PV system applied on the new PUC-NPC inverter

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ABSTRACT
In this article, the authors present a new competitive Packed-U-cell and neutral point clamped (PUC-NPC) 9-level converter that utilizes a small number of power switches and passive components. Only seven switches are added to a single DC source. However, the proposed converter takes benefits of the neutral point clamped (NPC) converter’s capability to connect capacitors in series, all with a simple control that enables the algorithm associated to the proposed inverter operate correctly in an open loop operation. A technique of pulse width modulation (PWM) is employed to maintain capacitor voltage at desired values. The proposed inverter produces an almost sinusoidal waveform output voltage, as result, a perfectly sinusoidal charge current with minimal impact on the economy and energy consumption are optioned. The converter has been integrated with a photovoltaic system to minimize its impact on the electricity supply and enhance energy efficiency. In order to take a maximum power from the photovoltaic panel, authors employ a maximum power point tracking (MPPT) technique based on disturbance and observe (P and O). When combined with the proposed control technique, it offers a competitive system suitable for standalone use or as an energy source, eliminating the need for PI regulators or additional investments. The proposed 9-level converter has been validated through simulation, utilizing the MATLAB Simulink environment to model the proposed system. Dynamics of this later were verified by changing the load charge.

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1. INTRODUCTION
Current research is focused on power electronics to achieve more efficient energy conversion for electrical power applications and facilitate the renewable energy integration, specifically solar energy, to support solar photovoltaic panels. Multilevel converters, use medium power switches to deliver an efficient power and convert energy from DC current side to an AC current side. Various topologies have been introduced, with cascading H-bridge (CHB) [1] and neutral point clamped (NPC) [2], largley employed in industry, and flying capacitor (FC) [3] being popular choices. The exploration of new multilevel inverter topologies that produce increased output levels while utilizing fewer power switches and DC power sources is a crucial aspect in power electronics researches. That pursuit aims to enhance quality and reduce manufacturing costs.

This study investigated the effects of applying a photovoltaic system using the new 9-level Packed-U-cell and neutral point clamped (PUC-NPC) [4] inverter, combined with the (P and O) maximum power point tracking (MPPT) technique [5], [6]. While earlier studies have explored the impact of irradiation changes on
photovoltaic voltage output. The proposed system ensures high-quality power on the load side, contributing to good energy conversion efficiency. The proposed PUC-NPC inverter is comprised of seven power switches and four capacitances, enabling it to offer nine-level output voltage through pulse width modulation (PWM) control. This control technique, based on the presence of redundant switching states, provides nine levels with a self-balancing of capacitor voltages, resulting in a low-profile design and reduced cost [7]–[10].

2. METHOD

2.1. Proposed PUC-NPC 9-level topology, different switching states and the technique to balance capacitors voltages

The PUC-NPC converter is based on the classical PUC [11], a seven-level inverter that utilizes closed-loop regulation for capacitors voltage balancing [12]–[25]. Figure 1 illustrates a single phase of the proposed topology, which is based on a series association of two multilevel topologies: PUC and the NPC topologies. To operate in open loop condition, it is necessary to decrease the target of voltage number levels, leading to development of the proposed system.

![Figure 1. Proposed single phase of the PUC-NPC 9-level inverter](image)

To generate the 9 level desired voltage we suppose that \( Vc1 = Vc2 = E/2 \) and \( Vc3 = Vc4 = E/2 \). The nine required levels are duplicated in Table 1. Using the presence of redundant states, the system achieves the auto-balancing of capacitors voltage in open loop operation without using any PI regulators or filters.

<table>
<thead>
<tr>
<th>State</th>
<th>Interconnexion</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>E</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
</tr>
<tr>
<td>8</td>
<td>Vc1+Vc4</td>
<td>Disch</td>
<td>N.E</td>
<td>N.E</td>
<td>Disch</td>
</tr>
<tr>
<td>7</td>
<td>E-(Vc3+Vc4)</td>
<td>N.E</td>
<td>N.E</td>
<td>Charg</td>
<td>Charg</td>
</tr>
<tr>
<td>6</td>
<td>Vc1-Vc3</td>
<td>Disch</td>
<td>N.E</td>
<td>Charg</td>
<td>N.E</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
</tr>
<tr>
<td>4</td>
<td>-(Vc2-Vc4)</td>
<td>N.E</td>
<td>Disch</td>
<td>N.E</td>
<td>Charg</td>
</tr>
<tr>
<td>3</td>
<td>(Vc3+Vc4)-E</td>
<td>N.E</td>
<td>N.E</td>
<td>Charg</td>
<td>Charg</td>
</tr>
<tr>
<td>2</td>
<td>-(Vc2+Vc3)</td>
<td>N.E</td>
<td>Disch</td>
<td>Charg</td>
<td>N.E</td>
</tr>
<tr>
<td>1</td>
<td>-E</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
<td>N.E</td>
</tr>
</tbody>
</table>

N.E: Non effect, Charg: charging, Disch: discharging

A PWM technique is assured to achieve capacitors voltage balancing. No PI regulators, voltage or currents sensors are employed which makes the implementation very easy. Figure 2 presents the technique of control used.
2.2. Photovoltaic system based on the PUC-NPC 9 inverter

The system comprising the PUC-NPC multilevel inverter associated with a photovoltaic source consists of three main components. Firstly, there's the PUC-NPC 9 inverter, capable of providing nine levels of output voltage using only a few power electronics components. The second component is the SunPower SPR305-WHT PV system, which comprises three series-connected modules and three parallel strings. Each module consists of 96 cells. SunPower PV panels were chosen for their efficiency, quality, and ease of implementation.

To maximize power generation, a third component is employed, which involves a MPPT technique developed based on the perturb and observe (P&O) method. This technique adjusts the operating voltage to obtain maximum power from the PV system. The algorithm used for MPPT is illustrated in Figure 3 [26], where $\delta$ represents the duty cycle and $k$ is an integer. Additionally, Figure 4 [26] depicts the I-V and Ppv-V characteristics of the SPR 305WHT PV system.

![Figure 2. Switches gates pulses generation](image)

**Figure 2. Switches gates pulses generation**

**Figure 3. Principle of P&O MPPT technique**
Each perturbation leads to either a reduction or augmentation in the power output of the PV panel. When power increases, the duty cycle should track the trend of the PV panel voltage. Conversely, if power decreases, the duty cycle should adjust in the opposite direction to the PV panel voltage evolution. This iterative cycle continues until the maximum power point is attained. Figure 4 depicts the I-V and Ppv-V characteristics of the Canadian Solar CS5P-220P PV array.

3. RESULTS AND DISCUSSION

To simulate the proposed system, we chose to analyze the PUC-NPC nine-level inverter using a constant DC power source. Subsequently, we introduced a constant irradiation level. However, to verify the dynamics of our system, we also incorporated variable irradiation levels in the simulation. This simulation was performed using the Matlab Simulink and SimPowerSystems environment. System parameters are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2. System parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUC-NPC inverter</td>
</tr>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>SPUC-NPC capacitors</td>
</tr>
<tr>
<td>Load resistor</td>
</tr>
<tr>
<td>Load inductance</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
<tr>
<td>SPR 305WHT PV panel</td>
</tr>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Moduls</td>
</tr>
<tr>
<td>Strings</td>
</tr>
</tbody>
</table>

3.1. In constant DC source

The proposed system is simulated with a constant DC source of 380 V. As depicted in Figure 5, the capacitors reach their desired voltage values. Specifically, Vc1 and Vc2 stabilize around half of the DC source, while Vc3 and Vc4 are maintained at the desired value of E/4.

This achievement is facilitated by the presence of redundant states, eliminating the need for voltage sensors or closed-loop systems. Figure 6 presents the output voltage of the inverter proposed, it is constituted from nine voltage levels. Load current is nearly sinusoidal as represented in Figure 7.

A remarkably low total harmonic distortion (THD) is attained without the use of any voltage sensor or regulation loop. The THD level of this nine-level inverter is measured at 2.31% for the current waveform, as illustrated in Figure 8. It's noteworthy that the load current THD can be further reduced by increasing the modulating signal frequency.
Figure 5. DC source and capacitors voltages

Figure 6. Load voltage waveform

Figure 7. Load current waveform

Figure 8. Zoom on the THD of the proposed inverter output current
3.2. In constant irradiance condition

The proposed system is attacked by a constant irradiation condition of 750 W/m². Consequently, the MPPT technique P&O is employed to extract the maximum power, resulting in an approximate output of 2 kW, as shown in Figure 9. Simultaneously, the PV panel voltage remains in a steady state around the desired value of 165 V, as depicted in Figure 10.

![Figure 9. PV power evolution](image)

![Figure 10. PV voltage evolution](image)

As illustrated in Figure 11, the capacitors are maintained around their desired values, with capacitors 1 and 2 at half of the PV source and capacitors 3 and 4 at a quarter of the PV source. These results are achieved without the use of any active or passive filters, operating in an open loop. The load voltage consists of nine levels, as shown in Figure 12, and the load current is nearly sinusoidal, as depicted in Figure 13.

![Figure 11. DC-Link and inverter capacitors voltages evolution](image)
4. COMPARATION WITH OTHER TOPOLOGIES

The proposed inverter is highly optimized, benefiting from its significant advantage of employing only seven switches, with six being current reversible and the seventh being both voltage and current reversible. Additionally, the use of a single DC source significantly reduces the cost of the conversion block. These advantages, combined with the capability to achieve self-balancing of capacitor voltages in open-loop operation through the proposed control technique, contribute to the overall efficiency of the system. Table 3 provides a comparison of the proposed inverter with recent nine-level inverters.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Switches number</th>
<th>DC source number</th>
<th>Capacitors number</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUC</td>
<td>7</td>
<td>1</td>
<td>4</td>
<td>Very easy</td>
</tr>
<tr>
<td>NPC</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>Easy</td>
</tr>
<tr>
<td>SPUC [7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PUC [10]</td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>Easy</td>
</tr>
</tbody>
</table>

5. CONCLUSION

This paper introduces a novel photovoltaic system centered around the PUC-NPC inverter. Employing the SunPower SPR305-WHT PV panel, the system utilizes the P&O MPPT technique to extract maximum power. The system's response is validated initially with a constant DC source and subsequently with a PV system under 750 W/m² irradiation conditions. Simulation results confirm the paper's concepts, demonstrating that capacitor voltages are achieved in open-loop operation without the need for filters or sensors, simplifying the implementation process.
REFERENCES


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