Analysis of Hybrid MLI Based Active Power Filter Topology for PV Grid-Tied Systems

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Abstract—This paper proposes a hybrid cascaded multilevel inverter topology for active power filter (APF) applications. This topology is a combination of a cascaded H-bridge multilevel inverter (MLI) and the three-phase interconnected VSI topology. The combination is achieved by using open-end windings. The proposed APF topology used to compensate the unwanted harmonic contents generated by the nonlinear load and hence reduce the THD of the grid currents. Closed-loop control for APF is proposed to perform this function. The proposed control scheme can be used to compensate the unwanted harmonics as well as used to suppress the reactive currents so that the unity power factor at the point of common coupling (PCC) can be achieved. The proposed APF system is simulated in a SIMULINK environment, and it is tested under nonlinear load for a photovoltaic (PV) grid-connected power system. The simulation results are presented to verify the proposed topology effectiveness and reliability.

Keywords—Multilevel Inverter, Active Power Filter, Solar Photovoltaic System, Total Harmonic Distortion, Power Quality.

I. INTRODUCTION

Traditional multilevel inverter (MLI) topologies have received great attention due to their advantages over the conventional two-level inverter topologies such as improving the voltage and current quality, reducing the filter sizes, reducing the switching frequency, improving the efficiency, etc. [1-4]. Cascaded H-bridge MLI is one of the multilevel inverter topologies that have proved to be an attractive solution for various applications, such as standalone systems [5], static reactive power (VAR) compensations, and grid-connected photovoltaic (PV) systems [6, 7]. The cascaded H-bridge inverter has a simple layout, extreme modularity, a simple construction, control, and no voltage balance problems, and compared with the other multilevel topologies, it requires the fewest components for generating the same voltage levels [8]. Cascaded H-bridge MLI is an attractive solution for a grid-connected PV system. DC sources can be replaced with a PV module/panel, and due to the separated DC-link feature, voltage control is possible. However, if more levels are required to improve the current and voltage’s quality, the number of components can be increased. Increasing the number of switches can lead to an increase in the cost, the conduction, and the switching losses, thus reducing the system efficiency. In addition, with increasing the number of switches, the control system will be more complex.

Many modified topologies based on cascaded-H bridge MLI have been proposed to increase the number of voltage levels by reducing the components counts as in [6, 9]. However, the advantages of the CHB are lost, such as simplicity, simple construction, simple control, and modularity. In addition, hybrid topologies based on CHB and three-leg two-level topologies have been proposed [10, 11]. However, in these topologies, the CHB advantages described above are lost. In addition, the H-bridges are connected to floating capacitors whose voltages should be controlled carefully to be maintained at required asymmetrical values. This adds more complexity to the control algorithm. Therefore, a new multilevel inverter topology conjoins the cascaded H-bridge MLI topology and the cascaded three-phase two-level VSI topology is proposed by the authors [12]. In addition, this new topology has been lastly patented as seen in [12]. This combination generates a higher number of voltage levels with a lesser number of components compared to conventional MLI configurations at the same level. This combination has been achieved by combining both topologies using open-end winding transformers. The proposed topology can be used for various applications such as grid-connected photovoltaic applications, static VAR combination, active power filter, etc. The proposed topology of [12] is used for APF applications in this paper.

Recently, the researches in developing APF applications have been increased, especially using renewable energy resources [13, 14][15-17]. APFs are power electronic devices, which can be accurately used to eliminate the harmonic contents in the current. Power system harmonics are created by non-linear loads connected to the public grid. Some of these loads are computers with switched-mode power supply, motor drives, electronic light ballasts, fax machines, medical equipment, etc. These harmonics may cause unwanted effects such as heating of sensitive electrical equipment, heating of the generators and transformers that lead to increased core loses and maybe cause the failure of transformers, malfunction of sensitive equipment, random tripping of circuit breakers, flickering lights, high neutral currents due to zero sequence harmonics, losses in conductors, etc [18, 19]. Therefore, these harmonics must be suppressed. Two types of harmonic filters can be used; passive or active filters. Passive filters are known to cause resonance with other system parameters, which may affect the power system stability. In addition, the performance of the passive power filters is affected by the variations of the
frequency of the power system. Therefore, active filters can be used instead of passive filters. APFs are characterized by their robustness in eliminating the undesired harmonics [4]. The basic principle of the APF as seen in Fig. 1 is to use power electronics technologies to generate specific current components that cancel the harmonic current components caused by the nonlinear load. APFs have several advantages over the passive filters. Such as, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems [18, 20, 21]. Consequently, the APFs performances are independent of the power distribution system properties.

This paper proposes a hybrid MLI topology for APF applications. A control scheme is proposed in this study to control the proposed APF. The proposed hybrid topology is used to compensate the harmonic currents of the nonlinear load while the grid supplies the fundamental positive sequence currents of the load. This paper is organized as follows: the proposed MLI-APF topology and the mathematical modeling are described in section 2; in section 3, the simulation results are provided and discussed.

II. THE PROPOSED MULTILEVEL BASED ACTIVE POWER FILTER TOPOLOGY

The proposed multilevel inverter-based APF (MLI-APF) topology is shown in Fig. 2. As shown in this figure, the proposed MLI is used to supply the extracted PV power to the nonlinear loads as well as to inject the power into the grid. The idea is to compensate for the harmonics generated by the nonlinear loads and at the same time supply balanced three-phase currents to the grid.

The control scheme proposed in [22] is extended to be used for the proposed APF in this paper. The proposed control scheme is used to inject balanced three-phase low harmonic currents into the grid. If the three-phase loads are not linear, the load currents will contain harmonics, which may reduce the current quality of the grid. Therefore, the harmonic contents of the load currents must be extracted in order to be compensated by the multilevel inverter. Consequently, the grid current will be balanced and contains low harmonic contents. The current of the nonlinear loads may contains positive, negative, and zero sequence harmonics. Therefore, the following steps will be considered:

1. Extract the fundamental positive sequence component of the load current using the following:

\[
\begin{bmatrix}
    i_{Lzero} \\
    i_{Lpos} \\
    i_{Lneg}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
    1 & 1 & 1 \\
    1 & a & a^2 \\
    1 & a^2 & a
\end{bmatrix} \begin{bmatrix}
    i_{La} \\
    i_{Lb} \\
    i_{Lc}
\end{bmatrix}
\]

where \(i_{Lzero}, i_{Lpos}, \) and \(i_{Lneg}\) are the zero, positive, and negative components of the load currents, respectively. \(i_{La}, i_{Lb}, \) and \(i_{Lc}\) are the load currents in phases \(a, b,\) and \(c\) respectively.

2. The maximum value of the fundamental component of the load current is extracted and the harmonic contents of the load currents can be extracted using:

\[
\begin{bmatrix}
    i_{LA(harm)} \\
    i_{LB(harm)} \\
    i_{LC(harm)}
\end{bmatrix} = i_{Lpos, max} \begin{bmatrix}
    \sin (0) \\
    \sin (60) \\
    \sin (120)
\end{bmatrix} - \begin{bmatrix}
    i_{La} \\
    i_{Lb} \\
    i_{Lc}
\end{bmatrix}
\]

where \(i_{LA(harm)}, i_{LB(harm)}, \) and \(i_{LC(harm)}\) are the extracted harmonic components of the load currents of phases \(a, b,\) and \(c\) respectively.

The extracted harmonic components of the load currents are then converted into dq frame as shown in Fig. 3.

From another point of view, the main aim of the inverter controller is to generate the reference currents to provide only available active power at the DC links to the grid with zero reactive power in order to guarantee unity power factor. The DC-links \(C_{dcA}, C_{dcB}, C_{dcC}\) and \(C_3\) share the same active grid current of phase \(a\). On the other hand, the DC-links \(C_{dcB}, C_{dcC}, C_{dcA}\) and \(C_4\) share the same active grid current of phase \(b\). In addition, the DC-links \(C_{dcC}, C_{dcA}, C_{dcB}\) and \(C_5\) share the same active grid current of phase \(c\). The DC-link voltages of these capacitors are compared with their respective reference voltages.

The DC-link voltage controllers of the proposed topology can be seen in Fig. 4. The reference active current of the grid can be given as:

\[
i_{dref} = \frac{2}{3} \frac{u_{dcA}}{V_{max}} V_{dca} + \frac{2}{3} \frac{u_{dcB}}{V_{max}} V_{dcb} + \frac{2}{3} \frac{u_{dcC}}{V_{max}} V_{dcd}
\]

(3)

where: \(V_{max}\) is the maximum value of the grid voltage, \(u_{dc}\) is the resulting signal from the PI controller, \(V_{dca}, V_{dcb}, V_{dcd}\) are the reference voltages of the DC-link capacitors of phases \(A, B,\) and \(C\) respectively.

As presented from (3), the resulting signal from the DC-link controllers is the reference active current of the inverter, \(i_{dref}\. Therefore, the harmonic load current in the \(d\) axes \(i_{Ld(harm)}\) given from (2) is then added to the \(i_{dref}\) generated form the DC-link controllers. The total reference inverter currents are given as:

\[
i_{drefTOT} = i_{dref} + i_{Ld(harm)}
\]

\[
i_{qrefTOT} = i_{Lq(harm)}
\]

Equation (4) states that the reference active current of the inverter equals the active current produced by the DC-links and the active harmonic load current.
Fig. 2: The proposed MLI-based APF topology.

According to the proposed control scheme, two cases can be applied:

1. **The proposed MLI acts as an active filter only:**

   The reference currents of the inverter are the harmonic load currents. The inverter is responsible to compensate the harmonic load currents while the grid then supplies the fundamental positive sequence currents of the load.

2. **If the proposed MLI is responsible to deliver the PV power to the grid and the load:**

   The control system forces the inverter to supply the balanced positive sequence current to the grid and, in addition, supplies the active load current and at the same time compensates harmonic load currents.

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**Fig. 3: Extraction of the load harmonic currents.**

**Fig. 4: The proposed control scheme.**
The load current harmonics are then transferred into dq frame. These currents are then used as reference MLI currents, which are then used in the current controller in Fig. 5. The resulting signals from Fig. 5 are transformed into abc reference signals \( (M_a, M_b, \text{ and } M_c) \). These signals are then used to generate switching pulses to drive the IGBTs of the proposed hybrid multilevel inverter by comparing them with the triangular carrier waveforms as shown in Fig. 6.

To generate the required pulses for the IGBTs of stage 1, the carrier waveform of \( H_{a1} \) is shifted from the \( H_{a2} \) by \( 180^\circ / N \), where \( N \) in the number of cascaded H-bridge cells per phase. Only the carrier waveforms of phase a in stage 1 are displayed in Fig. 2. Moreover, the modulation waveforms \( M_a, M_b, \text{ and } M_c \) are also used to fire the IGBTs of the stage 2 in the proposed configuration by comparing them with the phase-shifted carrier waveforms as seen in Fig. 2. The carrier waveform which is used to generate the pulses of unit 2 is shifted by \( (T/3) \) from that of unit 1, and the carrier waveform of unit 3 is shifted by \( (T/3) \) from that of unit 2.

III. SIMULATION RESULTS AND DISCUSSION

The proposed ML-APF topology is modeled in the SIMULINK environment. For simplicity, two H-bridge cells are used per phase in the proposed topology. The system consists of twelve HIT-N220A01 PV modules; six of them are connected to the stage 1 of the proposed topology. On the other hand, the other six PV modules are connected to the stage 2 of the proposed topology.

As mentioned in the previous section, two cases can be applied. Only case 1 is considered in the simulation results.

The grid is responsible to supply the balanced three-phase currents to the non-linear load; and the proposed multilevel inverter is controlled to only compensate the harmonic currents of the load. The values of the nonlinear load parameters are \((R_{L1} = R_{L2} = 48\Omega, \ X_{L1} = X_{L2} = 154\ m\Omega)\). In order to allow the grid to supply the active power to the load, the duty cycle of the DC-DC converter is kept constant at 0.3 (No MPPT is used). The DC-link voltages are regulated to 40 V. The PV module parameters are shown in Table I while the system parameters are shown in Table II.

The three-phase nonlinear load currents can be seen in Fig. 7, while the three-phase low harmonized grid currents can be seen in Fig. 8. As demonstrated in Fig. 8, the grid currents are balanced and the nonlinear load was not affected the grid currents.

On the other hand, the harmonic currents extracted from the nonlinear load currents can be seen in Fig. 9(a). These currents act as reference currents of the multilevel inverter. The multilevel inverter currents follow these currents as revealed in Fig. 9(b). The control scheme succeeds in keeping the grid currents in phase with the grid voltages as seen in Fig. 10. The grid currents are shown out of phase with the grid voltages because the grid is responsible to supply the active power to the load (default current measurements measure currents flowing from the inverter into the grid). In addition, the THD of the grid current \( i_\text{grid} \) is 4.2% that has an acceptable harmonic content of less than 5% defined by IEEE standard as revealed in Fig. 10. Comparing the THD of the grid current of the proposed APF with that THD of the grid.

### TABLE I. THE PV MODULE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (P_{max})</td>
<td>245W</td>
</tr>
<tr>
<td>Maximum Power Voltage (V_{max})</td>
<td>28.8V</td>
</tr>
<tr>
<td>Maximum Power Current (I_{max})</td>
<td>8.5A</td>
</tr>
<tr>
<td>Open Circuit Voltage (V_{oc})</td>
<td>31.5V</td>
</tr>
<tr>
<td>Short Circuit Current (I_{sc})</td>
<td>9.5A</td>
</tr>
</tbody>
</table>

### TABLE II. THE SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-Link Capacitor</td>
<td>4mF</td>
</tr>
<tr>
<td>Connection Inductor L_s</td>
<td>4.2mH</td>
</tr>
<tr>
<td>Ćuk switching frequency f_s</td>
<td>30kHz</td>
</tr>
<tr>
<td>Grid rated RMS voltage</td>
<td>80V</td>
</tr>
<tr>
<td>Reference voltage each DC-link capacitor</td>
<td>40V</td>
</tr>
<tr>
<td>Inverter switching frequency f_{inv}</td>
<td>1.5kHz</td>
</tr>
</tbody>
</table>

Fig. 5: The current controller.

Fig. 6: Phase-shifted PWM technique.
current if only 4.2mH interface inductor is used without using APF, the THD without using APF is 17.17% as seen in Fig. 12, which is much more than the acceptable harmonic content defined by IEEE standard.

![Fig. 7: The load currents.](image)

![Fig. 8: The grid currents.](image)

![Fig. 9: (a): The harmonic load currents. (b): The active power filter currents.](image)

![Fig. 10: The grid currents in phase with the grid voltages.](image)

![Fig. 11: Harmonic spectrum of the grid current $i_a$ using APF.](image)

![Fig. 12: Harmonic spectrum of the grid current $i_a$ without using APF.](image)

IV. CONCLUSION

This paper proposed a new topology based on a cascaded H-bridge multilevel inverter to be used for APF applications. A control scheme is proposed to execute the proposed topology for APF application. The proposed MLI-based APF is used to compensate the harmonic load currents while the grid supplies the fundamental positive sequence currents of the load. The proposed APF topology is simulated using the MATLAB Simulink environment. The nonlinear load is implemented by using a three-phase diode bridge circuit connected to the resistive inductive loads. The simulation results show that the proposed APF is well functioning in...
eliminating the unwanted harmonics generated by the nonlinear load, and the THD of the grid currents has obtained an acceptable harmonic content less than 5% defined by IEEE standard.

ACKNOWLEDGMENTS

This work was supported by the National Plan for Science, Technology, and Innovation, King Abdullah City for Science and Technology, Kingdom of Saudi Arabia, Award Number (13-ENE1157-02).

REFERENCES


