A Novel Nested T-Type Four-Level Inverter for Medium Voltage Applications

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Abstract—Multi-Level converter topologies have gained much attention during recent three decades due to their significant benefits in a wide range of applications especially for high power and medium voltage applications. This paper presented a novel Nested T-Type (NT-Type) four-level inverter for high power and medium voltage applications. Main advantages of NT-Type four-level topology are: operating over a wide range of voltage without the requirement to connect to power devices in series, high quality output voltage, and less proportion of components in comparison with other classical four-level topologies. Also, comparison of the conduction losses between the NT-Type and Nested Neural Point Clamped (NNPC) inverter is determined. The three type Sinusoidal Pulse Width Modulation (SPWM) schemes, which are the most popular modulation schemes in industry applications, are utilized in this study for NT-Type and NNPC topologies. The performance of the NT-Type inverter is verified by MATLAB/Simulink.

Keywords—Nested T-Type four level inverter; medium voltage applications.

I. INTRODUCTION

Multi-level converter topologies have achieved much attention during the three decades because of their significant advantages in a wide range of applications, especially for high power and medium voltage applications [1]-[23]. Theoretically, any numbers of voltage levels can be obtained through these topologies. But due to technical restrictions, the three, four, and five-level versions of these converters are generally employed in the industry [1]-[23]. Low harmonic distortion, the limitation of voltage transient’s dv/dt, exhibiting higher output voltage with the same device ratings, the small size of the required filter elements, the high efficiency of the system, as well as the reduced common-mode voltages are benefits of multi-level converters. Multilevel voltage source converter (VSC) topologies can be classified into two groups; conventional multilevel and advanced multilevel topologies. The conventional multilevel topologies can be categorized into three main groups; the Cascaded H-Bridge (CHB) [24] converters, the Flying Capacitor (FC) [25], and the Neutral-Point-Clamped (NPC) (named Diode-Clamped) [26]. The conventional multilevel topologies have some drawbacks which limit their applications. For example, NPC topology with higher number of levels gets less attention and this is resulted due to the number of clamping diodes increments significantly with the voltage level. For FC structure, the number of flying capacitors increments with the voltage level, also balancing of flying capacitor voltages is the main drawback of it. The CHB structure needs a large proportion of isolated dc sources as well as an costly and bulky phase-shifting transformer. The advanced topologies which can be called hybrids multilevel topologies are introduced to overcome conventional topologies limitations [1]-[23]. Although these hybrid topologies reduce some limitations of the conventional multilevel topologies, they still have some drawbacks which limits their applications. Some limitations of these topologies can be listed as follows: topologies that introduced in [1]-[4], [14]-[16] have H bridge in their structures. Furthermore, all above mentioned topologies need a large number of isolated dc sources and an expensive and bulky phase-shifting transformer. Topologies that introduced in [6]-[8], [10]-[14] have a number of switches in their structures which not only increase topology cost, but also have complicated control techniques. Topologies that are used in [19], [20] can be distribute the losses between the outer and inner switching devices in each converter leg and thus improve the cooling system design and enhance the highest power ratio of the converter. Topologies introduced in [21], [23], increase the number of voltage levels. These converters could reach higher output levels without needing...
add series-connected diodes. In addition, the restriction of capacitor voltage balancing when using passive front ends is covered. These converters, however, are complex due to their need to control the FC voltages. To overcome some mentioned limitations, Nested Neutral Point Clamped (NNPC) introduced in [27] (see Fig 1a).

In this paper, a novel Nested T-Type (NT-Type) four-level inverter is proposed for high power and medium voltage applications. Not only this topology has less components count compared to classical four level and NNPC topologies, but also has less conduction losses compared to them. Also, proposed topology has some benefits as follows: operating over a wide range of voltage without the need for connecting power devices in series, high quality output voltage, as well as capability of employing various modulation schemes (e.g. SPWM, SVM, and etc.).

II. PROPOSED NT-TYPE TOPOLOGY, OPERATION PRINCIPLE, AND COMPARISON OF CONDUCTION LOSSES BETWEEN NNPC AND NT-TYPE TOPOLOGIES

Fig. 1b shows the topology configuration of the NT-Type four-level inverter, which is composed of a flying capacitor (FC) with T-Type topologies. Each phase includes six switches, and two flying capacitors. NT-Type can operate in a wide range of voltage without need to any device in series. Following assumptions are given as follows: voltages of flying capacitors as well as dc-link capacitors are constant. The list of switching pattern for NNPC and NT-Type topologies are illustrated in Table I and Table II, respectively.

![Fig. 1. Four level three phase topologies: (a) NNPC inverter. (b) NT-Type inverter.](image)

<table>
<thead>
<tr>
<th>Phase voltage</th>
<th>Phase switching State, Sk</th>
<th>Redundant Phase switching states</th>
<th>Switching state of each device</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}/2$</td>
<td>3</td>
<td>3</td>
<td>1 1 1 0 0 0</td>
</tr>
<tr>
<td>$V_{dc}/6$</td>
<td>2A</td>
<td>0</td>
<td>1 1 0 0 1 1</td>
</tr>
<tr>
<td>$V_{dc}/6$</td>
<td>2B</td>
<td>1</td>
<td>0 1 1 0 0 0</td>
</tr>
<tr>
<td>$V_{dc}/6$</td>
<td>1A</td>
<td>1</td>
<td>0 0 1 1 0 0</td>
</tr>
<tr>
<td>$V_{dc}/6$</td>
<td>1B</td>
<td>1</td>
<td>0 0 0 1 1 0</td>
</tr>
</tbody>
</table>

The four phase voltages are $-V_{dc}/2$, $-V_{dc}/6$, $V_{dc}/6$, and $V_{dc}/2$, mentioning the four phase switching state 0, 1, 2, and 3 respectively. The phase voltage is determined as the voltage at the output terminal of every phase according to the neutral point of dc bus. The relationship between phase voltage $v_k$ and phase switching state $sk$ could be expressed through (1).

$$v_k = \frac{(2sk - 3)}{6} \times V_{dc}$$  \hspace{1cm} (1)

Note: In NNPC, switches Sk1, Sk2, and Sk3 operate complementary with Sk6, Sk4, and Sk5 respectively. Likewise, in proposed NT-Type topology switches Sk1, Sk2, and Sk3 operate complementary with Sk4, Sk6, and Sk5 respectively.

According to Table I, Table II, and Fig. 2, the operation stages of NNPC and NT-Type can be described as follows:
Switching state 0, for NNPC (see Fig. 2a-right):
With switches Sk4, Sk5, and Sk6 ON, and Sk1, Sk2, and Sk3 OFF, the output phase voltage is \(-\frac{V_{dc}}{2}\). If \(i_k<0\), switches Sk4, Sk5, and Sk6 conduct. And if \(i_k>0\), body diodes of switches Sk4, Sk5, and Sk6 conduct.

Switching state 0, for NT-Type (see Fig. 2a-left):
With switches Sk3, Sk4, and Sk6 ON, and Sk1, Sk2, and Sk5 OFF, the output phase voltage is \(-\frac{V_{dc}}{2}\). Although switch Sk6 is ON, it does not affect load current path. If \(i_k<0\), switches Sk3, and Sk4 conduct. And if \(i_k>0\), body diodes of switches Sk3, and Sk4 conduct.

Switching state 1A, for NNPC (see Fig. 2b-right):
With switches Sk3, Sk4, and Sk6 ON, and Sk1, Sk2, and Sk5 OFF, the output phase voltage is \(-\frac{V_{dc}}{6}\). If \(i_k<0\), switches Sk4, Sk6, and bottom diode clamped conduct. And if \(i_k>0\), body diodes of switches Sk6, switch Sk6, and up diode clamped conduct.

Switching state 1A, for NT-Type (see Fig. 2b-left): with switches Sk4, Sk5, and Sk6 ON, and Sk1, Sk2, and Sk3 OFF, the output phase voltage is \(-\frac{V_{dc}}{6}\). If \(i_k<0\), switches Sk6, Sk4, and body diode of switch Sk5 conduct. And if \(i_k>0\), body diodes of switches Sk4, Sk6, and switch Sk5 conduct.
Switching state 1B, for NNPC (see Fig. 2c-right):
with switches Sk4, Sk5, and Sk1 ON, and Sk6, Sk2, and Sk3 OFF, the output phase voltage
is $-\frac{V_{DC}}{6}$. If ik<0, switches Sk5, Sk4, and body diode of switch Sk1 conduct. And if ik>0, body diodes of switches Sk4, Sk5, and Sk1 conduct.

Switching state 1B, for NT-Type (see Fig. 2c-left): with switches Sk3, Sk1, and Sk6 ON, and Sk4, Sk2, and Sk5 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. In spade of switch Sk6 is ON, don’t have influence in load current path. If ik<0, switch Sk3, and body diode of switch Sk1 conduct. And if ik>0, body diode of switch Sk3, and switch Sk1 conduct.

Switching state 2A, for NNPC (see Fig. 2d-right):
With switches Sk2, Sk3, and Sk6 ON, and Sk1, Sk2, and Sk5 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. If ik<0, switch Sk6, and body diodes of 6 switches Sk2, and Sk3 conduct. And if ik>0, body diode of switch Sk6, and switches Sk2, and Sk3 conduct.

Switching state 2A, for NT-Type (see Fig. 2d-left): with switches Sk2, Sk4, and Sk5 ON, and Sk1, Sk3, and Sk6 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. Although switch Sk5 is ON, it does not affect current path. If ik<0, switch Sk4, and body diode of switch Sk2 conduct. And if ik>0, body diode of switch Sk4, and switch Sk2 conduct.

Switching state 2B, for NNPC (see Fig. 2e-right):
With switches Sk4, Sk3, and Sk1 ON, and Sk6, Sk2, and Sk5 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. If ik<0, switch Sk4, body diode of switch 6 Sk1, and bottom diode clamped conduct. And if ik>0, switches Sk1, and Sk3, and up diode clamped conduct.

Switching state 2B, for NT-Type (see Fig. 2e-left): with switches Sk1, Sk6, and Sk5 ON, and Sk2, Sk3, and Sk4 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. If ik<0, switch Sk6, and body diodes of switches Sk1, and Sk5 conduct. And if ik>0, body diodes of switch Sk6, and switches Sk1, and Sk5 conduct.

Switching state 3, for NNPC (see Fig. 2f-right):
With switches Sk2, Sk3, and Sk1 ON, and Sk6, Sk2, and Sk5 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. If ik<0, body diodes of switches Sk1, Sk2, and Sk3 conduct. And if ik>0, switches Sk1, Sk2 and Sk3 conduct.

Switching state 3, for NT-Type (see Fig. 2f-left): with switches Sk1, Sk2, and Sk5 ON, and Sk3, Sk6, and Sk4 OFF, the output phase voltage is $-\frac{V_{DC}}{6}$. Switch Sk5 is ON, however, it does not affect load current path. If ik<0, body diodes of switches Sk1, Sk2, and Sk3 conduct. And if ik>0, switches Sk1, and Sk5 conduct.

Brief comparison of conduction losses between NNPC and NT-Type topologies are shown in Table III. According to Table I, Table II, Table III, and Fig. 2 in both topologies, only in 1A and 2B, the number of conduction devices are the same. In other states NNPC has one device more than NT-Type topology in conducting. Furthermore, conduction losses in NT-Type topology are lower than NNPC.
III. MODULATION TECHNIQUE AND COMPARISON NUMBER OF DEVICES AMONG SEVERAL EXISTING TOPOLOGIES

The modulation method used by NT-Type topology of this paper is the sinusoidal PWM, using three triangular carrier waveforms in in-phase disposition (IPD), alternative phase opposite disposition (APOD), and phase opposite disposition (POD) [16].

Comparison the number of devices among the conventional four level (including: FC, NPC, and CHB), NNPC, and NT-Type topologies is presented in Table IV. NT-Type has less number of components and complexities. Compared to four-level NPC, and NNPC the number of diodes has been reduced considerably and in comparison to four-level FC, proposed topology has less number of capacitors. Also, unlike four-level CHB, NT-Type does not need to have a transformer for isolated DC sources.

IV. SIMULATION RESULTS

To verify the possibility of the presented topology, a 0.5 MVA simulation model of the three phase NT-Type four level inverter has been established with MATLAB/Simulink. The system parameters are as follows: Input DC voltage: 3.3KV, 1.1KV DC source for flying capacitors, Output frequency: 60Hz, Switching frequency: 2 kHz, Output inductance: 5mH, Output load: 7.5Ω, Power factor: 0.8, Modulation index: 0.7, and Step simulation: 1μs. Figs. 4-6 indicate the output waveforms of NT-Type four level inverter consisting of output line to line voltage, phase voltage and three phase currents using IPD, APOD, and POD modulation methods. According to Figs. 4-6, the IPD modulation method has the best harmonic spectrum in line-to-line voltage and it is the better choice for NT-Type four level inverter. Comparison of THD in NT-Type inverter using IPD, APOD, and POD is shown in Table V.

<table>
<thead>
<tr>
<th>Modulation method</th>
<th>V(L-L) THD%</th>
<th>V(phase) THD%</th>
<th>Current THD%</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPD</td>
<td>24</td>
<td>41.34</td>
<td>4.45</td>
</tr>
<tr>
<td>APOD</td>
<td>34.7</td>
<td>41.37</td>
<td>4.65</td>
</tr>
<tr>
<td>POD</td>
<td>36.4</td>
<td>41.56</td>
<td>4.67</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper, a novel NT-Type four level inverter topology proposed for high power and medium voltage applications. Operating over a wide range of voltage without needing connecting power devices in series, high quality output voltage, less number of devices compared to other conventional four level and NNPC topologies, less conduction losses compared to classical and NNPC topologies, and ability of operation utilizing various industrial modulation methods are main advantages of proposed topology.
REFERENCES


