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# Modular Switched-Capacitor Multilevel Inverter for Photovoltaic Applications with Lower Devices

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## Abstract

In this paper, a new structure for a multilevel inverter based on the switched capacitor is presented. The proposed sub-module with one source and one capacitor is able to generate 5 voltage levels at the output, in addition to this, the proposed cascade structure with two isolated DC voltage sources along with two capacitors is able to generate 25 voltage levels at the output. Also, this structure is able to increase the input voltage using a capacitor. The proposed structure is able to charge the capacitor without using a sensor, in other words, the proposed structure is self-charging. In addition to working separately from the grid, the proposed structure can also be used connected to the grid for photovoltaic applications. To confirm the proposed structure, a quantitative comparison with similar structures has been done. In addition, a heat loss simulation has been done for the proposed structure. The simulation results confirm the functionality of the proposed structure.

## Keywords:

Multi-level inverter; Thermal loss simulation; Reduce devices; Grid connection; Photovoltaic; 25 level.

## 1. Introduction

Multilevel inverters (MLIs) have attracted considerable attention in medium- and high-power conversion applications because of their capability to synthesize multistep voltage waveforms with improved power quality and reduced voltage stress on power semiconductor devices. Compared with conventional two-level inverters, MLIs can provide lower output-voltage harmonic distortion and reduced voltage variations, while enabling the generation of higher output voltages using semiconductor devices with lower voltage ratings. These characteristics have made MLIs attractive for a wide range of applications, including renewable energy systems, motor drives, uninterruptible power supplies, reactive power compensation, and electric vehicles.

Conventional MLI topologies are mainly categorized into neutral-point-clamped (NPC), flying-capacitor (FC), and cascaded H-bridge (CHB) structures. Despite their well-established performance, these topologies generally suffer from an increasing number of power electronic components as the number of output voltage levels increases. In NPC inverters, maintaining the balance of the dc-link capacitor voltages is a major challenge, whereas FC structures require a large Multilevel inverters (MLIs) have attracted considerable attention in medium- and high-power conversion applications because of their capability to synthesize multistep voltage waveforms with improved power quality and reduced voltage stress on power semiconductor devices. Compared with conventional two-level inverters, MLIs can provide lower output-voltage harmonic distortion and reduced voltage variations, while enabling the generation of higher output voltages using semiconductor devices with lower voltage ratings. These characteristics have made MLIs attractive for a wide range of applications, including renewable energy systems, motor drives, uninterruptible power supplies, reactive power compensation, and electric vehicles.

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The performance and effectiveness of the proposed topology are evaluated through quantitative comparison with existing switched-capacitor multilevel inverter structures in terms of the number of switches, drivers, capacitors, diodes, voltage sources, and total blocking voltage. Furthermore, power-loss and thermal analyses are performed to investigate the practical operating characteristics of the proposed submodule. Finally, MATLAB-based simulations and experimental results are presented for the five-level basic submodule and the cascaded 25-level configuration under different loading conditions. The proposed structure is also investigated for grid-connected photovoltaic applications, demonstrating its potential for renewable-energy-based power conversion systems.

## 2. Analysis of the Proposed Structure

As the proposed module is analyzed in this section, the operating modes, switching table, selection of source values, and blocking voltage of the switches of the proposed module are presented in this section.

### 2.1. Proposed Submodule

The structure of the proposed boost module is depicted in Figure 1. The proposed module consists of 6 one-way switches and a diode, and a total of 7 power electronic devices. Also, 1 isolated voltage source and a switched capacitor constitute the proposed module.

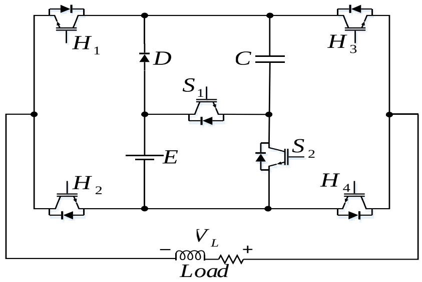



**Figure 1. Proposed submodule structure**

The input source voltage is assumed to be $E = V_{dc}$. In this case, the voltage of the proposed module and the switching states are presented in Table 1. In this table, the number 1 indicates that the switch is on, the number zero indicates that the switch is off, the symbol ⋏ indicates that the capacitor is charging, and the symbol ⋎ indicates that the capacitor is discharging.

If the switch $S_2$ is turned on, the capacitor C is connected in parallel with the voltage source and is charged, and in the charging state, its voltage becomes equal to E, and if the switch $S_1$ is turned on, the capacitor C is connected in series with the voltage source and is discharged. The proposed module is able to produce levels $\pm V_{dc}$ , $\pm 2V_{dc}$ and zero. In other words, the proposed module is able to produce 5 levels at the output.

**Table 1. Switching modes and output voltage of the proposed module**

| $H_1$ | $H_2$ | $H_3$ | $H_4$ | $S_1$ | $S_2$ | $V_C$ | $V_o$ |
|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 0 | 1 | 0 | ⋎ | $+2V_{dc}$ |
| 0 | 1 | 1 | 0 | 0 | 1 | ⋏ | $+V_{dc}$ |
| 1 | 0 | 1 | 0 | 0 | 1 | ⋏ | 0 |
| 0 | 1 | 0 | 1 | 0 | 1 | ⋏ | 0 |
| 1 | 0 | 0 | 1 | 0 | 1 | ⋏ | $-V_{dc}$ |
| 1 | 0 | 0 | 1 | 1 | 0 | ⋎ | $-2V_{dc}$ |

### 2.2. Cascade structure for producing high voltage levels

The proposed module cannot produce higher levels. Therefore, to produce higher levels, the proposed module is connected in series and a cascade structure is presented with the aim of producing higher levels. The proposed module is suitable for low power applications and is not suitable for high powers due to the increase in the rating of the switches and the sharp increase in the price of the switches. However, the cascade structure has a lot of application in high powers due to the low rating of the switches. By connecting m number of the proposed modules in series, the generalized structure can be presented as a new structure, which is shown in Figure 2.

The selection of sources in the cascade structure is done in two ways:

a) The size of the voltage sources is symmetrical:

$$E_1 = E_2 = ... = E_m = V_{dc} \tag{1}$$

b) The voltage source sizes of the different modules of the cascade structure should be considered incrementally. In other words, if the voltage source size of the first submodule is $E_1 = V_{dc}$ , the voltage source size of the second submodule will be $E_2 = 5V_{dc}$ .

## 3. Comparison of the proposed basic structure with other structures

Results To demonstrate the advantages of the proposed basic structure, a detailed comparison with similar structures has been made in this section. The number of sources, number of switches, number of drivers, number of capacitors, number of diodes and maximum voltage withstand of switches have been compared with other structures. This comparison has been made for similar basic structures. Since the number of output voltage levels of other structures presented is different, the following relationship has been used in order to make a fair comparison. Table 2 presents the comparison of the proposed structure with other structures in terms of the number of components.

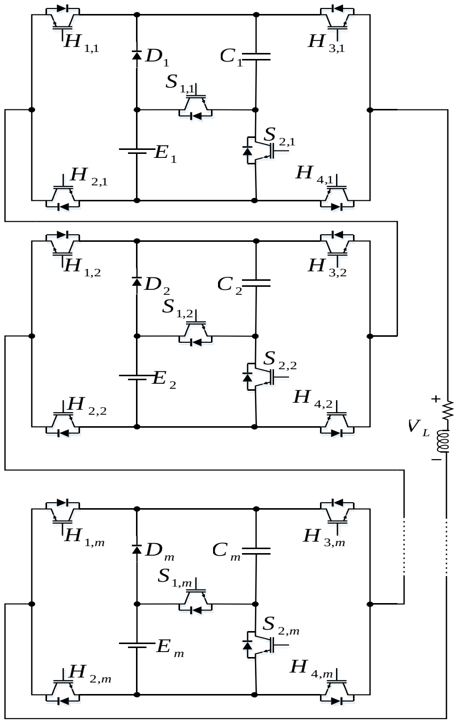



**Figure 2. Proposed submodule structure**

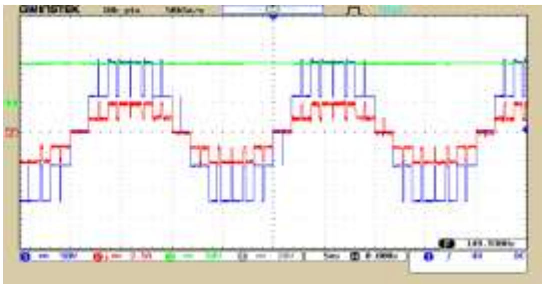
**Table 2. Comparison of the proposed base structure with other references in terms of number of equipment and blocking voltage per number of levels**

| | $N_{Level}$ | $N_v$ | $N_{Sw}$ | $N_{Dr}$ | $N_C$ | $N_D$ | $TBV$ | Boost | Negative Level |
|---|---|---|---|---|---|---|---|---|---|
| [17] | 13 | 2 | 11 | 10 | 1 | 1 | 20 | Yes | H-Bridge |
| [18] | 7 | 1 | 10 | 10 | ۲ | 4 | 18 | Yes | Innate |
| [19] | 13 | 1 | 15 | 14 | 3 | 0 | 32 | Yes | Innate |
| [20] | 9 | 2 | 8 | 7 | 3 | 0 | 20 | No | Innate |
| [21] | 9 | 2 | 12 | 12 | 1 | 0 | 24 | Yes | Innate |
| [22] | 7 | 2 | 7 | 7 | 1 | 5 | 20 | No | H-Bridge |
| [23] | 9 | 2 | 9 | 9 | 1 | 0 | 23 | Yes | H-Bridge |
| Proposed | 5 | 1 | 6 | 6 | 1 | 1 | 10 | Yes | Innate |
| | 25 | 2 | 12 | 12 | 2 | 2 | 60 | Yes | Innate |

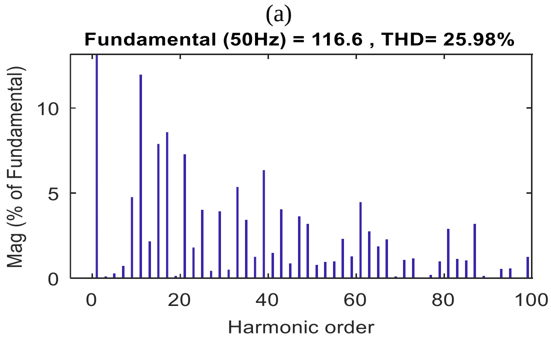
## 4. Simulation and laboratory results

In this section, the simulation results of the proposed topology are presented along with the experimental results. MATLAB software is used for the simulation and to investigate the performance of the proposed topology, a low-power laboratory sample is built and evaluated. Phase-shift pulse width modulation is used for switching the proposed topology. In this section, the simulation and experimental results of the proposed 5-level basic topology and the 25-level cascade topology, which consists of the cascade connection of two basic topologies, are presented.

Figure 3 shows the experimental results of the output voltage and current and the voltage of the capacitor C for the ohmic load. Also shown in this figure is the total harmonic distortion (THD) of the output voltage. As Figure 3 shows, the output voltage is 5 levels and the capacitor voltage is also stabilized at the input voltage value. Figure 4 also shows the same results for the inductive ohmic load.

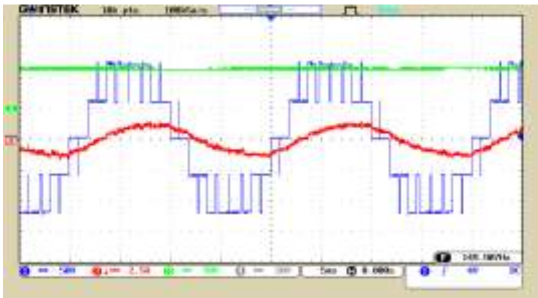


(a)

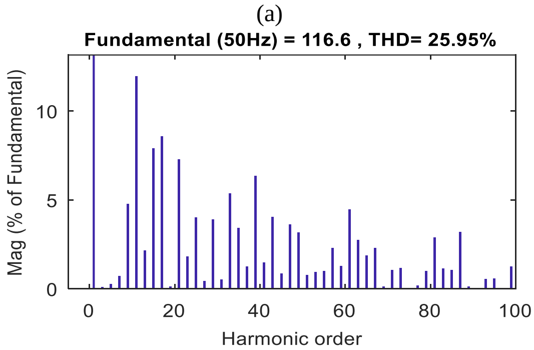



(b)

**Figure 3. Output voltage and current waveform of the proposed submodule along with capacitor voltage and b) THD of output voltage at ohmic load for the proposed submodule**



(a)




(b)

**Figure 4. a) Output voltage and current waveform and b) THD of output voltage at ohmic-self load for the proposed submodule**

## 5. Conclusion

In this paper, a new basic structure for a five-level inverter based on switched capacitors is presented, which has the ability to balance the capacitor voltage and boost the input voltage inherently. The proposed structure has advantages such as low number of switching devices, suitable blocking voltage, negative polarity generation without the need for an H-bridge. These advantages lead to reduced power losses and justify the proposed structure for medium/high voltage applications with better efficiency. A comprehensive comparison with similar structures confirms the merit of the proposed structure. The proposed structure is suitable for renewable energy source applications such as solar cells and fuel cells. In solar cells and fuel cells applications, a dc/dc voltage converter is required for voltage boosting and MPPT, and this is inevitable. Since the proposed structure has the inherent ability to boost the voltage, the size of the dc/dc converter is reduced. To verify the operation of the proposed structure and control simulation is presented.

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