWM.

The figure 4 presents THD values for two Pulse Width Modulation techniques (PWM and SPS-PWM) across different inverter levels. As the number of levels increases, the THD decreases for both techniques. Notably, SPS-PWM consistently outperforms traditional PWM in terms of lower THD across all levels. This suggests that for better harmonic performance, especially in multilevel inverters with higher levels, SPS-PWM is the preferable choice.

CONCLUSION

This research confirmed the effectiveness of the proposed SPS-PWM technique in generating symmetrical, independent switching states across multiple inverter levels. Visual analyses demonstrated its advantages over conventional PSPWM, especially in balancing flying capacitor voltages and handling sudden voltage changes. SPS-PWM proves to be a robust and efficient modulation strategy, well-suited for smart grid applications. Looking ahead, it opens avenues for further studies on real-world deployment, integration with renewable systems, AI-based optimization, and performance benchmarking—laying the foundation for future innovations in power electronics and smart energy systems

References

[1] Smart Grid, Smart Inverters for a Smart Energy Future | State, Local, and Tribal Governments | NREL." https://www.nrel.gov/state-local-tribal/blog/posts/smart-grid-smart-inverters-for-a-smart-energy-future.html (accessed Aug. 08, 2023).

[2] E. Akbari et al., "A Fault-Tolerant Cascaded Switched-Capacitor Multilevel Inverter for Domestic Applications in Smart Grids," IEEE Access, vol. 10, no. September, pp. 110590–110602, 2022, doi: 10.1109/ACCESS.2022.3214817.

[3] T. Wang, H. Xu, J. Han, E. Elbouchikhi, and M. Benbouzid, "Cascaded H-Bridge Multilevel Inverter System Fault Diagnosis Using a PCA and Multi-class Relevance Vector Machine Approach," IEEE Trans. Power Electron., vol. 30, p. 1, 2015, doi: 10.1109/TPEL.2015.2393373.

[4] V. Meena and C. Gupta, "A Review of Design , Development , Control and Applications of DC − DC Converters," no. 2581, pp. 28–33, 2018.

[5] S. Khan, C. Gupta, and A. Kumar, "An Analysis of Electric Vehicles Charging Technology and Optimal Size Estimation," vol. 04, no. 04, pp. 125–131, 2021.

[6] P. Verma and C. Gupta, "A Survey on Grid Connected Solar Photovoltaic System," *Int. Conf. Contemp. Technol. Solut. Towar. fulfilment Soc. Needs*, pp. 106–110, 2018, [Online]. Available: https://www.academia.edu/37819420/A_Survey_on_Grid_Connected_Solar_Photovoltaic_System

[7] C. B. Singh, A. Kumar, C. Gupta, S. Cience, T. Echnology, and D. C. Dc, "Comparative performance evaluation of multi level inverter for power quality improvement," vol. 12, no. 2, pp. 1–7, 2024.

[8] C. Gupta and V. K. Aharwal, "Design of Multi Input Converter Topology for Distinct Energy Sources," *SAMRIDDHI*, vol. 14, no. 4, pp. 1–5, 2022, doi: 10.18090/samriddhi.v14i04.09.

[9] C. Gupta and V. K. Aharwal, "Design and simulation of Multi-Input Converter for Renewable energy sources," *J. Integr. Sci. Technol.*, vol. 11, no. 3, pp. 1–7, 2023.

[10] A. Kumar and S. Jain, "Enhancement of Power Quality with Increased Levels of Multi-level Inverters in Smart Grid Applications," vol. 14, no. 4, pp. 1–5, 2022, doi: 10.18090/samriddhi.v14i04.07.

[11] A. Kumar and S. Jain, "Critical Analysis on Multilevel Inverter Designs for," vol. 14, no. 3, 2022, doi: 10.18090/samriddhi.v14i03.22.

[12] A. Kumar and S. Jain, "Predictive Switching Control for Multilevel Inverter using CNN-LSTM for Voltage Regulation," vol. 11, pp. 1–9, 2022.

[13] A. Kumar and S. Jain, "Multilevel Inverter with Predictive Control for Renewable Energy Smart Grid

Applications," *Int. J. Electr. Electron. Res.*, vol. 10, no. 3, pp. 501–507, 2022, doi: 10.37391/IJEER.100317.

[14] C. Gupta and V. K. Aharwal, "Optimizing the performance of Triple Input DC-DC converter in an Integrated System," *J. Integr. Sci. Technol.*, vol. 10, no. 3, pp. 215–220, 2022.

[15] L. You, Z. Ling, Y. Cui, W. Cai, and S. He, "Open Circuit Fault Detection of T-Type Grid Connected Inverters Using Fast S Transform and Random Forest," Entropy, vol. 25, no. 5, May 2023, doi: 10.3390/E25050778.

[16] F. Fallah, A. Ramezani, and A. Mehrizi-Sani, "Integrated Fault Diagnosis and Control Design for DER Inverters using Machine Learning Methods".

[17] R. Jyothi, T. Holla, K. Uma Rao, and R. Jayapal, "Machine learning based multi class fault diagnosis tool for voltage source inverter driven induction motor," Int. J. Power Electron. Drive Syst., vol. 12, no. 2, pp. 1205–1215, Jun. 2021, doi: 10.11591/IJPEDS.V12.I2.PP1205-1215.

[18] S. Gupta, V. Kekatos, and M. Jin, "Deep learning for reactive power control of smart inverters under communication constraints," 2020 IEEE Int. Conf. Commun. Control. Comput. Technol. Smart Grids, SmartGridComm 2020, 2020, doi: 10.1109/SmartGridComm47815.2020.9302970.

[19] F. Muhammad and H. Rasheed, "Power Loss Distribution And Characterization Of Modular Multilevel Converter For Smart Grid Applications," Int. J. Renew. Energy Res., vol. 12, no. 3, pp. 1540–1551, Sep. 2022, doi: 10.20508/IJRER.V12I3.13067.G8539.

[20] M. Q. Taha, "Advantages and recent advances of smart energy grid," Bull. Electr. Eng. Informatics, vol. 9, no. 5, pp. 1739–1746, 2020, doi: 10.11591/eei.v9i5.2358.

[21] G. Kamurthy and S. B. Veeranna, "Hybrid bypass technique to mitigate leakage current in the grid-tied inverter," Int. J. Electr. Comput. Eng., vol. 12, no. 1, pp. 131–140, Feb. 2022, doi: 10.11591/IJECE.V12I1.PP131-140.

[22] Srinivasan, Ganesh Kumar, et al. "Trends and challenges in multi-level inverter with reduced switches." Electronics 10.4 (2021): 368.

[23] Jayakumar, Vinoth, BharatirajaChokkalingam, and Josiah Lange Munda. "A comprehensive review on space vector modulation techniques for neutral point clamped multi-level inverters." IEEE Access 9 (2021): 112104-112144.

[24] Suresh, K., and E. Parimalasundar. "A modified multi level inverter with inverted SPWM control." IEEE Canadian Journal of Electrical and Computer Engineering 45.2 (2022): 99-104.

[25] Ali, Murad, et al. "Open switch fault diagnosis of cascade H-bridge multi-level inverter in distributed power generators by machine learning algorithms." Energy reports 7 (2021): 8929-8942.

[26] Arif, M. Saad Bin, et al. "An improved asymmetrical multi-level inverter topology with boosted output voltage and reduced components count." IET Power Electronics 14.12 (2021): 2052-2066.

[27] Ezhilvannan, Parimalasundar, and Suresh Krishnan. "An Efficient Asymmetric Direct Current (DC) Source Configured Switched Capacitor Multi-level Inverter." Journal Européen des SystèmesAutomatisés 53.6 (2020).