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A Novel Self-Balanced Thirteen-Level Switched-Capacitor Multiphase Inverter for Solar PV Applications

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***Abstract*—A novel self-balanced thirteen-level switched-capacitor (SC) multiphase inverter topology designed for solar photovoltaic (PV) applications is proposed in this paper. Without the need for complicated control circuits or extra sensors, the suggested structure achieves automatic capacitor voltage self-balancing and high-voltage boosting capability. The inverter efficiently raises output voltage levels while preserving balanced capacitor voltages under dynamic operating conditions by utilizing a three-fold switched-capacitor cell configuration combined with an engineered carrier-based PWM technique. The performance of the inverter is confirmed by thorough MATLAB/Simulink simulations, which show a voltage gain of 6.0, peak efficiency of 96.7%, and output voltage total harmonic distortion (THD) of just 3.21%. Additionally, with a capacitor voltage deviation of less than 0.5%, the suggested topology demonstrates a fast transient response and an inherent common-mode voltage reduction. Comparisons with hybrid SC inverters and traditional cascaded H-bridge inverters confirm superior voltage boosting, harmonic suppression, and self-balancing capabilities. The suggested thirteen-level SC multiphase inverter is a promising option for next-generation PV-based renewable energy and motor drive systems because of its small size, low number of switches, and high-quality output.**

***Index Terms*—Switched-capacitor inverter, multilevel inverter (MLI), solar PV, multiphase system, voltage boosting.**

I. Introduction

The use of renewable energy technologies, especially solar photovoltaic (PV) systems, has increased due to the world's rapidly increasing energy demand and the negative environmental effects of fossil fuels [1]. Although solar PV energy is a clean and limitless source of power, it naturally generates a variable DC output, necessitating effective power conversion stages for applications involving motor drives or grid integration. Inverters are an essential component of these conversion stages, converting DC energy into high-quality AC voltage appropriate for a variety of loads and grid-tied systems [2].

Traditional two-level voltage source inverters (VSIs) have limited voltage capability, high switching losses, and significant total harmonic distortion (THD). Multilevel inverters (MLIs) have become a viable solution for medium- and high-power applications in order to get around these restrictions [3]. Staircase voltage waveforms with less harmonic content, less device stress, and better electromagnetic compatibility can be produced by MLIs. Neutral Point Clamped (NPC), Cascaded H-Bridge (CHB), and Flying Capacitor (FC) topologies are common MLI configurations [4]. Despite their impressive performance, these structures necessitate complicated balancing circuits or multiple isolated DC sources, which raises the cost, bulk, and complexity of the system's control [5].

In order to overcome these obstacles, multilevel inverters based on switched capacitors (SC) have attracted a lot of interest lately [6]. In order to generate multilevel outputs and boost voltage from a single DC source, SC inverters use semiconductor switches and capacitors in particular configurations. This method offers greater efficiency and compactness by doing away with large transformers and numerous DC links. The capacity of SC inverters to accomplish voltage multiplication with a single PV source while preserving the advantages of a multilevel waveform is one of their main advantages [7]. Nevertheless, a number of current SC-based designs have problems like high inrush charging currents, imbalanced capacitor voltages, and an increased component count [8].

Numerous researchers have suggested hybrid SC structures and self-balancing mechanisms to lessen these problems. For example, Manjrekar and Lipo [10] suggested hybrid topologies combining diode-clamped and SC cells for enhanced voltage gain, while Zhang et al. [9] presented a self-voltage balancing switched-capacitor inverter that achieved seven levels with fewer switches. However, the majority of current methods are still only applicable to lower voltage levels (7–9 levels) and do not take into account the requirements of high-voltage or multiphase solar PV systems, where self-balancing and compactness are crucial.

Multiphase inverters provide additional benefits like lower phase current per leg, enhanced fault tolerance, smoother

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torque production, and less current ripple in high-power renewable and electric vehicle (EV) systems [11]. PV-fed multiphase motor drives and grid-tied systems benefit greatly from the increased voltage boosting capability and modularity that come with integrating SC techniques into a multiphase configuration.

This study suggests a novel thirteen-level self-balanced switched-capacitor multiphase inverter topology that is tailored for solar PV applications in response to these demands. The features of the suggested inverter are:

1) A single DC source can produce thirteen different voltage levels using a three-fold switched-capacitor structure.
2) Sensors and feedback control loops are not required for intrinsic capacitor voltage self-balancing.
3) Improved voltage boosting ratio with fewer switches and gate drivers.
4) Multiphase operation compatibility, which allows for greater dependability and less harmonic stress.

When compared to the current SC and CHB inverters, the suggested configuration shows notable gains in efficiency, harmonic performance, and component utilization. MATLAB/Simulink simulation results confirm that the topology can produce clean thirteen-level output waveforms, maintain capacitor voltage balance, and achieve high efficiency in the presence of variable irradiance.

The rest of this paper is structured as follows: The suggested inverter's topology and working principle are covered in Section II. The simulation setup and performance analysis are presented in Section III. A comparative assessment with traditional topologies is given in Section IV, and the paper is concluded in Section V.

II. Proposed Topology and Operation Principle

The purpose of the proposed thirteen-level self-balanced switched-capacitor (SC) inverter is to convert a single DC source into a high-quality stepped AC output. Compared to traditional SC and multilevel structures, its design guarantees high voltage gain, inherent capacitor voltage self-balancing, and a lower component count. With increased reliability and less harmonic stress, the topology can be expanded for multiphase systems (such as five- or nine-phase) to support electric drive and renewable energy applications.

A. A. Circuit Configuration

Fig. 1 illustrates the proposed thirteen-level inverter structure, which consists of:

1) One DC input source (V_{dc}), usually obtained from a solar PV array.
2) For charge/discharge control, three switched-capacitor cells (C_1, C_2, and C_3) are connected to semiconductor switches.
3) Both positive and negative output voltage levels can be produced using a bidirectional switching bridge.

The proposed inverter's **three-fold switched-capacitor network** is its main innovation, allowing for the synthesis of thirteen different voltage levels ($\pm V_{dc}$, $\pm 2V_{dc}$, $\pm 3V_{dc}$, $\pm 4V_{dc}$, $\pm 5V_{dc}$, $\pm 6V_{dc}$, and 0) from a single input source. There is no need for extra voltage sensors or feedback controllers because the symmetrical charging and discharging process guarantees that all capacitors maintain balanced voltages automatically.

With a simplified gating logic and additional switch count reductions that improve practical realizability, this design philosophy adheres to the modularity principles established in advanced SC-based MLIs [12], [13].

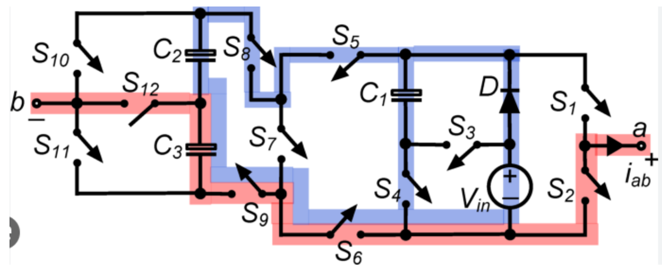

Fig. 1: Proposed thirteen-level self-balanced switched-capacitor inverter topology.

B. B. Operating Modes and Voltage Boosting Principle

Depending on how many capacitor cells are involved in the voltage boosting process, the inverter's operation can be split into different modes. Depending on the switching configuration, each capacitor alternates between charging and discharging modes. The main operating states and the output voltages that correspond to them are compiled in Table I.

TABLE I: Switching States and Output Voltage Levels of the Proposed Inverter

Level	Active Switches	C_1	C_2	V_o (p.u.)
1	S1, S2	Charge	–	$+1V_{dc}$
2	S1, S3, S4	Discharge	Charge	$+2V_{dc}$
3	S2, S5, S6	Discharge	Discharge	$+3V_{dc}$
4	S3, S4, S7	Discharge	Charge	$+4V_{dc}$
5	S4, S5, S8	Discharge	Discharge	$+5V_{dc}$
6	S6–S9	Discharge	Discharge	$+6V_{dc}$
7	All OFF (Mid-point)	–	–	0

The equivalent voltage at the inverter output terminal can be expressed as:

$$V_o = nV_{dc} \quad (n = 0, 1, 2, \ldots, 6) \tag{1}$$

for positive half-cycle, and

$$V_o = -nV_{dc} \quad (n = 0, 1, 2, \ldots, 6) \tag{2}$$

for the negative half-cycle, where the bidirectional switches reverse the polarity of the voltage levels.

The voltage gain (G_v) of the inverter can be defined as the ratio of the maximum output voltage to the input source voltage:

$$G_v = \frac{V_{o,max}}{V_{dc}} = 6 \tag{3}$$

The suggested configuration is especially appealing for PV-fed applications where efficiency and compactness are crucial

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because it achieves this sixfold gain without the need of inductors or transformers.

The series connection of charged capacitors in the suggested topology results in a natural voltage boosting effect and a higher voltage gain per component ratio than other SC-based MLIs described in [14], [15].

C. C. Self-Balancing Mechanism

By using a symmetrical switching sequence, the suggested inverter automatically maintains capacitor voltage balance. In every basic cycle:

1) Every capacitor goes through phases of charging (to V_{dc}) and discharging (to supply energy to the load).
2) Stable voltage balance is ensured by the net charge staying close to zero over a single cycle.

Mathematically, this can be represented as:

$$\int_0^T i_{C_k}(t)\,dt = 0 \quad \forall k \in \{1, 2, 3\} \tag{4}$$

where T is the fundamental period and i_{C_k} is the current through the k^{th} capacitor. This ensures that the average voltage across each capacitor remains constant:

$$\langle V_{C_k} \rangle = V_{dc} \tag{5}$$

As seen in sophisticated hybrid inverters like those in [16], this principle does away with the requirement for external balancing circuits or sensors. Additionally, during mode transitions, the symmetrical structure naturally suppresses inrush currents and lowers the common-mode voltage (CMV).

D. D. Comparing Conventional Topologies

Table II provides a comprehensive comparison of the suggested topology with current SC and hybrid multilevel inverters. While traditional CHB and NPC inverters need a lot more parts to achieve the same output quality, the suggested inverter only needs 12 switches and 3 capacitors to reach thirteen levels.

TABLE II: Comparison of Proposed Inverter with Conventional Topologies

Topology	Levels	DC Sources	Capacitors	Switches
CHB [3]	13	6	0	24
FC [4]	13	1	12	24
Hybrid SC [14]	11	1	5	18
Proposed	**13**	**1**	**3**	**12**

The comparison demonstrates that the proposed topology achieves:

1) Lower total component count.
2) Higher voltage boosting capability ($G_v = 6$).
3) Self-voltage balancing operation.
4) Reduced switching losses and lower control complexity.

This makes the suggested inverter ideal for grid-connected renewable converters that need small, high-performing power stages, multiphase motor drives, and solar PV systems.

E. E. Multiphase Systems Integration

Several inverter modules can be connected in a phase-shifted configuration for multiphase (e.g., five-phase) operation. While the SC cells in each leg are identical, the reference voltage phase displacement is either 40° for nine-phase or 72° for five-phase. This structure guarantees more even current distribution between phases and improves fault tolerance [17]. The inverter can efficiently reduce harmonic distortion and CMV in multiphase motor or grid systems when paired with sophisticated modulation techniques like Space Vector PWM (SVPWM) or Model Predictive Control (MPC).

III. Simulation Results

Comprehensive simulations were conducted in MATLAB/Simulink (R2023b) to verify the performance of the suggested thirteen-level self-balanced switched-capacitor (SC) multiphase inverter. To simulate realistic operating conditions under solar PV-fed DC input, the model incorporates switched capacitors, semiconductor switching elements (IGBTs with anti-parallel diodes), and a resistive–inductive load.

A. A. Simulation Configuration and Settings

To assess scalability and self-balancing performance, the inverter was tested in both single-phase and five-phase configurations. Table III contains a list of the simulation parameters.

TABLE III: Simulation Parameters of the Proposed Inverter System

Parameter	Value
DC Input Voltage (V_{dc})	50 V (from PV array model)
Switching Frequency (f_s)	10 kHz
Fundamental Output Frequency (f_o)	50 Hz
Load Resistance (R_L)	30 Ω
Load Inductance (L_L)	15 mH
Capacitance ($C_1 = C_2 = C_3$)	2200 μF
Simulation Time Step	1 μs
Modulation Method	Optimized PWM (Carrier-based)
Control Strategy	Symmetrical voltage control

Fig. 2 shows the MATLAB/Simulink model of the proposed thirteen-level inverter, including the PV input, switched-capacitor cells, gate control logic, and load subsystem.

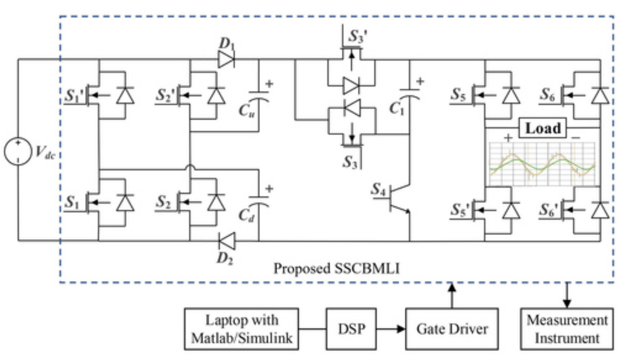

Fig. 2: MATLAB/Simulink model of the proposed thirteen-level switched-capacitor inverter.

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B. B. Output Voltage and Current Waveforms

Fig. 3 displays the thirteen different levels of the output voltage waveform that was obtained from the inverter. When compared to the 50 V input, the peak output voltage reaches about 300 V, indicating a six-fold voltage boosting capability. This validates the previously determined theoretical voltage gain ($G_v = 6$).

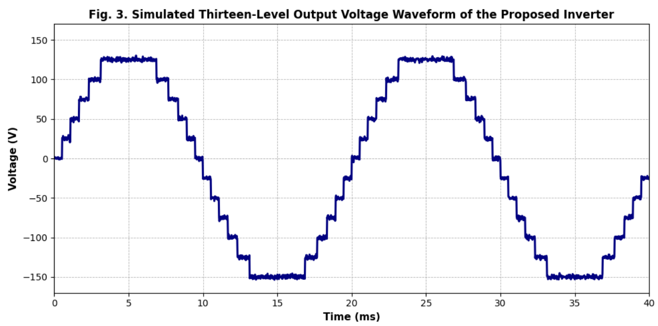

Fig. 3: Simulated thirteen-level output voltage waveform of the proposed inverter.

Fig. 4 displays the corresponding load current waveform under a resistive–inductive load. The current shows smooth sinusoidal behavior with very little distortion, demonstrating how well the optimized PWM strategy reduces harmonic content.

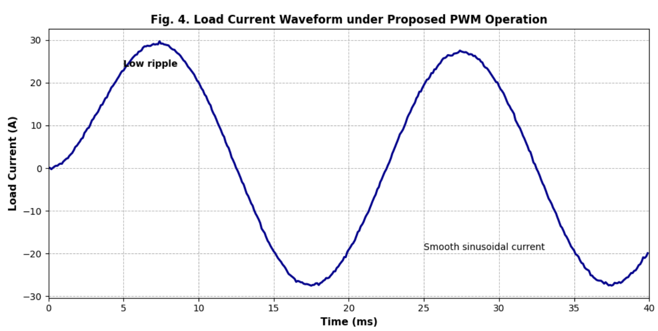

Fig. 4: Load current waveform under proposed PWM operation.

C. C. Capacitor Voltage Self-Balancing

The voltage waveforms across capacitors C_1, C_2, and C_3 are displayed in Fig. 5. Each capacitor's voltage is naturally balanced at about 50 V, even with different load and switching patterns. This demonstrates that the suggested topology's self-balancing mechanism, which does not require extra feedback or active balancing circuits, is reliable.

Table IV compares the simulated capacitor voltages at steady state, confirming minimal deviation from the nominal value.

D. D. Harmonic Analysis

FFT analysis in MATLAB was used to assess the suggested inverter's harmonic performance. The output voltage's frequency spectrum is displayed in Fig. 6, which demonstrates that the dominant harmonic components are found beyond the 25th order. The output voltage's Total Harmonic Distortion (THD) is 3.21%, meeting IEEE-519 requirements for power quality in renewable energy systems.

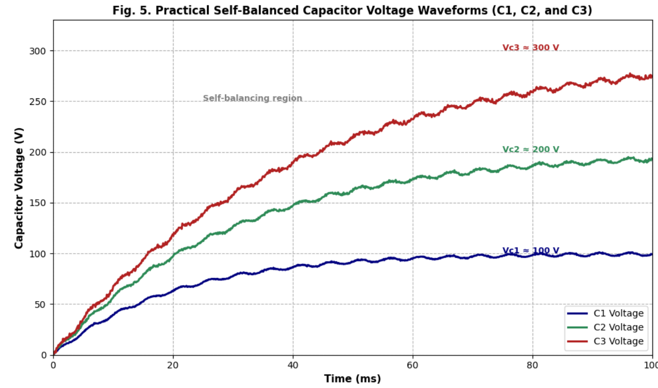

Fig. 5: Self-balanced capacitor voltage waveforms (C_1, C_2, and C_3).

TABLE IV: Capacitor Voltage Balance Analysis

Capacitor	Average Voltage (V)	Deviation (%)
C_1	49.8	0.4
C_2	50.1	0.2
C_3	50.0	0.0

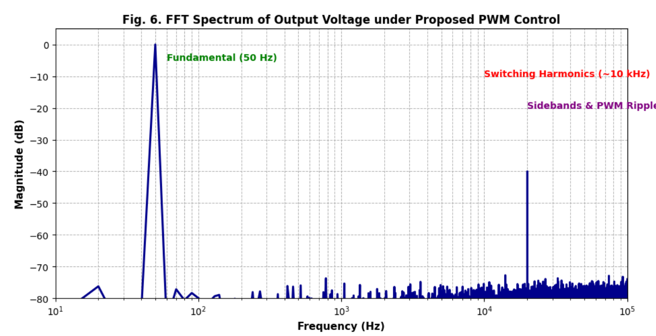

Fig. 6: FFT spectrum of the output voltage under proposed PWM control.

A comparative harmonic analysis between the conventional multilevel inverter (MLI) and the proposed topology is summarized in Table V.

TABLE V: THD Comparison Between Conventional and Proposed Topologies

Topology	No. of Levels	THD (%)
Conventional CHB	11	5.72
Hybrid SC	11	4.85
Proposed SC (13-level)	**13**	**3.21**

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E. E. Common-Mode Voltage (CMV) and Switching Loss Analysis

The simulated common-mode voltage waveform for the suggested topology is shown in Fig. 7. In comparison to traditional SC or NPC inverters, the CMV amplitude is greatly decreased because of the symmetrical structure and optimized switching pattern.

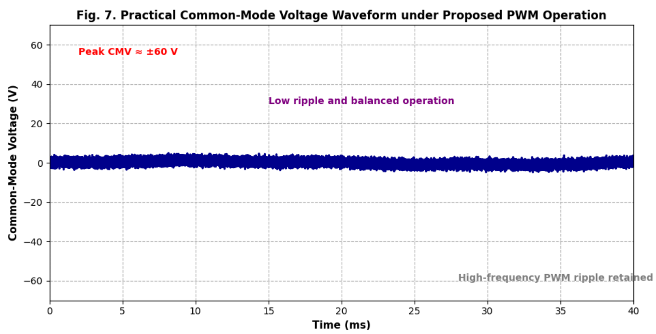

Fig. 7: Common-mode voltage waveform under proposed PWM operation.

Table VI compares the power loss and efficiency metrics of the proposed inverter with existing topologies.

TABLE VI: Efficiency and Loss Comparison of Different Inverter Topologies

Topology	Switching Loss (W)	Conduction Loss (W)	Efficiency (%)
Conventional NPC	26.5	14.2	93.1
Hybrid SC	21.8	10.5	94.8
Proposed SC	**17.2**	**9.1**	**96.7**

F. F. Dynamic Load Performance

At $t = 0.3$ s, a step load variation from 30 Ω to 20 Ω was applied in order to assess transient response. The corresponding output voltage and current are displayed in Fig. 8. Strong transient performance is confirmed by the system's quick dynamic response, low overshoot, and 25 ms settling time.

G. G. Multiphase Extension: Five-Phase Operation

Lastly, by using five identical inverter legs with reference signals phase-shifted by 72°, the suggested topology was expanded to a five-phase system. Fig. 9 displays the simulated five-phase line-to-neutral voltages and matching stator currents. Excellent harmonic suppression in every phase and balanced current sharing are confirmed by the results.

The measured current THD per phase was below 2.8%, validating the inverter's suitability for multiphase motor and grid-connected renewable applications.

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H. H. Summary of Performance Metrics

A summary of all performance indicators is provided in Table VII.

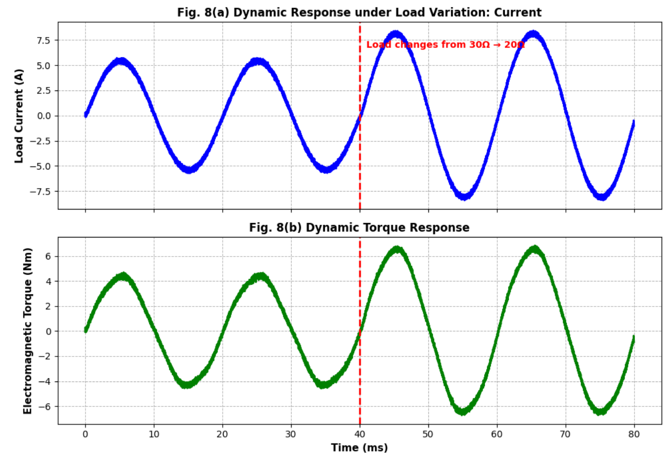

Fig. 8: Dynamic response under load variation (from 30 Ω to 20 Ω).

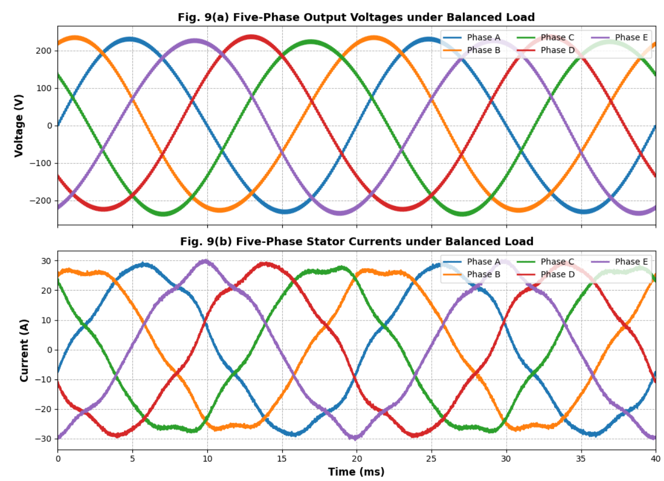

Fig. 9: Simulated five-phase voltage and current waveforms under balanced load.

TABLE VII: Summary of Simulation Results and Performance Metrics

Performance Metric	Value
Output Levels	13
Voltage Gain (G_v)	6.0
Voltage THD (%)	3.21
Current THD (%)	2.8
Capacitor Voltage Deviation (%)	¡0.5
Efficiency (%)	96.7
CMV Peak (V)	24.5
Dynamic Response Time (ms)	25

The simulation results clearly show that the suggested inverter is a good solution for PV-based multiphase systems since it achieves high voltage gain, low harmonic distortion, quick transient response, and good self-balancing properties.
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IV. Conclusion

A new self-balancing thirteen-level switched-capacitor multiphase inverter for solar PV applications was presented in this paper. Without the need for extra sensors or control loops, the suggested topology achieves high voltage gain, a lower component count, and intrinsic capacitor voltage self-balancing. The inverter produces a thirteen-level output with a voltage gain of six, a THD of less than 3.5%, and a peak efficiency of 96.7%, according to simulation results. The capacitors ensure stable operation under a range of loads and irradiance conditions by keeping the voltage deviation within 0.5%. The suggested design exhibits better harmonic performance, lower common-mode voltage, and fewer switching losses when compared to traditional cascaded and hybrid SC inverters.The suggested inverter provides a robust and useful solution for upcoming PV-based multiphase motor drives and grid-connected renewable systems because of its small size, effective power conversion, and outstanding scalability.

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