LEAKAGE CURRENT ELIMINATION IN TRANSFORMERLESS PHOTOVOLTAIC GRID-TIED INVERTERS WITH NEUTRAL POINT CLAMPED FULL-BRIDGE TOPOLOGIES

T. PRAVEEN KUMAR¹, CH. USHA SRI²
¹Pg Scholar Vaagdevi College Of Engineering Warangal Affiliated To Jntu Hyderabad
²Asst Professor Vaagdevi College Of Engineering Warangal Affiliated To Jntu Hyderabad

Abstract – Eliminating the leakage current is one of most important issues for transformerless inverters in grid connected photovoltaic applications. Due to the characteristics of low cost, smaller size weight and high efficiency the transformerless PV grid connected inverters have attracted more attention in the application of photovoltaic generation system. The technical challenge is how to keep the common mode voltage constant to reduce the leakage current. However, the leakage current through the parasitic capacitors and the utility grid is harmful. Neutral point clamped (NPC) topology is an effective way to eliminate the leakage current. In this paper, two kinds of basic switching cells, the positive neutral point clamped cell and the negative neutral point clamped cell are proposed to built NPC topologies, with a systematic method of topology generation given. A novel positive–negative point (PN-NPC) topology is analyzed with operational modes and modulation strategy. The PN-NPC topology exhibits similar leakage current with the full–bridge inverter with dc bypass (FB-DCBP) which is lower than that of the H5 topology. The performance of proposed topology is confirmed through simulation investigations.

Index terms - Common mode voltage, grid-tied inverter, neutral point clamped inverter, Photovoltaic(pv) generation system

I. INTRODUCTION

Due to the rapid increase in human population and limitation reserve of natural resources such as coal and fuel, solar power is considered to be better option to meet these challenges since it is naturally available, pollution free and inexhaustible. Besides, with the help of government incentives and decrease in PV module prices, grid-connected PV systems plays an important role in distributed power generation. The decrease in cost of PV system, the advancement of power electronics and semiconductor technology and incentives from government strongly encourage the growth of grid connected PV systems. Grid connected PV system can be classified into two categories: with and without transformer. Most of the PV systems are designed with transformer for safety purpose with galvanic isolation. Galvanic isolation ensures no injection of DC current into the grid and reduces the leakage current between PV module and grid. In DC side, high frequency transformer is used whereas bulky low frequency transformer is used in output side of the inverter. However, the transformer is big, heavy and expensive. Also, it reduces the overall frequency of the conversion stage. To overcome these problems, transformerless PV system is introduced.
Transformerless grid tied PV inverters such as full bridge topology shown in Fig. 1 have many advantages e.g., higher efficiency, lower cost, smaller size, and weight. However the common mode voltage of \( V_{AN} \) and \( V_{BN} \) may induce a leakage current flowing through the loop consisting of the parasitic capacitors (\( C_{PV1} \) and \( C_{PV2} \)), the filters, the bridge, and the utility grid [7], [8]. In an isolated topology, the loop for the leakage current is broken by the transformer, and the leakage current is very low. But in a transformerless topology, the leakage current is too high to induce serious safety [9] and radiated interference issues [8], [10]. Therefore, the leakage current must be limited within a reasonable margin. The instantaneous common-mode voltage \( V_{CM} \) in the full bridge topology shown in Fig. 1 is represented as follows [7]–[12]:

\[
V_{CM} = 0.5(V_{AN} + V_{BN})
\]

where \( V_{AN} \) and \( V_{BN} \) are voltages from mid-point A and B of the bridge leg to terminal N, respectively. In order to eliminate the leakage current, the common-mode voltage \( V_{CM} \) must be kept constant during all operation modes and many solutions have been proposed [7], [8], [10]–[12] as follows:

1) Bipolar sinusoidal pulse width modulated (SPWM) fullbridge type inverter topologies. The common-mode voltage of this inverter is kept constant during all operating modes [7], [13]. Thus, it features excellent leakage-current characteristics. However, both of the current ripples across the filter inductors and the switching losses are large. Therefore, the unipolar SPWM full-bridge inverters are attractive for its excellent differential mode characteristics such as higher dc-voltage utilization, smaller inductor current ripple and higher power efficiency.

2) Improved unipolar SPWM full-bridge inverters. The conventional unipolar SPWM full-bridge inverter is shown in Fig. 1. In the active modes, the common-mode voltage \( V_{CM} \) is equal to \( 0.5U_{pv} \). In the freewheeling modes, \( V_{CM} \) is equal to \( U_{pv} \) or zero depending on the leg mid-points (point A and B) connected to the positive or negative terminal of the input. Therefore, the common-mode voltage of conventional unipolar SPWM full-bridge inverter varies at switching frequency, which leads to high-leakage current [7], [13]. To solve this problem, new freewheeling paths need to be built, and they should separate the PV array from the utility grid in freewheeling modes [10]. A solution named highly efficient and reliable inverter concept (HERIC) topology is proposed in [13]. In the freewheeling modes of HERIC inverter, the inductor current flowing through \( S_5 \) and \( S_6 \); thus, PV array is disconnected from the utility grid. And two extended HERIC topologies are proposed in [11] and [12], respectively. The disconnection can also be located on the dc side of the inverter, such as the H5 topology [9]. Although these topologies mentioned earlier feature the simple circuit structure, the common mode voltage depends on both of the
parasitic parameters of the leakage current loop and
the voltage amplitude of the utility grid [8], which is
not good for the leakage current reduction.

To eliminate the leakage current completely, the
common mode voltage should be clamped to half of
the input voltage in the freewheeling mode to keep
$V_{CM}$ always constant [12]. An example solution is
OH5 topology as shown in Fig. 2(a). A switch $S_6$ and
a capacitor leg employed and $S_6$ turns on to let
$V_{CM}=0.5U_{PV}$ in freewheeling mode. Unfortunately,
there must be a dead time between the gate signals of
S5 and S6 to prevent the input split capacitor $C_{dc1}$
from short circuit. As a result, $V_{CM}$ varies in the dead
time, which still induces leakage current. Full-bridge
inverter with dc bypass (FB-DCBP) topology proposed in [7] is another solution, as given in Fig.
2(b). It exhibits no dead-time issue mentioned, and
the leakage current suppression effect only depends
on the turn-on speed of the independent diodes. But
FB-DCBP suffers more conduction losses from the
inductor current flowing through four switches in the
active mode. On the other hand, many power
converters, such as dc–dc converters, voltage-source
inverters, current-source inverters and multilevel
inverters, have been investigated from the basic
switching cells to constructing the topology. Both of
the OH5 topology and the FB-DCBP topology can be
regarded as the transformer less grid-tied inverters
with the same feature of neutral point clamped
(NPC). However, these topologies have not yet been
analyzed from the view of topological relationships
and switching cells. In this paper, a systematic
method is proposed to generate transformer less grid-
tied NPC inverter topologies from two basic
switching cells based on the arrangement of the
freewheeling routes. And a family of novel NPC
inverters is derived with high efficiency and excellent
leakage current performance. The paper is organized
as follows. In Section II, an NPC switching cell
concept is proposed with two basic cells, a positive
neutral point clamped cell (P-NPCC) and a negative
clamped cell (N-NPCC), respectively. A family of
NPC topologies is generated from the two basic
switching cells in Section III. In Section IV, one of
the new topologies is analyzed in detail with
operational principle, modulation strategy, and power
loss comparison with OH5 and FB-DCBP given.
Experimental results are presented in Section V, and
Section VI concludes the paper.

Fig. 2 Some of existing transformerless full-bridge inverter
topologies. (a) OH5. (b) FB-DCBP

II. NPC SWITCHING CELL CONCEPT

Based on the survey and analysis in Section
I, the principles of leakage current elimination can be
summarized as follows: 1) disconnect the PV array
from the utility grid in the freewheeling modes with a
switch; and 2) let the common mode voltage equal to
half of the input voltage in the freewheeling modes
with another switch. As a result, two basic NPC
switching cells are found with two extra switches
mentioned earlier combined with the original power switch to be used to build inverters instead of the original power switch. These two basic NPC switching cells, as shown in Fig. 3, are defined as P-NPCC which the clamp switch $S_3$ connected to the mid-point of the bridge with its collector, and N-NPCC which the clamp switch $S_3$ connected to the mid-point of the bridge with its emitter. There are three terminals in both of P-NPCC and N-NPCC ($P^+$) or ($N^+$), ($P^−$) or ($N^−$), and ($O_1$) or ($O_2$). To build a NPC inverter topology with cells mentioned, the following rules should be followed.

**Fig. 3.** Two basic NPC switching cells. (a) P-NPCC. (b) N-NPCC

**Rule 1:** Terminal ($O_1$) and ($O_2$) should be connected to the neutral point of the input split capacitors and the potential is

$$V(0_1) = V(0_2) = 0.5U_{pv},$$

where $U_{pv}$ is the voltage of PV array

**Rule 2:** The P-NPCC has its ($P^+$) and ($P^−$) to be connected to the positive terminal of PV array and output filter inductor, respectively. On the other hand, the N-NPCC has its ($N^−$) and ($N^+$) to be connected to the negative terminal of PV array and output filter inductor, respectively.

**Rule 3:** One NPCC at least should appear in each bridge leg. Because we have to have three switches to separate grid from the PV array and still maintain the inductor current a loop during freewheeling mode.

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**III. NPC TRANSFORMERLESS FULL-BRIDGE TOPOLOGIES DERIVED FROM NPCC**

**Family Of Novel Npc Full Bridge Topologies Generation:**

The universal topology structure of a single-phase transformerless full-bridge inverter is shown in Fig. 4 where “AU,” “AL,” “BU,” and “BL” are four leg switch modules of the full bridge inverter, respectively.

**Fig. 4.** Universal topology structure of single-phase transformerless full bridge inverter.

**Fig. 5.** A family of transformerless full-bridge NPC inverter topologies. (a) PN-NPC. (b) NP-NPC. (c) DP-NPC. (d) DN-NPC.

Conventional single-phase full-bridge inverter topology employs single power switch in each switch module. If there is only one P-NPCC or one N-NPCC employed in the inverter, the purpose of disconnecting both the positive and negative terminals of PV array from the utility grid during the freewheeling period can not be achieved. Therefore, two NPCCs should be employed in phase A and
phase B, respectively, the rest still employ the original power switches. As a result, a family of novel single-phase transformer less full-bridge NPC inverters is generated, as shown in Fig. 5. Fig. 5(a) shows the topology in which modules “AU” and “BL” employ P-NPCC and N-NPCC, respectively. Thus, this topology is named as PN-NPC inverter topology. Fig. 5(b) shows the topology in which modules “AL” and “BU” employ N NPCC and P-NPCC, respectively. So this topology is named as NP-NPC inverter topology. With the same principle, the dual P-NPCC (DP-NPC) and dual N-NPCC (DN-NPC) topologies are shown in Fig. 5(c) and (d), respectively.

IV. ANALYSIS OF THE PROPOSED PN-NPC TOPOLOGY AND COMPARISON WITH OTHER NPC TOPOLOGIES

To analyze the operation principle, the proposed PN-NPC topology is redrawn in Fig. 6

A. Modes of operation

The operation principle contains four operation modes in each period of utility grid as shown in Fig. 5 where, $V_{AN}$ is the voltage between terminal A and N, and $V_{BN}$ the voltage between terminal B and terminal N, and $V_{AB}$ is the differential mode voltage of the topology $V_{AB}=V_{AN}-V_{BN}$.

1) **Mode-I** is the active mode in the positive half period of the utility grid as shown in Fig. 5(a). In this mode the turn ON switches are $s1$, $s2$, $s5$ and $s6$ and remaining switches are turned off. The voltage across the phase A and B are $V_{AN}=V_{PV}$ and $V_{BN}=0$ thus $V_{AB}=V_{PV}$, and the common mode voltage is $V_{CM}=(V_{AN}+V_{BN})=0.5V_{PV}$.

2) **Mode-II** is the freewheeling mode in the positive half period of the utility grid as shown in Fig. 5(b). The activating switches in this mode are $s2$ and $s5$, the other remaining switches are turned off. The inductor current flows through the anti parallel diode of $s7$ and $s8$. Therefore, the voltage across the phase A and B are $V_{AN}=0.5V_{PV}$ and $V_{BN}=0.5V_{PV}$, thus $V_{AB}=0$, and the Common mode voltage is $V_{CM}=(V_{AN}+V_{BN})/2=0.5V_{PV}$.

3) **Mode-III** is the active mode in the negative half period of the utility grid, as shown in Fig. 5(c). The turn ON switches are $S_3$, $S_4$, $S_7$ and $S_8$ and the other switches are turned off. Even though the $S_7$ and $S_8$ are turned ON, there is no inductor current flowing through these two switches. The voltage across the phases are $V_{AN}=0$ and $V_{BN}=V_{PV}$, thus $V_{AB}=-V_{PV}$, and Common mode voltage is $V_{CM}=(V_{AN}+V_{BN})/2=0.5V_{PV}$.

4) **Mode-IV** is the freewheeling mode in the negative half period of the utility grid as shown in Fig. 5(d). The turned on switches are $S_7$ and $S_8$ and the other switches are turned OFF. The inductor current flows through the anti parallel diode of $S_2$ and $S_5$ and the
voltage across the phase A and B are \( V_{AN} = 0.5U_{PV} \), \( V_{BN} = 0.5U_{PV} \), thus, \( V_{BN} = 0 \) and the Common mode voltage is 
\[ V_{CM} = (V_{AN} + V_{BN})/2 = 0.5U_{PV} \].

Fig. 8. Equivalent circuits of operation modes (a) Active mode in the positive half period. (b) Freewheeling mode in the positive half period. (c) Active mode in the negative half period. (d) Freewheeling mode in the negative half period.

B. Comparison Of Npc Topologies

The calculated power losses on switches of the PN-NPC topology proposed, FB-DCBP topology [7] and oH5 topology [18], with the same parameters as that of the 1-kW prototypes given in Table I. On the other hand, the inductor losses in the three topologies are the same due to the same \( V_{AB} \) modulation. The numbers of power devices and isolated driving power are summarized in Table II.

From Table I, Table II, and Fig. 13, it can be seen that the power losses in PN-NPC inverter is much lower than that in FB DCBP because the voltage rating of some switches in PN-NPC topology are 600 V, half of that in FB-DCBP. The power loss in PN-NPC inverter is close to that in OH5 which with the least number of power device. However, PN-NPC inverter features lower leakage current than OH5 as analyzed above.

V. SIMULATION RESULTS

![Fig. 9 Simulation model of FB-DCBP topology]

(a) simulation results \( V_x, I_x, V_{BN}, V_{CM}, V_{AN} \)

(b) simulation results \( V_x, I_x, I_{LEAKAGE} \)

Fig 10 (a) Common-mode voltage in FB-DCBP topology (b) leakage current in FB-DCBP topology

A universal prototype of the three NPC topologies has been built up in order to verify the operation principle and compare their performances. The specifications of the NPC inverter topologies are listed in Table I. The measure point of leakage current is shown in Fig 4. The common-mode voltage and the leakage current waveforms of these three topologies in unified experimental conditions are
shown in Figs.10-12 respectively. Where \( v_g \) and \( i_g \) are grid voltage and grid-tied current, respectively. \( V_{AN} \) and \( V_{BN} \) are voltages of mid-point A and B to terminal N, respectively. \( V_{CM} \) is the common-mode voltage, which equals to 0.5(\( V_{AN} + V_{BN} \)). \( i_{Leakage} \) is the leakage current. The tested leakage current of FB-DCBP, oH5, and PN-NPC inverter are 3mA [Fig. 10(b)], 4.5mA [Fig. 11(b)], and 3mA [Fig. 12(b)], respectively. Therefore, the leakage current of FB-DCBP and PN-NPC is the same, and less than that of oH5. The drain–source voltage waveforms of switches in PN-NPC topology are shown in Fig. 13. where \( V_{ds3}, V_{ds4}, V_{ds7}, \) and \( V_{ds8} \) are drain–source voltages of \( S_3, S_4, S_7, \) and \( S_8, \) respectively. It can be seen that the voltage stresses of all the switches shown in Fig. 13(a) and Fig 13(b) are half of the input voltage. Furthermore, the maximum voltage stress on \( S_7 \) and \( S_8 \) are half of the input voltage. The experimental results are in accordance with the theoretical analysis well. Since PN-NPC topology uses more 600-V IGBT than the FB-DCBP topology, the conduction loss of the proposed PN-NPC topology is less. \( U_{dc1} \) and \( U_{dc2} \) are the voltages on the capacitors \( C_{dc1} \) and \( C_{dc2}, \) respectively. From Fig. 12(a), it can be seen that the output voltage \( V_{AB} \) has three levels as \( U_{PV}, 0, \) and \( -U_{PV}. \) It indicates that the PNNPC topology proposed is modulated with unipolar SPWM, and features as excellent differential-mode characteristic as FBDCBP and OH5 topologies under unipolar SPWM. Fig.14 shows the mid-point voltage waveforms of \( V_{dc1} \) and \( V_{dc2}. \) It can be seen that this voltage is well shared between these two divided capacitors.

Moreover, the power device loss of the PN-NPC topology is the lowest. Therefore, it could be a very good solution for singlephase transformerless grid-tied applications.
TABLE- I
PARAMETERS OF THE EXPERIMENTAL PROTOTYPE

<table>
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<tr>
<th>Parameters</th>
<th>Value</th>
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<td>Rated power</td>
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<tr>
<td>Input voltage</td>
<td>380~700 V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20kHz</td>
</tr>
<tr>
<td>Filter inductor $L_1,L_2$</td>
<td>3mH</td>
</tr>
<tr>
<td>Filter capacitor</td>
<td>0.47 uF</td>
</tr>
<tr>
<td>Grid voltage /frequency</td>
<td>230v/50HZ</td>
</tr>
<tr>
<td>1200V IGBT</td>
<td>IRG4PH40U</td>
</tr>
<tr>
<td>600V IGBT</td>
<td>SGH40N60UFD</td>
</tr>
<tr>
<td>1000V diode</td>
<td>MUR8100T</td>
</tr>
<tr>
<td>PV capacitors $C_{PV1},C_{PV2}$</td>
<td>0.1 uF</td>
</tr>
</tbody>
</table>

Fig. 12 Simulation model of proposed PN-NPC topology
(a) simulation results $V_g, I_g, I_{LEAKAGE}$
(b) Leakage current in PN-NPC topology

Fig. 13 Drain–source voltages in PN-NPC topology
(a) voltage stress on S3 and S4 switches
(b) voltage stress on S7 and S8 switches

Fig 14 capacitor divider voltages $V_{dc1}, V_{dc2}$
TABLE II
NUMBER OF POWER DEVICE COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>FB-DCBP</th>
<th>OH5</th>
<th>PN-NPC</th>
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<tr>
<td>IGBT(1200V)</td>
<td>4</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>IGBT(600V)</td>
<td>2</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Diode</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Isolated driving power</td>
<td>5</td>
<td>5</td>
<td>6</td>
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VI CONCLUSION

In this paper, the basic universal structure and operating characteristics of a single phase transformerless full bridge NPC inverter topologies with low leakage current based on the basic switching cells have been described by taking existing FB-DCBP,OH5 and proposed PN-NPC configurations. Suppression of leakage can be obtained by clamping the common mode voltage to a constant level and the excellent differential mode characteristics are achieved. Reactive power injection capability is the major advantage of future PV inverters. The proposed NPC topologies also have the capability of injecting reactive power, which is a major advantage of future PV inverters. Therefore, the NPC topology family is an attractive solution for transformerless grid-tied PV applications.

REFERENCES


T. PRAVEEN KUMAR received the B.Tech degree in electrical & electronics engineering from Vaagdevi Engineering College Warangal affiliated to JNTU Hyderabad in 2012. Currently he is pursuing M.Tech in power electronics from Vaagdevi College of engineering Warangal affiliated to JNTU Hyderabad Telangana India. His research interests include grid tied Photovoltaic systems and drives.

E-mail id: praveen.tumma234@gmail.com

CH. USHA SRI received the B.Tech & M.Tech degree in electrical and electronics engineering from Vaagdevi college of engineering Warangal affiliated to JNTU Hyderabad in 2008 and 2012 respectively. Currently she is working as Assistant professor in Vaagdevi College of engineering Warangal. Her research interests includes power converters Multi level inverters and drives.

E-mail id: cheralaushasree@gmail.com