A novel switched-capacitor multilevel inverter for efficient voltage level generation

Parimalasundar Ezhilvannan[1], Annam Venkata Padmavathi[2], Ummi Hani[3], Vyanktesh Panchkumar Dhote[4], Busireddy Hemanth Kumar[1], Arvind Ramnarayan Singh[5]

[1]Department of Electrical and Electronics Engineering, Mohan Babu University, Tirupati, India
[2]College of Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, India
[3]Department of Electrical and Electronics Engineering, Ballari Institute of Technology and Management, Ballari, India
[4]Department of Electrical Engineering, Government College of Engineering, Jalgaon, India
[5]Honorary Research Fellow, Applied Science Research Center and Applied Science Private University, Amman, Jordan

Article Info

Article history:

Received Aug 26, 2024
Revised Nov 20, 2024
Accepted Dec 25, 2024

Keywords:

DC source
Modulation index
Multilevel inverter
Total harmonic distortion
Voltage gain

ABSTRACT

This paper presents a novel single direct current (DC) source with switched-capacitor multilevel inverter (MLI) architecture capable of achieving seven output voltage levels using only eight switches, one diode, and two capacitors. The proposed topology (P) is compared with recent MLI configurations to assess its efficiency and performance. MATLAB/Simulink tools are utilized for simulation studies, and experimental validation is conducted to corroborate the theoretical findings. The investigation explores the impact of modulation index and switching frequency variations on the P output characteristics. Results indicate that the proposed MLI topology offers significant advantages in terms of component count reduction and simplicity while maintaining competitive performance compared to state-of-the-art alternatives. Additionally, the study provides insights into the influence of modulation index and switching frequency changes on the output voltage waveform, highlighting the adaptability and robustness of the P under varying operating conditions. This research contributes to the advancement of MLI designs by offering a streamlined and efficient solution suitable for various power electronic applications, including renewable energy systems and motor drives, where minimizing component count and complexity are crucial design considerations.

Corresponding Author:

Parimalasundar Ezhilvannan
Department of Electrical and Electronics Engineering, Mohan Babu University
Sree Sainath Nagar, Tirupati, Andhra Pradesh-517102, India
Email: parimalpsg@gmail.com

1. INTRODUCTION

Multilevel inverter (MLI) represent a significant advancement in power electronics, offering numerous advantages over traditional two-level inverters in various applications ranging from renewable energy systems to motor drives. This introduction serves as a preamble for a journal paper exploring the design and analysis of MLI, focusing on their significance, operational principles, and recent advancements. In today's era of burgeoning energy demands and increasing environmental concerns, the quest for efficient and sustainable power conversion technologies has intensified. MLI have emerged as pivotal solutions, providing enhanced performance, improved efficiency, and greater reliability compared to their conventional counterparts. At the heart of MLI lies their ability to synthesize stepped output voltage waveforms using multiple levels of direct current (DC) voltage sources. Unlike two-level inverters, which switch between two voltage levels (typically the positive and negative DC terminals), MLI utilize several voltage levels, enabling finer control of the output waveform. This feature results in reduced harmonic distortion, lower electromagnetic interference (EMI), and smoother output voltages, making them ideal for applications demanding high-quality power conversion. The fundamental operational principle of MLI revolves around the concept of pulse width modulation (PWM). By employing PWM techniques, such as carrier-based modulation or space vector modulation (SVM), MLI can generate precise output voltage waveforms by intelligently switching the semiconductor devices (typically insulated gate bipolar transistors (IGBT) or metal-oxide-semiconductor field-effect transistor (MOSFETs)) at high frequencies. These modulation schemes facilitate the synthesis of multilevel output voltages by appropriately adjusting the duty cycles of the switching signals [1]-[3].

The paper begins by discussing the fundamental topologies of MLI, including diode-clamped (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded H-bridge configurations. Each topology is examined in terms of its operating principles, advantages, limitations, and applications. Comparative analyses between different topologies are also presented to highlight their respective performance characteristics and suitability for specific applications [4]-[6]. Modulation techniques play a crucial role in controlling MLI to generate the desired output voltage waveform. This section provides an overview of commonly used modulation techniques, such as PWM, selective harmonic elimination (SHE), SVM, and phase disposition PWM (PD-PWM). The survey discusses the principles, implementation, advantages, and limitations of each modulation technique, along with recent advancements and research trends in this area. Effective control strategies are essential for ensuring the stable and efficient operation of MLI under various operating conditions. This section reviews different control strategies employed in MLI, including traditional proportional-integral (PI) control, advanced control techniques such as model predictive control (MPC) and fuzzy logic control, and predictive control methods. The survey evaluates the performance, complexity, and implementation challenges associated with each control strategy, highlighting recent developments and emerging trends in MLI control [7]-[9].

One of the key advantages of MLI with single DC sources and generalized switched capacitors is their ability to achieve multiple voltage levels with minimal components. This section of the survey discusses the fundamental principles behind these inverters, including the utilization of switched capacitors to generate multiple voltage levels from a single DC source. Various circuit topologies, such as cascaded H-bridge and flying capacitor configurations, are explored, highlighting their operating principles, advantages, and limitations [10], [11].

Modulation techniques play a crucial role in controlling the output voltage waveform of MLI. This section reviews different modulation strategies used in conjunction with single DC source inverters and generalized switched capacitors. PWM techniques, such as SVM and carrier-based PWM, are discussed, along with their implementation challenges and performance considerations [12], [13].

One of the significant challenges faced by MLI with single DC sources and generalized switched capacitors is voltage balancing among the capacitors. In these systems, capacitors are utilized to generate multiple voltage levels, and ensuring balanced voltage across all capacitors is crucial for stable and efficient operation. However, due to mismatches in component parameters, switching delays, and other factors, achieving perfect voltage balancing can be challenging, leading to unequal stress on capacitors and potential reliability issues. The operation of MLI involves high-frequency switching of power electronic devices, leading to switching losses that can significantly impact system efficiency. In systems with single DC sources and switched capacitors, the number of switches involved in generating multiple voltage levels is relatively high, which increases switching losses and reduces overall efficiency. Mitigating switching losses while maintaining desired output voltage levels is a critical challenge in these systems [14]-[17].

MLI with single DC sources and generalized switched capacitors require sophisticated control algorithms to regulate the switching of power electronic devices and maintain desired output voltage waveforms. The complexity of control algorithms increases with the number of voltage levels and the intricacies of switched capacitor operation. Developing efficient and robust control strategies that can handle system non-linearities, parameter variations, and dynamic operating conditions is a significant challenge in these systems. The operation of MLI with single DC sources and switched capacitors imposes significant stress on power electronic components such as switches, diodes, and capacitors. High-frequency switching, voltage transients, and current ripple can accelerate component degradation and reduce system reliability over time. Ensuring the longevity and reliability of components under harsh operating conditions is a key challenge in the design and implementation of these systems [18]-[20].

Despite their potential benefits, the cost of components and manufacturing processes for MLI with single DC sources and switched capacitors can be higher compared to traditional inverter topologies. Optimizing system cost without compromising performance and reliability is a significant challenge faced by researchers and practitioners in this field. Implementing artificial intelligence (AI), machine learning, and fuzzy logic techniques in seven and nine-level MLI enhances performance and efficiency [21]-[23]. AI algorithms optimize modulation strategies in real-time based on load conditions, improving waveform quality and reducing harmonic distortion. Machine learning models predict system behaviour, enabling proactive fault detection and adaptive control to mitigate voltage imbalances and ensure stability [24], [25].

MLI with single DC sources and switched capacitors face significant challenges, including the need for sophisticated control algorithms to regulate switching and maintain output voltage waveforms. These approaches can be complex and may not effectively address system non-linearities and dynamic conditions. Additionally, the high-frequency switching and voltage transients stress power electronic components, leading to potential degradation and reduced reliability. Furthermore, the cost of components and manufacturing processes remains higher than traditional topologies, complicating optimization efforts without sacrificing performance.

This research work is having the following objectives: to introduce a novel single DC source with switched-capacitor MLI architecture capable of generating seven output voltage levels with minimal component count; to compare this proposed topology (P) with recent MLI configurations to evaluate its efficiency and performance metrics comprehensively; to employ MATLAB/Simulink tools for simulation studies, ensuring thorough analysis and validation of theoretical findings; to conduct experimental validation, corroborating simulation results and confirming the practical viability of the P; lastly, to investigate the impact of modulation index and switching frequency variations on the output characteristics, providing insights into the adaptability and robustness of the P under diverse operating conditions.

2. PROPOSED MULTILEVEL INVERTER WITH MODES OF OPERATION

The proposed seven-level MLI features two floating capacitors, C_2 and C_1, alongside a power diode (D) and eight IGBT power switches. With only one DC source, the charging path of the capacitors ensures efficient energy transfer. During operation, the capacitors charge through the DC source, maintaining voltage levels for each output stage. Notably, the design is inherently self-balanced, mitigating the need for external balancing circuits. Upon activation, the power switches regulate the flow of energy, enabling seamless voltage level transitions. The floating capacitors facilitate the creation of multiple voltage levels, enhancing the inverter’s versatility and performance. This configuration optimizes component utilization and reduces complexity, making it suitable for various power electronic applications. Figure 1 depicts a proposed seven-level inverter topology, offering enhanced voltage levels for improved performance. Figure 2 illustrates IGBT modules with anti-parallel diodes, ensuring bidirectional current flow and minimizing voltage spikes. Figure 3 showcases IGBTs without anti-parallel diodes, necessitating external diodes for freewheeling during reverse current conditions. Figure 4 illustrates the generation of a +3 V_{DC} output voltage in the seven-level inverter configuration. Figure 5 demonstrates a +2 V_{DC} output.

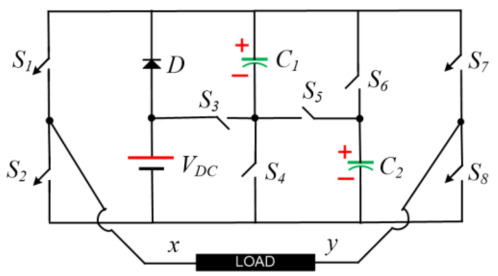


Figure 1. Proposed seven level inverters

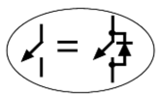


Figure 2. IGBT with anti-parallel diode

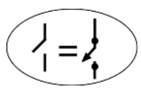


Figure 3. IGBT without anti-parallel diode

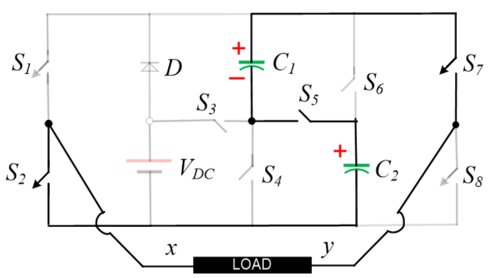


Figure 4. +3 V_{DC} output voltage

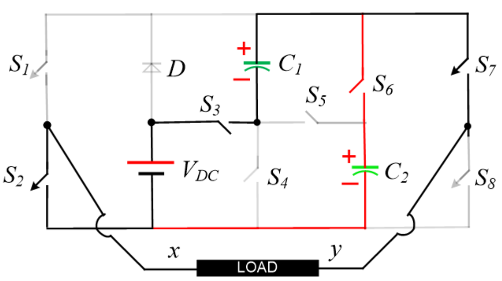


Figure 5. +2 V_{DC} output voltage

Figure 6 shows a +Vdc output. Figure 7 displays a 0 V_{DC} output, while Figures 8 and 9 represent a -V_{DC} and -2 Vdc output. Figure 10 showcases the -3 V_{DC} output voltage in a seven-level single DC source system utilizing generalized switched capacitors. Each figure demonstrates a specific voltage level output achieved through the inverter's operation.

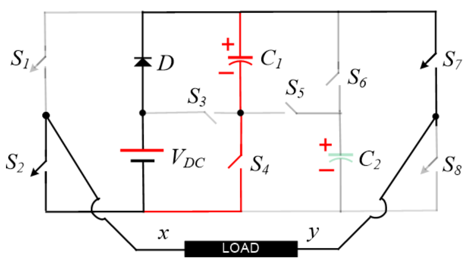


Figure 6. V_{DC} output voltage

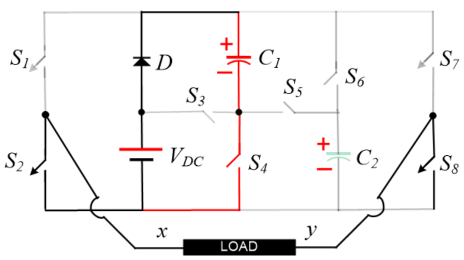


Figure 7. 0 V_{DC} output voltage

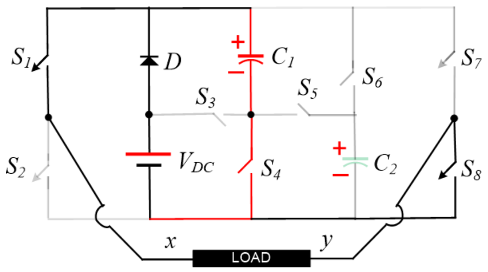


Figure 8. -V_{DC} output voltage

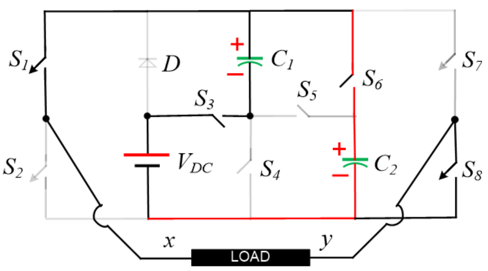


Figure 9. -2 V_{DC} output voltage

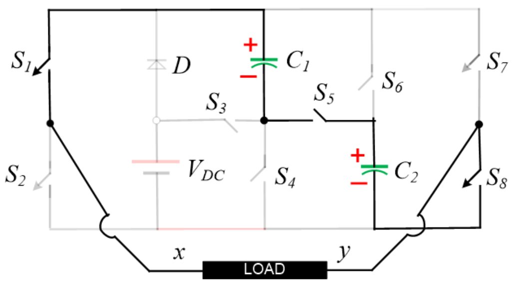


Figure 10. -3 V_{DC} output voltage

3. SIMULATION RESULTS AND ANALYSIS

Figure 11 illustrates the analysis of output voltage, current, and capacitor link voltages with a modulation index of 1, where the peak output voltage is 150 V and the peak current is 5 A. Capacitor 1 voltage is maintained at 50 V, while capacitor 2 voltage is set at 100 V. This analysis provides insights into the behavior of the system under full modulation index conditions, aiding in understanding the performance and stability of the inverter. Figure 12 examines the system response with modulation index varying from 0.95 to 0.7, following a load current change from 3 A to 5 A. This dynamic analysis captures the inverter's behavior under varying modulation depths and load conditions, assisting in optimizing the control strategy for different operating scenarios. In Figure 13, the modulation index ranges from 0.7 to 0.5 after a 0.1 sec change in voltage total harmonic distortion (THD). This analysis evaluates how changes in modulation depth impact output characteristics, particularly in terms of THD, aiding in designing robust control algorithms to minimize distortion and enhance system efficiency. Figure 14 explores the system's behavior with modulation index varying from 0.5 to 0.2. This analysis provides insights into the inverter's performance under reduced modulation depth conditions, facilitating the design of efficient control strategies for low-power operation while ensuring stable and reliable output voltage and current waveforms across the load range.

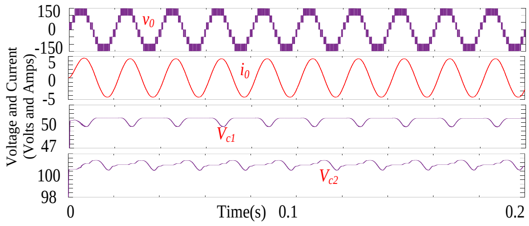


Figure 11. Simulation analysis of output voltage, current, and capacitor link voltages under normal condition

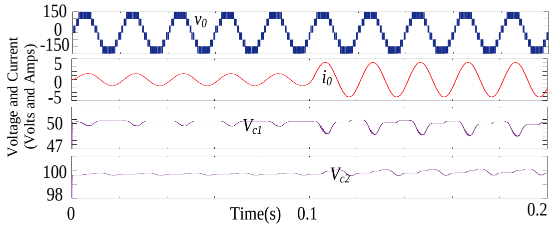


Figure 12. Simulation analysis of output voltage, current, and capacitor link voltages under change in load after 0.1 sec

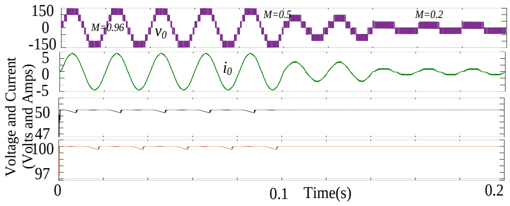


Figure 13. Simulation analysis of output voltage, current, and capacitor link voltages under change modulation index from 0.96 to 0.2 after 0.1 sec

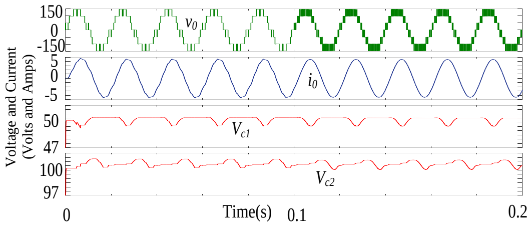


Figure 14. Simulation analysis of output voltage, current, and capacitor link voltages under change modulation index from 0.96 to 0.7 after 0.1 sec

4. EXPERIMENTAL VALIDATION

Figure 15 showcases the experimental setup designed for thorough testing and validation of the inverter system across diverse operating conditions. The DSO DL750P oscilloscope serves as a reliable tool for precise data acquisition, enabling accurate analysis of voltage and current waveforms. The host PC, equipped with specialized software, assumes control and conducts in-depth analysis of system performance, offering insights into efficiency, stability, and harmonic distortion. The controller board plays a pivotal role in signal processing, executing control algorithms, and facilitating real-time adjustments to ensure optimal operation. Gate drivers like the TLP250 are employed to interface between the control signals and the power switches, ensuring efficient switching operations. The inclusion of resistive and inductive loads mimics real-world scenarios, allowing for comprehensive testing under varying load conditions. Additionally, a regulated power supply ensures consistent and reliable power delivery to the entire setup, enhancing the accuracy and repeatability of experimental results.

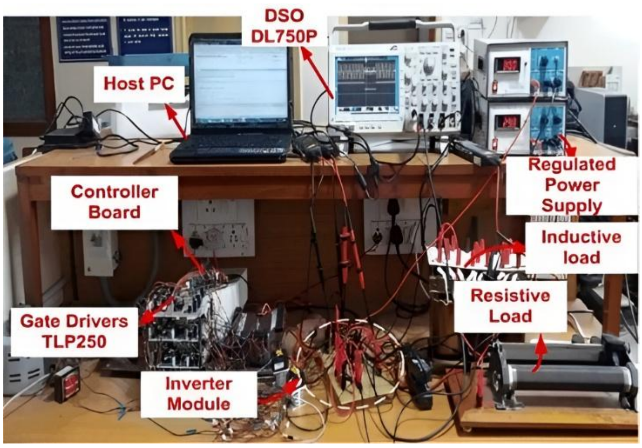


Figure 15. Simulation analysis of output voltage, current, and capacitor link voltages under change modulation index from 0.96 to 0.7 after 0.1 sec

Figure 16 presents real-time results of voltage, current, and capacitor voltage under normal operating conditions. These results serve as a baseline for performance evaluation and comparison with other operating scenarios. Figure 17 illustrates real-time analysis of voltage, current, and capacitor voltage under variable load conditions. This analysis helps understand the inverter’s response to changes in load impedance and ensures robust performance across different load scenarios. In Figure 18, real-time analysis of voltage, current, and capacitor voltage is conducted under variable frequency conditions. This investigation provides insights into the inverter’s behaviour at different operating frequencies, aiding in optimizing frequency control algorithms and ensuring stability over a wide frequency range.

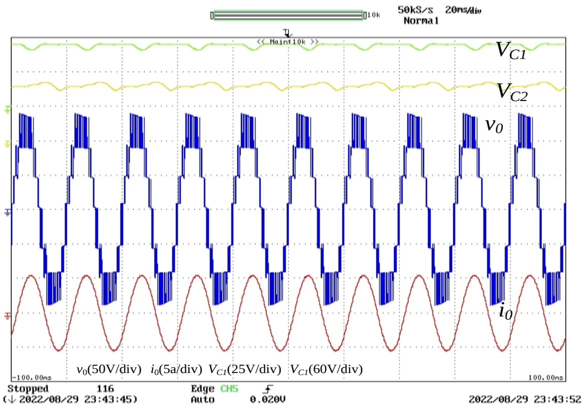


Figure 16. Real time analysis of voltage, current, and capacitor voltage at normal condition

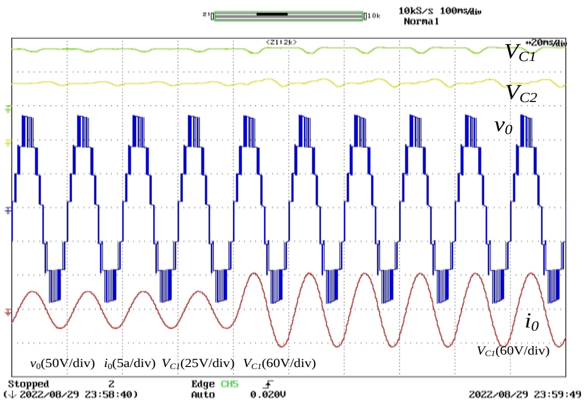


Figure 17. Real time analysis of voltage, current, and capacitor voltage at variable load condition

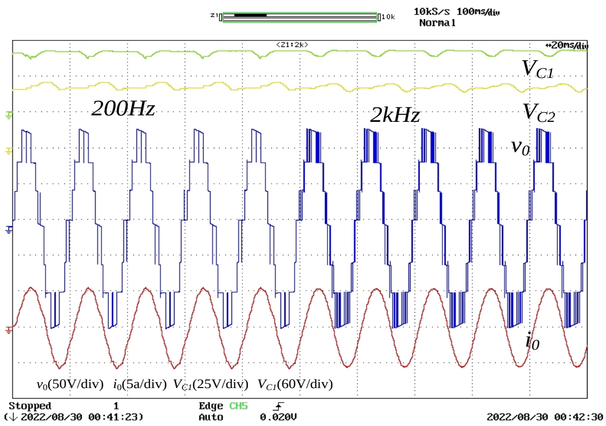


Figure 18. Real time analysis of voltage, current, and capacitor voltage at variable frequency condition

Figure 19 presents real-time analysis of voltage, current, and capacitor voltage with variations in modulation index. This analysis examines the impact of modulation depth on output waveforms and system efficiency, guiding the selection of optimal modulation strategies for different applications. Figures 20 and 21 showcase THD analysis of output voltage and current respectively. These analyses quantify the distortion levels in the output waveforms, enabling assessment of waveform quality and compliance with harmonic standards.

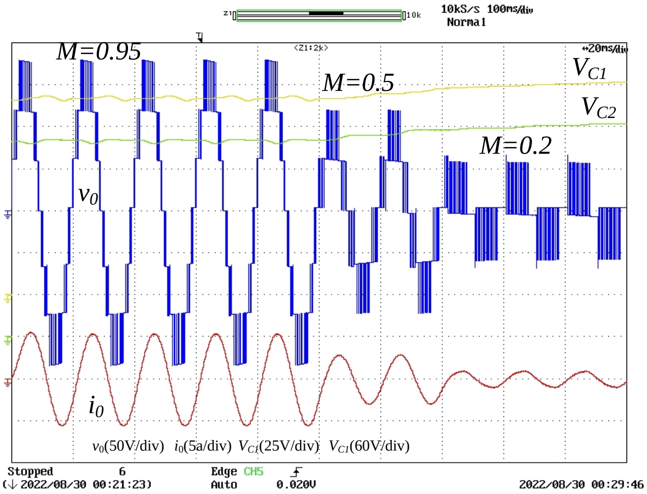
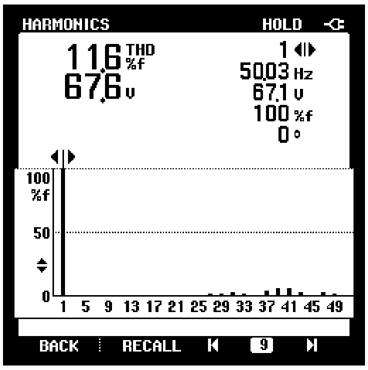


Figure 19. Real time analysis of voltage, current, and capacitor voltage at change in modulation index



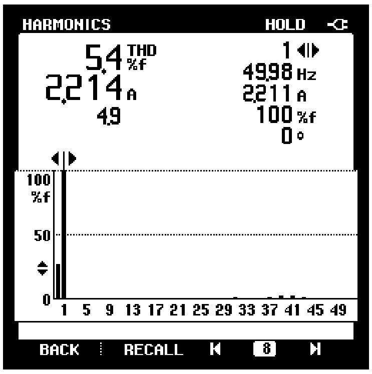


Figure 20. THD analysis of output voltage Figure 21. THD analysis of output current

Figure 22 compares performance parameters of DC sources, levels, and switches between the P and various other topologies. Parameters such as efficiency, voltage regulation, and switching losses are evaluated to demonstrate the advantages of the P over existing alternatives. Figure 23 compares performance parameters of diodes, gain, cost function, maximum blocking voltage, and switching component level between the P and other topologies. This comparison helps identify the strengths and weaknesses of each topology in terms of component characteristics and overall system performance. Table 1 illustrates the various parameter comparisons of proposed and conventional topologies.

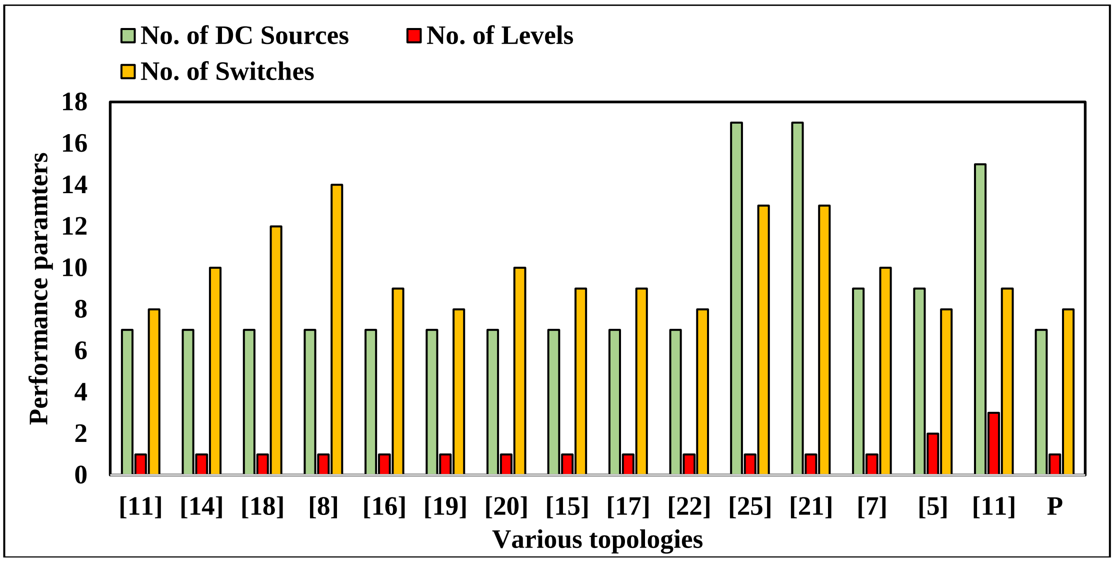


Figure 22. Performance parameters of DC sources, level, and switches with P and various topologies

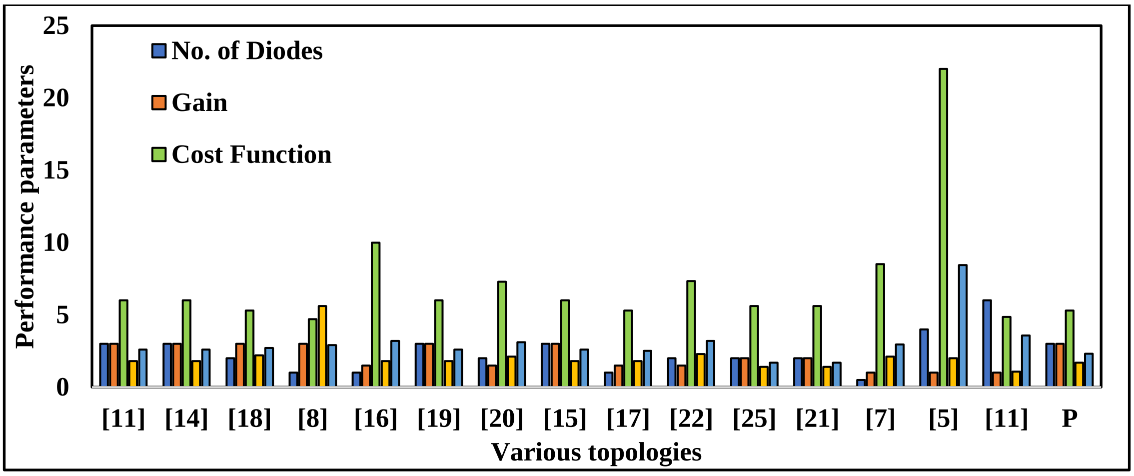


Figure 23. Performance parameters of diodes, gain, cost function, maximum blocking voltage, and switching component level with P and various topologies

Table 1. Comparative analysis of proposed MLI P and various topologies

A	[4]	[6]	[7]	[11]	[13]	[15]	[19]	[P]
N_L	7	7	7	7	7	7	7	7
N_s	1	1	1	1	1	1	1	1
N_{sw}	8	12	14	9	10	9	9	8
N_c	2	2	2	3	4	2	3	2
N_D	2	-	-	-	-	1	-	1
B	3	2	1	1	2	3	1	3
G	3	3	3	1.5	1.5	3	1.5	3
C	6	5.3	4.7	10.	7.3	6	5.3	5.3
$F_{C/L}$	1.8	2.2	5.6	1.8	2.1	1.8	1.8	1.7
D	2.6	2.7	2.9	3.2	3.1	2.6	2.5	2.3

N_S: number of sources, N_L: number of levels, N_{SW}: number of switches, N_C: number of capacitors, N_D: number of diodes, B: maximum blocking voltage, $F_{C/L}$: switching component per level, D: cost function (CF), A: parameter, C: per unit total standing voltage (TSV_{pu}), G: gain, P: proposed topology

5. CONCLUSION

The proposed novel single DC source with switched-capacitor MLI architecture, achieving seven output voltage levels with minimal components. Through MATLAB/Simulink simulations and experimental validation, the P demonstrates efficiency and performance comparable to recent MLI configurations. The investigation reveals the topology's robustness under modulation index and switching frequency variations, offering insights into its adaptability across diverse operating conditions. Future research could explore advanced control strategies to further enhance performance and efficiency, as well as scalability for higher voltage levels. Additionally, extending the experimental validation to larger-scale implementations and diverse applications would strengthen the practical relevance of the P. Overall, this research contributes to advancing MLI designs by offering a simplified yet efficient solution suitable for various power electronic applications, addressing the need for reduced component count and complexity in modern power systems. In terms of future scope, there are several promising areas to explore. First, advanced control strategies such as MPC or SVM could be implemented to further improve the performance, efficiency, and dynamic response of the inverter.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Parimalasundar Ezhilvannan	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Annam Venkata Padmavathi	✓		✓	✓			✓			✓	✓			
Ummi Hani	✓		✓	✓			✓			✓	✓			
Vyanktesh Panchkumar Dhote	✓		✓	✓			✓			✓	✓			
Busireddy Hemanth Kumar	✓		✓	✓			✓			✓	✓			
Arvind Ramnarayan Singh	✓		✓	✓			✓			✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] A. Srivastava and J. Seshadrinath, "A Single-Phase Seven-Level Triple Boost Inverter for Grid-Connected Transformerless PV Applications," in *IEEE Transactions on Industrial Electronics*, vol. 70, no. 9, pp. 9004-9015, Sep. 2023, doi: 10.1109/TIE.2022.3215815.

[2] R. Sindhuja and S. Padma, "Implementation of M-Type Carrier-based PWM Method for 13-Level Multilevel Inverter," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 10, no. 2, pp. 172-179, 2023, doi: 10.14445/23488379/IJEEE-V10I2P116.

[3] K. Higasa, K. Sekine, and E. Itoh, "Effectiveness of Aircraft Inter-Arrival Control in Upstream Traffic Flow via a Combined Tandem Fluid Queue Model and Integer Programming Approach," in *IEEE Access*, vol. 11, pp. 15252-15270, 2023, doi: 10.1109/ACCESS.2023.3241951.

[4] E. Parimalasundar, R. S. Kumar, V. S. Chandrika, and K. Suresh, "Fault diagnosis in a five-level multilevel inverter using an artificial neural network approach," *Electrical Engineering & Electromechanics*, no. 1, pp. 31–39, 2023, doi: 10.20998/2074-272X.2023.1.05.

[5] A. Avila, A. Garcia-Bediaga, I. Alzuguren, M. Vasić, and A. Rujas, "A Modular Multifunction Power Converter Based on a

Multiwinding Flyback Transformer for EV Application," in *IEEE Transactions on Transportation Electrification*, vol. 8, no. 1, pp. 168-179, March 2022, doi: 10.1109/TTE.2021.3107951.

[6] S. K, P. E., J. S., and R. R., "Encapsulated 3Ø Converter for Power Loss Minimization in a Grid-Connected System," *Journal for Control, Measurement, Electronics, Computing and Communications*, vol. 64, no. 1, pp. 189-197, 2023, doi: 10.1080/00051144.2022.2119501.

[7] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii, and I. Batarseh, "A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications," in *IEEE Access*, vol. 10, pp. 40753-40793, 2022, doi: 10.1109/ACCESS.2022.3166935.

[8] P. Ezhilvannan, S. Krishnan, B. H. Kumar, K. Janardhan, and S. Ramachandran, "Analysis of the Effectiveness of a Two-Stage Three-Phase Grid-Connected Inverter for Photovoltaic Applications," *Journal of Solar Energy Research*, vol. 8, no. 2, pp. 1471-1483, 2023, doi: 10.22059/jser.2023.357025.1285.

[9] G. Waltrich, J. L. Duarte and M. A. M. Hendrix, "Multiport Converter for Fast Charging of Electrical Vehicle Battery," in *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2129-2139, Nov.-Dec. 2012, doi: 10.1109/TIA.2012.2226694.

[10] J. Venkataramanaiah, Y. Suresh, and A. K. Panda, "A Review on Symmetric, Asymmetric, Hybrid and Single DC Sources Based Multilevel Inverter Topologies," *Renewable Sustainable Energy Reviews*, vol. 76, pp. 788–812, Oct. 2017, doi: 10.1016/j.rser.2017.03.066.

[11] E. Babaei, M. F. Kangarlu, and M. Sabahi, "Extended Multilevel Converters: An Attempt to Reduce the Number of Independent DC Voltage Sources in Cascaded Multilevel Converters," *IET Power Electronics*, vol. 7, no. 1, pp. 157–166, Feb. 2014, doi: 10.1049/iet-pel.2013.0057.

[12] S. Sreelakshmi, M. S. Sujatha, and J. R. Rahul, "Multi-Level Inverter with Novel Carrier Pulse Width Modulation Technique for High Voltage Applications," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 26, no. 2, pp. 667-674, May 2022, doi: 10.11591/ijeecs.v26.i2.pp667-674.

[13] S. R, P. S, P. E, and S. K, "Comparison between Symmetrical and Asymmetrical 13 Level MLI with Minimal Switches," *2022 International Conference on Automation, Computing and Renewable Systems (ICACRS)*, Pudukkottai, India, 2022, pp. 187-191, doi: 10.1109/ICACRS55517.2022.10029308.

[14] S. A. Khan, M. R. Islam, Y. Guo, and J. Zhu, "A New Isolated Multi-Port Converter With Multi-Directional Power Flow Capabilities for Smart Electric Vehicle Charging Stations," in *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 2, pp. 1-4, March 2019, Art no. 0602504, doi: 10.1109/TASC.2019.2895526.

[15] K. Suresh and E. Parimalasundar, "Design and Implementation of Dual-Leg Generic Converter for DC/AC Grid Integration," *International Journal of Circuit Theory and Applications*, vol. 51, no. 8, pp. 3865-3879, April 2023, doi: 10.1002/cta.3614.

[16] M. F. Kangarlu and E. Babaei, "Cross-switched multilevel inverter: an innovative topology," *IET Power Electronics*, vol. 6, no. 4, pp. 642–651, Aug. 2013, doi: 10.1049/iet-pel.2012.0265.

[17] E. Babaei, S. Laali, and S. Alilu, "Cascaded Multilevel Inverter With Series Connection of Novel H-Bridge Basic Units," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 12, pp. 6664-6671, Dec. 2014, doi: 10.1109/TIE.2014.2316264.

[18] P. B., S. K., and P. E., "Fault analysis in the 5-level multilevel NCA DC–AC converter," *Journal for Control, Measurement, Electronics, Computing and Communications*, vol. 64, no. 3, pp. 606-612, Apr 2023, doi: 10.1080/00051144.2023.2203553.

[19] E. Samadaei, S. A. Gholamian, A. Sheikholeslami, and J. Adabi, "An Envelope Type (E-Type) Module: Asymmetric Multilevel Inverters With Reduced Components," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 11, pp. 7148-7156, Nov. 2016, doi: 10.1109/TIE.2016.2520913.

[20] H. Vahedi and K. Al-Haddad, "Real-Time Implementation of a Seven-Level Packed U-Cell Inverter with a Low-Switching-Frequency Voltage Regulator," in *IEEE Transactions on Power Electronics*, vol. 31, no. 8, pp. 5967-5973, Aug. 2016, doi: 10.1109/TPEL.2015.2490221.

[21] K. Suresh, E. Parimalasundar, M. S. Sujatha, and N. M. G. Kumar, "Design and Implementation Bidirectional DC–AC Converter for Energy Storage System," in *IEEE Canadian Journal of Electrical and Computer Engineering*, vol. 46, no. 2, pp. 130-136, Spring 2023, doi: 10.1109/ICJECE.2022.3233840.

[22] V. Anand and V. Singh, "A 13-Level Switched-Capacitor Multilevel Inverter With Single DC Source," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 2, pp. 1575-1586, Apr. 2022, doi: 10.1109/JESTPE.2021.3077604.

[23] K. Janardhan, M. Nayak, C. Venkataramana, P. M. Rao, and B. H. Kumar, "Performance Investigation of Solar Photovoltaic System for Mobile Communication Tower Power Feeding Application," *International Journal of Electrical and Electronics Research (IJEER)*, vol. 10, no. 04, pp. 921-925, Oct. 2022, doi: 10.14445/23488360/IJEER-V10I4P107.

[24] N. Sandeep, "A 13-Level Switched-Capacitor-Based Boosting Inverter," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 3, pp. 998-1002, March 2021, doi: 10.1109/TCSII.2020.3017338.

[25] A. A. and A. K. Parvathy, "Modular multilevel inverter for renewable energy applications," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 1, pp. 1-14, Feb. 2020, doi: 10.11591/ijece.v10i1.pp1-14.

BIOGRAPHIES OF AUTHORS

Parimalasundar Ezhilvannan received the B.E. degree from the Department of Electrical and Electronics Engineering, Government College of Engineering, Bargur, Tamil Nadu, in 2007, the M.E. degree in Power Electronics and Drives from the PSG College of Technology, Coimbatore, India, in 2009, and the Ph.D. degree in Electrical Engineering from Anna University, Chennai, India, in 2016. He is currently working as a Professor in the Department of Electrical and Electronics Engineering, Mohan Babu University (Formerly known as Sree Vidyanikethan Engineering College), Tirupati, Andhra Pradesh, India. His research interests include in the area of DC–DC converters, AC–DC converters, multilevel inverters, renewable energy sources, and soft switching techniques in power electronics and drives. He can be contacted at email: parimalpsg@gmail.com.

Annam Venkata Padmavathi completed B.A. English from Maris Stella college in 1994, Andhra Pradesh, received M.A. English post-graduation degree from Nagarjuna University in 1996, received Ph.D. from the Department of English, Acharya Nagarajuna University, A.P., in January 2023. She is currently working as Assistant Professor in Koneru Lakshmaiah Education Foundation. Her research interest is on literature. She can be contacted at email: avpadmavathi@kluniversity.in or venkatapadmavathi27@gmail.com.

Ummi Hani is an Assistant Professor in the Department of Electrical and Electronics Engineering at Ballari Institute of Technology and Management (BITM), Ballari, Karnataka, India. She received her Bachelor of Engineering (B.E.) degree in Electrical and Electronics Engineering from RYM Engineering College, Ballari, Karnataka, in 2015. She completed her Master of Technology (M.Tech.) in Power Electronics from BITM in 2020, where she earned 1st rank and was awarded a gold medal by Visvesvaraya Technological University (VTU), Belagavi, Karnataka, India in 2021. Her research interests encompass a range of areas including DC-DC converters, inverters, cycloconverters, multilevel inverters, renewable energy sources, power electronics and industrial drives. Her work focuses on advancing technologies and solutions within these domains to address key challenges in electrical engineering. She can be contacted at email: ummi.hani@bitm.edu.in.

Vyanktesh Panchkumar Dhote received his B.E. degree in Electrical Engineering from Walchand College of Engineering, Sangli, in 1998 and the M.E. degree in Electrical Power Systems from Walchand College of Engineering, Sangli, in 2003 and Ph.D. in Electrical Engineering from VNIT, Nagpur in 2024. He is currently working at Government College of Engineering, Aurangabad as Assistant Professor in Electrical Engineering. His research interests include power quality, electric vehicle, and energy storage systems. He can be contacted at email: vpdhote@gmail.com.

Busireddy Hemanth Kumar received his B.Tech. degree in Electrical and Electronics Engineering from Narayana Engineering College (NRNG), Gudur, India, in 2012; and his M.Tech. degree in Instrumentation and Control Systems from Sri Venkateswara University (SVU), Tirupathi, India, in 2015. He successfully completed his Ph.D. degree from Visvesvaraya National Institute of Technology, Nagpur, India in 2020. During his Ph.D. work, he was working on development of multilevel inverter control strategies and its applications. He has published his work in many reputed international journals and conferences. Currently, he is working as an Assistant Professor in the Department of Electrical and Electronics Engineering, Mohan Babu University (Erstwhile Sree Vidyanikethan Engineering College) since June 2019. His current research interests include inverter control strategies, electric vehicle, renewable energy systems, and switched capacitor converters. He can be contacted at email: hemub09@gmail.com.

Arvind Ramnarayan Singh is an Associate Professor at HJNU, China, and a researcher at the Applied Science Research Center, Applied Science Private University, Amman, Jordan. He earned his Bachelor of Engineering in Electrical Engineering from Walchand College of Engineering, Sangli, India. He completed his Master's degree in Power Systems at the College of Engineering, Pune, under the Excellence TEQIP Scholarship, and his Doctoral Degree in Electrical Engineering from Visvesvaraya National Institute of Technology Nagpur, supported by the MHRD technical education quality improvement programme (TEQIP) Scholarship. He can be contacted at email: arvindsinghwce@gmail.com.