Cascaded H-Bridge MLI and Three-Phase Cascaded VSI Topologies for Grid-Connected PV Systems with Distributed MPPT

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AC cascaded multilevel inverter topologies have received a great deal of attention for grid-connected PV systems. In this paper, three-cascaded multilevel inverter configurations are proposed for grid-connected PV applications. These are the three-phase cascaded H-bridge multilevel inverter topology, three-phase cascaded voltage-source inverter topology using inductors, and three-phase cascaded voltage-source inverter topology using coupled transformers. Distributed maximum power point tracking (MPPT) of PV modules using perturbation and observation algorithm is used for all presented topologies. In all presented configurations, each PV module is connected to one DC-DC isolated Ćuk converter for best MPPT achievement. Simulation is achieved by using the SIMULINK environment. The simulation results show that the three proposed topologies function well in improving the grid’s power quality. The grid currents are kept in phase with the grid voltage to ensure unity power factor, and the THD of the grid currents are within the acceptable range. The proposed topologies are experimentally implemented in the lab, and the switching pulses are generated with the help of the MicroLabBox data acquisition system. Comparing the three topologies according to the number of switches, voltage, and current stresses on switches and THD of the generated voltages and grid currents and according to the efficiency has been achieved in this paper, both experimentally and by simulation. The simulation and experimental results and comparisons are presented to verify the proposed topologies’ effectiveness and reliability.

1. Introduction

According to the interconnection of the photovoltaic (PV) inverters in the grid, four types of topologies are possible. These are the centralized inverter topology, string inverter topology, multistring inverter topology, and AC module topology. All of these topologies are shown in Figures 1(a)–1(d), respectively. They each have merits and demerits compared to each other. AC module topology is based on using one PV module per converter; therefore, it is the most modular and has the best MPPT capability. Any mismatching between PV modules can be removed using the AC module inverter topology. In addition, it is easy to enlarge by simply adding one PV module connected to one converter. Another advantage is that it can be used by persons without knowledge of electrical installations [1]. Due to the advantages of the AC module topology, it will be used in the proposed topologies of this paper.

Recently, many multilevel inverter (MLI) topologies have been proposed and have gained attention in many applications, especially in grid-connected PV applications [2]. The most common MLI topologies can be classified into three
types: neutral-point MLI, flying capacitor MLI, and cascaded H-bridge (CHB) MLI.

Cascaded MLI features have gained attention as an attractive solution for many applications, such as use of CHB MLI in standalone systems, static VAR compensations, and grid-connected PV system [3–14].

The topology presented in [12] is an example of string inverter topology described in Figure 1(b). The authors proposed a three-phase cascaded H-bridge MLI and PV strings. The topology enables a large increase of the total power capacity of the PV system. However, this system is based on the string inverter topology in which multiple PV strings are connected to an H-bridge cell, and the H-bridge cells are then cascaded to generate multilevel voltage. Therefore, this type of topologies suffers from poor MPPT because of partial shading and module mismatch.

The topology presented in [8] is an example of multi-string inverter topology that is described in Figure 1(c). The presented configuration consists of string PV modules that are connected to one DC-DC converter and then to the H-bridge cell. Three H-bridge cells were cascaded to generate seven-level voltage. The DC-DC converter is responsible for tracking MPP and for amplifying the DC voltage if needed. This system suffers from the same disadvantages of not accurately tracking the MPP of the PV modules. In addition, the power rating of the DC-DC converter will be high, which increases the system cost. From another point of view, an example of the AC module inverter topology shown in Figure 1(d) is presented in [5]. The authors presented a modular cascaded H-bridge multilevel PV inverter for three-phase grid-connected applications. The AC module inverter topology uses only one PV module for each H-bridge cell. To realize the improved use of PV modules, and to maximize solar energy extraction, a distributed maximum power point tracking control scheme is applied to the three-phase multilevel inverter, which allows for the independent control of each DC-link voltage. With increasing the number of PV modules, the number of H-bridges is increased. The AC module topology is very suitable to improve system efficiency, since the best utilization of PV modules could be obtained; however, the system will be costly and the control will be complex if the number of PV modules increases.

Another type of cascaded MLI topology is based on the conventional two-level voltage-source inverter (VSI). It has been used in many motor-drive applications [15, 16]. This cascaded MLI can also be used for grid-connected renewable energy applications [15–17]. The authors in [15] used this topology to connect the wind farm to the grid, whereas others [17] used the three-phase cascaded VSI for grid-connected PV applications. However, the three-phase currents in each unit are not balanced, which means the current stresses on each leg are not equal. The authors [18] solved the problem of unbalanced three-phase currents in each unit by using intermediate transformers instead of inductors. However, the intermediate transformers are bulky [19].

In this paper, three-cascaded multilevel inverter configurations are used for grid-connected PV applications. These are the three-phase cascaded H-bridge MLI topology, three-phase cascaded VSI topology using inductors, and three-phase cascaded VSI topology using coupled transformers. Distributed maximum power point tracking is used for all presented topologies. The AC module inverter topology has a great advantage in fully optimizing the MPPT. Therefore, the AC module inverter topology is considered for all presented topologies in which only one PV module is considered for every DC-DC converter. The presented topologies are built in the SIMULINK environment and simulated with a grid interface. In order to validate the quality performance of the presented topologies as well as accurate control, the three topologies are experimentally implemented in the lab, and the switching pulses are generated with the help of the MicroLabBox data acquisition system. The presented
topologies have been compared to each other by simulation and experiment. The experimental results have verified the effectiveness and reliability of the proposed topologies.

2. Description of the Proposed Configurations

Three-cascaded multilevel inverter topologies are considered in this paper:

2.1. Three-Phase Cascaded H-Bridge MLI. The proposed configuration is a multilevel inverter consisting of two power-processing stages: DC-DC converter and inverter. The proposed configuration is shown in Figure 2. As shown in this configuration, each PV module is connected to one DC-DC converter—unlike the AC module inverter topology described in [5], in which each PV module is connected to one H-bridge for optimal MPP tracking. This in turn can lead to increasing the total system cost and increasing the switching losses. The DC-DC converter is able to track MPP for each PV module and hence improve efficiency and for voltage amplification if needed. In this paper, the DC-DC isolated Ćuk converter is used. The presence of a high-frequency isolation transformer within the DC-DC converter is for safety purposes. In addition, it is known that the H-bridge suffers from leakage current that may be introduced due to the presence of parasitic capacitance between the PV panel and the earth. This leakage current will cause distortion to the grid current, higher losses, and safety and electromagnetic interference problems. Therefore, the galvanic isolation will solve this problem and prevent leakage current.

2.2. Three-Phase Cascaded Voltage-Source MLI Using Inductors. The proposed three-phase cascaded VSI topology is displayed in Figure 3. The system is used for grid-connected PV applications and consists of the three two-level VSI units. The three units are then connected in such a manner as to generate seven-level line-to-line voltage as mentioned in the Introduction. The circulating current is limited by using a current-limiting inductor \( L_s \). Each VSI unit is connected to PV modules via the DC-DC isolated Ćuk converter. Each PV module is connected to one DC-DC Ćuk converter. The DC-DC converter is responsible for tracking MPP and for isolation purposes.

2.3. Three-Phase Cascaded Voltage-Source MLI Using Coupled Transformers. The proposed three-phase cascaded voltage-source inverter topology is seen in Figure 4. This system consists of the three two-level voltage-source inverter units. The three units are then connected in such a manner as to generate seven-level line-to-line voltage. This topology was proposed to solve the unbalanced three-phase currents inside each two-leg unit of the topology depicted in Figure 3. The authors [18] solved the problem of unbalanced three-phase currents in each unit by using intermediate transformers instead of inductors. The coupled transformers are characterized by their high magnetization inductance, which reduces the circulating current inside the converter.

Each VSI unit is connected to PV modules via the DC-DC isolated Ćuk converter. Each PV module is connected to one DC-DC Ćuk converter. The DC-DC converter is responsible for tracking MPP and for isolation purposes.

3. Analysis of the Proposed Topologies

3.1. Three-Phase Cascaded H-Bridge MLI Topology

3.1.1. Voltage Relationships. The phase voltage of each cascaded H-bridge inverter in phase \( a \) is given as

\[
v_{AN} = N m_a V_{dcH} \sin \omega t,
\]

where \( N \) is the number of H-bridges connected to each phase, \( V_{dcH} \) is the DC-link voltage for each H-bridge, and \( m_a \) is the modulation index.

The phase voltage of each cascaded H-bridge inverter of the phases \( b \) and \( c \) can be given as

\[
\begin{align*}
v_{BN} &= N m_a V_{dcH} \sin (\omega t - 120^\circ), \\
v_{CN} &= N m_a V_{dcH} \sin (\omega t + 120^\circ).
\end{align*}
\]

On the other hand, by applying Kirchhoff’s voltage law, the line-line voltages are given as

\[
\begin{align*}
U_{AB} &= (juL_s)i_a + v_{AB} - (juL_s)i_b, \\
U_{BC} &= (juL_s)i_b + v_{BC} - (juL_s)i_c, \\
U_{CA} &= (juL_s)i_c + v_{CA} - (juL_s)i_a,
\end{align*}
\]

where

\[
\begin{align*}
v_{AB} &= v_A - v_B, \\
v_{BC} &= v_B - v_C, \\
v_{CA} &= v_C - v_A, \\
v_A &= \sqrt{2}V \sin \omega t, \\
v_B &= \sqrt{2}V \sin (\omega t - 120^\circ), \\
v_C &= \sqrt{2}V \sin (\omega t + 120^\circ),
\end{align*}
\]

where \( V \) is the RMS phase voltage of the grid and \( \omega \) is the frequency of the voltage in radians. \( i_a, i_b, \) and \( i_c \) are the currents injected to the phases \( a, b, \) and \( c \), respectively, of the grid.

3.1.2. Current Relationships. The current in each phase can be expressed as

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = \begin{bmatrix}
\sqrt{2}I \sin (\omega t) \\
\sqrt{2}I \sin (\omega t - 120^\circ) \\
\sqrt{2}I \sin (\omega t + 120^\circ)
\end{bmatrix},
\]

where \( I \) is the RMS grid current.
3.1.3. Power Relationships. The total apparent power of cascaded H-bridge cells of each phase can be given as

\[ \begin{align*}
VA_a &= V_a I_{a,rms} = \left( \frac{N_{ma}}{\sqrt{2}} V_{dcH} \right) I_{a,rms}, \\
VA_b &= V_b I_{b,rms} = \left( \frac{N_{ma}}{\sqrt{2}} V_{dcH} \right) I_{b,rms}, \\
VA_c &= V_c I_{c,rms} = \left( \frac{N_{ma}}{\sqrt{2}} V_{dcH} \right) I_{c,rms},
\end{align*} \]

where \( VA_a, VA_b, \) and \( VA_c \) are the apparent powers of phases \( a, b, \) and \( c, \) respectively.

The power of each H-bridge cell in one phase is equal, which can be given as

\[ VA_{cell} = V_x I_{x,rms} = \left( \frac{m_n}{\sqrt{2}} V_{dcH} \right) I_{x,rms}, \]

where \( x \) represents the phases \( a, b, \) or \( c \) and \( i \) represents the cell number. It should be noted that this equation is...
satisfactory if the DC-link voltage \( V_{\text{dcH}} \) of each H-bridge cell is equal.

3.2. Three-Phase Cascaded VSI Using Inductors

3.2.1. Voltage Relationships. The line-to-line voltages of the inverter are

\[
\begin{align*}
U_{AB} &= v_{a1b1} + v_{b1a2} + v_{a2b2}, \\
U_{BC} &= v_{b2c2} + v_{c2b3} + v_{b3c3}, \\
U_{CA} &= v_{c3a3} + v_{a3c1} + v_{c1a1}.
\end{align*}
\]  

(9)

In the ideal case, the circulating current is small and can be neglected. Therefore, the voltages across the coupling inductors in the lower configuration can be neglected. Equation (11) can be written as

\[
U_{AB} = \sqrt{3} m_a V_{\text{dc}}.
\]  

(10)

Therefore, the instantaneous line-to-line voltages can be given as

\[
\begin{align*}
v_{AB} &= \sqrt{3} m_a V_{\text{dc}} \sin wt, \\
v_{BC} &= \sqrt{3} m_a V_{\text{dc}} \sin (wt - 120^\circ), \\
v_{CA} &= \sqrt{3} m_a V_{\text{dc}} \sin (wt + 120^\circ),
\end{align*}
\]

(11)

where \( V_{\text{dc}} \) is the DC-link voltage of each VSI unit.

The line-to-line voltages at the grid side can be represented by equations (3)-(5).

3.2.2. Current Relationships. In order to obtain the current equations of the system, subtracting \( U_{CA} \) from \( U_{AB} \) in (9), one gets

\[
\begin{align*}
(U_{AB} - U_{CA}) + V_{AA} &= v_{b1a2} - v_{a3c1}, \\
(U_{BC} - U_{AB}) + V_{BB} &= v_{c2b3} - v_{b1a2}, \\
(U_{CA} - U_{BC}) + V_{CC} &= v_{a3c1} - v_{c2b3},
\end{align*}
\]

(12)

where

\[
\begin{align*}
V_{AA} &= v_{c3a2} + v_{c1a1} - (v_{a1b1} + v_{a2b2}), \\
V_{BB} &= (v_{a1b1} + v_{a2b2}) - (v_{b2c2} + v_{b3c3}), \\
V_{CC} &= (v_{b2c2} + v_{b3c3}) - (v_{c3a3} + v_{c1a1}).
\end{align*}
\]

The grid currents can be given as

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} =
\begin{bmatrix}
i_{a1} \\
i_{b2} \\
i_{c3}
\end{bmatrix}.
\]  

(14)

On the other hand, the phase currents of each VSC unit of Figure 3 satisfy the following equations:

\[
\begin{bmatrix}
i_{a1} + i_{b1} + i_{c1} \\
i_{a2} + i_{b2} + i_{c2} \\
i_{a3} + i_{b3} + i_{c3}
\end{bmatrix} = 0.
\]  

(15)

In addition, the currents inside the VSI of Figure 3 have the following relationships:

\[
\begin{bmatrix}
i_{b1} \\
i_{c2} \\
i_{a3}
\end{bmatrix} = -
\begin{bmatrix}
i_{a1} \\
i_{b2} \\
i_{c3}
\end{bmatrix}.
\]  

(16)

From (15) and (16), we get

\[
\begin{align*}
i_{a1} &= -(i_{b1} - i_{a3}), \\
i_{b2} &= -(i_{c2} - i_{b1}), \\
i_{c3} &= -(i_{a3} - i_{c2}).
\end{align*}
\]  

(17)

Modifying (12) and (13) can get

\[
(U_{CA} - U_{AB}) + V_{AA} = L_x \frac{d(i_{a1})}{dt} = j\omega L_x (i_a).
\]  

(18)
Therefore:
\[ i_a = \frac{(U_{CA} - U_{AB}) - V_{AA}}{j\omega L_x}, \]
\[ i_b = \frac{(U_{AB} - U_{BC}) - V_{BB}}{j\omega L_x}, \]
\[ i_c = \frac{(U_{BC} - U_{CA}) - V_{CC}}{j\omega L_x}. \] (19)

Equation (19) defines the phase currents injected into the grid.

In addition, the phase currents flowing in the inductors can be defined as
\[ i_{b1} = \frac{i_b - i_a + (v_{bic1} + v_{a3b3} + v_{c2a2})/j\omega L_x}{3}, \]
\[ i_{c2} = \frac{i_c - i_b + (v_{bic1} + v_{a3b3} + v_{c2a2})/j\omega L_x}{3}, \] (20)
\[ i_{a3} = \frac{i_a - i_c + (v_{bic1} + v_{a3b3} + v_{c2a2})/j\omega L_x}{3}, \]
where \( i_a, i_b, \) and \( i_c \) are the phase currents of the phases a, b, and c, respectively, and their values could be obtained from (19).

3.2.3. Power Relationships. The apparent powers of units 1, 2, and 3 are
\[ V_Ac_1 = \sqrt{3}V_{a1b1}I_{a,rms} = \sqrt{3}\left(\frac{\sqrt{3}}{2\sqrt{2}}m_aV_{dc}\right)I_{a,rms} \]
\[ = \left(\frac{3}{2\sqrt{2}}m_aV_{dc}\right)I_{a,rms}, \]
\[ V_Ac_2 = \sqrt{3}V_{a2b2}I_{b,rms} = \sqrt{3}\left(\frac{\sqrt{3}}{2\sqrt{2}}m_aV_{dc}\right)I_{b,rms}, \] (21)
\[ V_Ac_3 = \left(\frac{3}{2\sqrt{2}}m_aV_{dc}\right)I_{c,rms}. \]

3.3. Three-Phase Cascaded VSI Using Coupled Transformers

3.3.1. Voltage Relationships. The line-to-line voltages of the inverter are
\[ U_{AB} = v_{a1b1} + v_{bic2} + v_{b1a2}, \]
\[ U_{BC} = v_{b2c2} + v_{c2a2} + v_{b3c3}, \]
\[ U_{CA} = v_{c3a3} + v_{a3c1} + v_{c1a1}. \] (22)

Due to the transformer action,
\[ v_{bic2} = v_{a3b3}. \] (23)

Substituting (23) into (22), we get
\[ U_{AB} = \frac{\sqrt{3}}{2\sqrt{2}}m_aV_{dc} + \frac{\sqrt{3}}{2\sqrt{2}}m_aV_{dc} + \frac{\sqrt{3}}{2\sqrt{2}}m_aV_{dc} \]
\[ = \frac{3\sqrt{3}}{2\sqrt{2}}m_aV_{dc}, \]
where \( V_{dc} \) is the DC-link voltage across each VSI unit.

In addition, equation (22) can be written as
\[ v_{AB} = \sqrt{3}\frac{m_a}{2}V_{dc}\sin wt, \]
\[ v_{BC} = \sqrt{3}\frac{m_a}{2}V_{dc}\sin (wt - 120^\circ), \] (25)
\[ v_{CA} = \sqrt{3}\frac{m_a}{2}V_{dc}\sin (wt + 120^\circ). \]

The line-to-line voltages at the grid side can be represented by the equations (3)-(5).

3.3.2. Current Relationships. The line currents injected to the grid can be given as
\[ i_{a1} + i_{b1} + i_{c1} = I < 0 \]
\[ i_{a2} + i_{b2} + i_{c2} = 0, \]
\[ i_{a3} + i_{b3} + i_{c3} = 0. \] (27)

In addition, the currents of each unit in the configuration of Figure 4 can be expressed as
\[ i_{a1} = i_{a2} = i_{a3} = i_y - i_x, \]
\[ i_{b1} = i_{b2} = i_{b3} = i_x - i_z, \]
\[ i_{c1} = i_{c2} = i_{c3} = i_z - i_y, \] (28)
where \( i_x, i_y, \) and \( i_z \) are the currents flowing in the primary windings of the coupled transformers as shown in Figure 4.

Assuming the magnetizing inductance of the coupled transformers is high enough that the circulating current is zero, therefore,
\[ i_x + i_y + i_z = 0. \] (29)
From (27), (28), and (29), the currents in each unit can be given as

$$
\begin{bmatrix}
    i_{a1} \\
    i_{b1} \\
    i_{c1}
\end{bmatrix} =
\begin{bmatrix}
    i_{a2} \\
    i_{b2} \\
    i_{c2}
\end{bmatrix} =
\begin{bmatrix}
    i_{a3} \\
    i_{b3} \\
    i_{c3}
\end{bmatrix} =
\begin{bmatrix}
    I < 0^\circ \\
    I < -120^\circ
\end{bmatrix}.
$$

(30)

### 3.3.3. Power Relationships

The apparent powers of units 1, 2, and 3 are

$$
VA_{a1} = \sqrt{3}V_{a1b1}I_{a,rms} = \sqrt{3}\left(\frac{3}{2}\frac{m_a V_{dc}}{2}\right)I_{a,rms},
$$

$$
VA_{a2} = \sqrt{3}V_{a2b2}I_{b,rms} = \sqrt{3}\left(\frac{3}{2}\frac{m_a V_{dc}}{2}\right)I_{b,rms},
$$

$$
VA_{a3} = \sqrt{3}V_{a3b3}I_{c,rms} = \sqrt{3}\left(\frac{3}{2}\frac{m_a V_{dc}}{2}\right)I_{c,rms}.
$$

### 4. Simulation Setup and the Control Schemes

The three presented topologies described in Section 2 were built in the SIMULINK environment. For best MPPT achievement, the AC module inverter topology is considered. Each proposed configuration is a multilevel inverter consisting of two power-processing stages: DC-DC isolated converter and inverter. In configuration A, each H-bridge cell is connected into two DC-DC converters and one PV module is connected to each DC-DC converter. On the other hand, each unit in configurations B and C is connected to six DC-DC converters. The DC-DC converter is responsible for tracking MPP for one PV module; hence, optimal MPPT can be achieved. The isolated DC-DC converter is also used for galvanic isolation at high frequency. The three presented topologies are used for grid-connected PV systems. Eighteen PV modules are considered for each configuration. The system parameters used for the simulation are shown in Table 1, while Table 2 shows the PV modules’ parameters.

### 4.1. Control Scheme of the Cascaded H-Bridge MLI Topology

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 $C_{dcA1}$, $C_{dcA2}$, \ldots, $C_{dcAN}$ share the same active grid current of phase a. On the other hand, the DC links $C_{dcB1}$, $C_{dcB2}$, \ldots, $C_{dcBN}$ share the same active grid current of phase b. In addition, the DC links $C_{dcC1}$, $C_{dcC2}$, \ldots, $C_{dcCN}$ share the same active grid current of phase c. The DC-link voltages of these capacitors are compared with their respective reference voltages.

### Table 1: The system parameter.

| The system parameters used for simulation | 4 mF |
| Grid interface inductor $L_s$ | 4.2 mH |
| DC-DC Cuk converter switching frequency $f_s$ | 40 kHz |
| Inverter switching frequency $f_{inv}$ | 1.5 kHz |
| Grid-rated RMS voltage | 120 V |
| Reference voltage of configuration A | 70 V |
| Reference voltage of configuration B | 150 V |
| Reference voltage of configuration C | 110 V |

### Table 2: The PV module parameters.

| Maximum power ($P_{max}$) | 245 W |
| Maximum power voltage ($V_{max}$) | 28.8 V |
| Maximum power current ($I_{max}$) | 8.5 A |
| Open-circuit voltage ($V_{oc}$) | 31.5 V |
| Short-circuit current ($I_{sc}$) | 9.5 A |

Assuming that the control system accurately regulates the DC-link voltages, then

$$
V_{dcA} = V_{dcB} = V_{dcC} = V_{dctot},
$$

(32)

where $V_{dcA}$, $V_{dcB}$, and $V_{dcC}$ are the equivalent DC voltages across the DC-link capacitors connected to phases a, b and c, respectively.

The modeling technique is based on Kirchhoff’s law of the MLI in the dq frame, so that one gets

$$
V_d = L_s \frac{di_d}{dt} - (\omega L_s)i_q + d_{nd} V_{dctot},
$$

$$
V_q = L_s \frac{di_q}{dt} + (\omega L_s)i_d + d_{nq} V_{dctot},
$$

(33)

where $d_{nX}$ is defined as the sequential function and is given by

$$
\begin{bmatrix}
    d_{nA} \\
    d_{nB} \\
    d_{nC}
\end{bmatrix} =
\begin{bmatrix}
    C_A \\
    C_B \\
    C_C
\end{bmatrix} - \frac{1}{3}(C_A + C_B + C_C),
$$

(34)
where \( C_A, C_B, \) and \( C_C \) are the equivalent DC-link capacitors connected to phases a, b, and c, respectively.

The DC current can be defined as

\[
C_{\text{dc}} \frac{dV_{\text{detot}}}{dt} = d_{\text{nd}}i_d + d_{\text{mq}}i_q. \quad (35)
\]

A new equivalent model can be introduced to analyze the nonlinearity problems. These inputs may be written as

\[
\begin{align*}
    u_d &= (\omega L_s)i_q - d_{\text{nd}}V_{\text{detot}} + V_d, \\
    u_q &= -(\omega L_s)i_d - d_{\text{mq}}V_{\text{detot}} + V_q.
\end{align*} \quad (36)
\]

As stated above, the active current \( i_d \) is responsible for regulating the DC-link voltages and compensates for losses in the dissipative elements of the inverter. In addition, the reactive current \( i_q \) should be set to zero to guarantee unity power factor. Therefore, equation (35) can be written as

\[
\begin{align*}
    u_{\text{dc}} &= C_{\text{dc}} \frac{dV_{\text{detot}}}{dt} = d_{\text{nd}}i_d, \quad (37) \\
    i_d &= \frac{u_{\text{dc}}}{d_{\text{nd}}}, \quad (38)
\end{align*}
\]

In normal operation and under accurate current loop control, the following properties apply:

\[
V_d = d_{\text{nd}}V_{\text{detot}} = d_{\text{nd}}V_{\text{detot}} = \frac{\sqrt{2}}{2}V_{\text{max}}, \quad (39)
\]

where \( V_{\text{max}} \) is the maximum value of the grid voltage. Replacing (39) into (38), one gets

\[
i_d = \sqrt{\frac{2}{3}} \frac{u_{\text{dc}}}{V_{\text{max}}} V_{\text{detot}}. \quad (40)
\]

The \( i_d \) current is the active current, which is responsible for regulating the DC-link capacitors of each phase. From (40), the active reference current which is responsible for regulating the DC-link capacitors of phase a can be expressed as

\[
i_{dA} = \sqrt{\frac{2}{3}} \frac{u_{\text{dcA}}}{V_{\text{max}}} V_{\text{dcA}}. \quad (41)
\]

The reference active current of the grid is the sum of the three \( i_d \) active currents:

\[
i_{\text{dref}} = i_{dA} + i_{dB} + i_{dC} = \sqrt{\frac{2}{3}} \frac{u_{\text{dcA}}}{V_{\text{max}}} V_{\text{dcA}} + \sqrt{\frac{2}{3}} \frac{u_{\text{dcB}}}{V_{\text{max}}} V_{\text{dcB}} + \sqrt{\frac{2}{3}} \frac{u_{\text{dcC}}}{V_{\text{max}}} V_{\text{dcC}}. \quad (42)
\]

The proposed control scheme based on the analysis above is shown in Figure 5. The reference active current of the grid \( i_{\text{dref}} \) is compared with the actual active grid current, \( i_d \). The resulting error is inserted into the PI controller in order to keep the actual active current following the reference active current. On the other hand, the reference reactive current of the grid \( (i_{\text{qref}} = 0) \) is compared with the actual reactive grid current \( i_q \) to guarantee unity power factor. The resulting signals, \( d_{\text{nd}} \) and \( d_{\text{mq}} \), obtained from equation (36), are transformed into abc reference signals \((V_{\text{refA}}, V_{\text{refB}}, \) and \( V_{\text{refC}})\). These signals are then used to generate switching pulses to drive the IGBTs of the proposed cascaded H-bridge MLI by comparing them with the phase-shifted triangular carrier waveforms. The phase-shift PWM (PSPWM) modulation technique causes equal sharing of losses among different switches. In addition, PSPWM needs only one carrier signal to generate the various necessary switching signals and helps to reduce the THD in the generated MLI output voltage.

4.2. Control Scheme of the Three-Phase Cascaded VSI Topologies. The same control scheme described in the previous section is used to control the cascaded three-phase VSI topologies described in Figures 3 and 4. This control scheme is shown in Figure 6. The DC links \( C_{\text{dc1}}, C_{\text{dc2}}, \) and \( C_{\text{dc3}} \) of the topology shown in Figure 4 share the same active grid current. The DC-link voltages of these capacitors are compared with their respective reference voltages. The reference active current of the grid \( i_{\text{dref}} \), which represents the summation of the comparison errors, is compared with the actual active grid current \( i_d \). The resulting error is inserted into the PI controller in order to keep the actual active current following the reference active current. On the other hand, the reference reactive current of the grid \( (i_{\text{qref}} = 0) \) is compared with the actual reactive grid current \( i_q \) to guarantee unity power factor. The resulting error is inserted into another PI controller, then transformed into abc reference voltage signals \((V_{\text{refA}}, V_{\text{refB}}, \) and \( V_{\text{refC}})\). These signals are used to generate switching pulses to drive the IGBTs of the proposed three-phase cascaded VSI topology by comparing them with the phase-shifted triangular carrier waveforms. The carrier triangular signal of unit 2 is shifted by \( Ts/3 \) from unit 1, and the carrier signal corresponding to unit 3 is shifted by \( Ts/3 \) from that corresponding to unit 2.

5. Simulation Analysis

5.1. Simulation Results. Simulation results of the three proposed configurations are carried out by using the SIMUNLINK environment. The system parameters used for simulation are shown in Table 1, while Table 2 shows the PV module parameters. To better describe the results, configuration A is assigned for the CHB MLI topology shown in Figure 2, configuration B is assigned for the three-phase cascaded VSI topology using inductor topology shown in Figure 3, and configuration C is assigned for the topology depicted in Figure 4.

5.1.1. Simulation Results of the Configuration A. In this configuration, for simplicity, three H-bridge cells are used per phase to generate three-phase seven-level voltages. The three-phase seven-level voltage generated by configuration A is shown in Figure 7(a). Figure 7(b) illustrates the grid voltage and the grid current of the CHB MLI. It is clear that the
control system is working perfectly and the grid currents are in phase with the grid voltages.

5.1.2. Simulation Results of the Configuration B. On the other hand, the same parameters listed in Tables 1 and 2 are used to simulate the proposed system depicted in Figure 3, with a reference DC-link voltage of 150 V. The generated seven-level line-line voltage is illustrated in Figure 8(a). The three-phase grid voltages and the grid currents are in phase, as can be seen in Figure 8(b).
Figure 7: (a) Simulation results of three-phase voltage generated from configuration A. (b) Simulation results of grid voltages and grid currents of configuration A.

Figure 8: (a) Simulation results of three-phase voltage generated from configuration B. (b) Simulation results of grid voltages and grid currents of configuration B.
5.1.3. Simulation Results of the Configuration C. On the other hand, the system topology depicted in Figure 4 is simulated under the same conditions as the other two topologies. The generated seven-level line-line voltages of this topology are revealed in Figure 9(a). On the other hand, the three-phase grid voltages and the grid currents are in phase, as seen in Figure 9(b).

5.2. Simulation Comparison. The three topologies are similar in modular structure and isolated DC buses, and a comparison is drawn between them, achieved under the same output power and the same grid voltage.

5.2.1. Comparison according to the Number of Switches and Switch Stresses. The voltage stress on the switches of configurations A, B, and C is shown in Table 3. The following symbols in the table have the following meanings:

\[ V \]: The RMS value of the line-line grid voltage,

\[ I \]: The RMS value of the line grid current,

\[ X \]: Switches of the legs, which are directly connected, to the grid (switches of legs \( a_1, b_2, \) and \( c_3 \) in Figures 3 and 4),

\[ Y \]: Other switches in the configuration.

The current stress on the switches in configuration A is the total RMS grid current. On the other hand, the current stress on the switches connected to the grid (\( X \) switches) of configuration B is the total RMS grid current, while the current stress on the other switches (\( Y \) switches) is the maximum current flowing in the inductors, which is \( I_{rms}/\sqrt{3} \). This is because the line currents of each VSI unit in configuration B are not balanced. On the other hand, the current stresses on the switches in configuration C are the total RMS grid current. This is because the circulating currents inside configuration C are very low due to higher magnetization inductances of the coupled transformers. Therefore, the three-phase currents in each unit in configuration C are balanced. From another point of view, the voltage ratings of the switches of configurations B and C are higher than those in the voltage stress on the switches of configuration A, which in turn increases the total cost of these topologies.

![Figure 9: (a) Simulation results of three-phase voltage generated from configuration C. (b) Simulation results of grid voltages and grid currents from configuration C.](image-url)

### Table 3: Comparison of number of switches and stresses.

|          | A  | B  | C  |
|----------|----|----|----|
| Number of switches | 36 | 18 | 18 |
| Number of inductors | 0  | 3  | 0  |
| Number of coupled transformers | 0  | 0  | 3  |
| Voltage stress | \( \sqrt{2V/\sqrt{3}} \) | \( \sqrt{2V/\sqrt{3}} \) | \( \sqrt{2V/\sqrt{3}} \) |
| Current stress | \( I_{rms} \) | \( X: I_{rms}/\sqrt{3} \) | \( Y: I_{rms} \) |
5.2.2. Comparison according to the Efficiency. In this part, the three topologies are compared to each other under the same power levels and the same grid voltage. The total number of PV modules in each configuration is 18 modules. Each PV module is connected to one DC-DC isolated Ćuk converter. Figure 10 shows the efficiency comparison of the three topologies under the same rated power. At a higher power, the efficiency of configuration A is lower than the efficiency of configuration B. This is because of the higher number of switches in configuration A. On the other hand, the efficiency of configuration C is the lowest due to the presence of three coupled transformers, which increases system losses.

5.2.3. Comparison according to the THD of the Voltage and Current. The change of THD of the grid current in the three configurations with the rated power is revealed in Figure 11(a). As shown in this figure, with increasing power, the THD of the current improves. In addition, the THD of the current in configuration C is the lowest compared to the other two configurations. On the other hand, Figure 11(b) reveals the changing in the THD of the line-line voltage with the rated power. The THD of the generated line-line voltage of configuration C has the least magnitude compared to the other configurations.

The harmonic spectrum of the grid current in all configurations, at rated power 5400 W, can be seen in Figure 12. It is noted that the magnitudes of the harmonic contents of the grid current in configuration C are lower than the magnitudes of the harmonic contents of the configurations A and B.

6. Experimental Setup

With the aim of validating the performance of the proposed topologies, each has been built in the laboratory and experimentally connected to the grid. The block diagrams of the presented topologies used in the experimental setup are depicted in Figures 13 and 14.

As shown in Figure 13, for simplicity, only two H-bridge cells are used in each phase in the CHB topology. In addition, one PV module is connected to one DC-DC isolated Ćuk converter. The isolated Ćuk converter is then connected to the H-bridge cell. Therefore, six PV modules and six DC-DC isolated Ćuk converters are used to implement configuration A. On the other hand, three PV modules and three DC-DC isolated Ćuk converters are used to implement
configurations B and C, as shown in Figure 14. The DC side of configuration C is the same as the DC side of configuration B.

The parameters of the PV module used in the experiment are shown in Table 2. Data acquisition and the control system are implemented by using the DS1202 MicroLabBox system, produced by dSPACE. The required switching pulses are generated inside the SIMUNLINK environment and then sent to the IGBTs via the DS1202 board. The parameters used in the hardware setup are listed in Table 1. Figure 15 reveals the hardware setup of the proposed configurations.

7. Experimental Results

The proposed topology has been built in the laboratory and experimentally connected to the grid via a 5 mH interface inductor. The whole closed-loop control scheme is built inside the SIMUNLINK environment, and the resulting reference signals, $V_{ref_a}$, $V_{ref_b}$, and $V_{ref_c}$, are applied to the phase-shifted PWM blocks. The resulting PWM pulses are then sent to the IGBTs via the DS1202 board.

7.1. Experimental Results of Configuration A

7.1.1. Closed-Loop Control for the Grid-Connected PV System. In this test condition, the configuration A depicted in Figure 13 is connected to the grid. In order to eliminate the adverse effect of the mismatches and increase the efficiency of the PV system, distributed MPPT is used. The PV modules are controlled independently to achieve optimal MPPT. The maximum power tracked of the six PV modules used in this configuration is seen in Figure 16(a). On the other hand, the control scheme depicted in Figure 5 is used in the experiment. The MLI topology is well-controlled, and the DC-link voltages are kept at the reference voltages as demonstrated in Figure 16(b). The oscilloscope measurements of the generated three-phase voltages are displayed in Figure 17. In addition, the three-phase currents are measured by using a Hall-Effect current sensor, model LTS 25-NP, and the
Figure 15: Hardware setup of the proposed topologies.

Figure 16: (a) DC-link voltages. (b) Maximum power point tracking of the PV modules.
resulting signals are plotted in the control desk of the dSPACE software. These signals are illustrated in Figure 18(a). The topology is carefully controlled to keep the grid currents in phase with the grid voltages; therefore, the power factor is kept in unity, as shown in Figure 18(b).

7.1.2. Distributed and Nondistributed MPPT for Grid-Connected PV System. In this section, the cascaded H-bridge MLI (configuration A) is tested under distributed MPPT as well as under nondistributed MPPT. PV mismatch is an important issue in the PV system, and due to the unequally received irradiance, different temperatures, and aging of the PV panels, the MPP of each PV module may be different. If each PV module is not controlled independently, the efficiency of the overall PV system will be decreased.

The separate DC links in the cascaded H-bridge multilevel inverter make independent voltage control possible. Therefore, the distributed MPPT is used in this system. The perturbation and observation (P&O) MPPT algorithm is used to extract the maximum power of each PV module. As stated earlier, in order to use distributed MPPT, each PV
A module is connected to one DC-DC isolated Ćuk converter. To show the necessity of individual MPPT control, the PV module of the H-bridge cell 1 in phase a is covered. The maximum power extracted from each PV module is demonstrated in Figure 19(a).

As shown in this figure, the PV power of module 1, which is connected to the first H-bridge cell in phase a of configuration A, is reduced to approximately zero, while the maximum power of the other PV modules remains at their MPP. This is the advantage of the distributed MPP, where control of each PV module is independent of the other PV modules and the maximum power will be optimal. Figure 19(b) reveals the total power extracted from whole PV modules connected to configuration A. The total power extracted was about 670 W before covering the PV module. When the PV module is covered, the total power was reduced to about 570 W.

Figure 20 reveals the DC-link voltages of the six H-bridge cells of configuration A. The DC-link voltages are controlled and kept constant at the reference voltage 40 V. As shown in this figure, only the DC-link voltage VDC1 is reduced from 40 V to 7 V, while the DC-link voltages of the other H-bridge cells are not much affected.

From another point of view, in order to verify the importance of individually controlling the PV modules, nondistributed MPPT is also used to extract the maximum power of all PV modules in the proposed system. The PV voltage and the PV current of the PV module of the H-bridge cell 1 in phase a are experimentally measured to be used in the P&O MPPT algorithm. The resulting duty cycle from the MPPT algorithm is then used to drive the IGBTs of the whole DC-DC isolated Ćuk converters in the system. Again, the PV module of H-bridge cell 1 is covered. The power extracted of the other PV modules is illustrated in Figure 21(a). As shown in this figure, the power extracted from the PV modules is decreased to zero due to the MPPT not being individualized. The total power extracted from the PV modules is decreased to zero at the instance of covering the PV module as demonstrated in Figure 21(b). In addition, the DC-link voltages are displayed in Figure 22.

7.2. Experimental Results of Configuration B. In this test, the configuration B depicted in Figure 14 is connected to the grid via a 5 mH interface inductor. As in configuration A, distributed MPPT is used, in which PV modules are controlled independently to achieve best MPPT. The control scheme depicted in Figure 6 is used in this experimental test. The resulting reference signals, Vrefa, Vrefb, and Vrefc, are applied to the phase-shifted PWM block. The resulting PWM pulses are then sent to the IGBTs via the DS1202 board.

The control system is used to keep the DC-link voltages of the three units of configuration B at the reference voltages. The oscilloscope measurements of the three-phase line-line voltages generated from this configuration are seen in Figure 23.

On the other hand, the experimental three-phase grid currents, measured by Hall-Effect current sensors, can be seen in Figure 24(a). The topology is well-controlled to keep the grid currents in phase with the grid voltages, and the power factor is thus kept in unity, as can be seen in Figure 24(b). As mentioned earlier, the three-phase currents
Figure 21: (a) Nondistributed MPPT control of PV modules under shading. (b) Total power extracted from the whole PV modules.

Figure 22: DC-link voltages with nondistributed MPPT control.

Figure 23: Experimental three-phase line-line voltages generated from configuration B.
of each unit in configuration B are not balanced. The three-phase currents of unit 1 are displayed in Figure 25(a). Due to the currents in each unit not being balanced, the circulating current flowing in the inductors is high, as can be seen in Figure 25(b).

7.3. Experimental Results of Configuration C. In this test, configuration C is also connected to the grid via a 5 mH interface inductor. The system parameters used for this experiment are shown in Table 1. As in configuration A, the PV modules are controlled independently to achieve best MPPT using distributed MPPT.

The oscilloscope measurements of the three-phase line-line voltages generated from this configuration are depicted in Figure 26. On the other hand, the experimental three-phase grid currents are shown in Figure 27(a). The topology is controlled to keep the grid currents in phase with the grid voltages, and thus, the power factor is kept in unity, as demonstrated in Figure 27(b). As mentioned earlier, the three-phase currents of each unit in configuration C are
symmetrical and balanced. The three-phase currents of unit 1 are displayed in Figure 28(a). Due to the currents in each unit being symmetrical and balanced, the circulating current flowing in the inductors is very low, as illustrated in Figure 28(b).

8. Experimental Comparison

The three configurations are experimentally compared to each other according to the THD of the generated voltage and according to the THD of the grid current. Table 4 shows the magnitude of the THD of the generated voltages, as well as the grid current for the three configurations.

The harmonic spectrum of the generated voltages of configurations A, B, and C is plotted in Figure 29(a). As shown in this figure, the magnitudes of the harmonic contents of the voltage generated from configuration A are the worst compared to the other configurations. This is because the number of voltage levels generated from configuration A is five levels, while the number of voltage levels generated from configurations B and C each are seven levels. On the other hand, the harmonic contents of the voltage generated by configuration C have the fewest magnitudes. The harmonic spectrum of the grid current of configurations A, B, and C can be seen in Figure 29(b). As shown in this figure, the magnitudes of the
harmonic contents of the grid current of configuration C are the lowest compared to configurations A and B. In addition, the magnitudes of the harmonic contents of configuration B are the highest. This conclusion coincides with the comparison conclusion of the simulation results displayed in Figure 12.

9. Conclusion

Three-cascaded multilevel inverter configurations have been used to connect PV modules to the grid, as presented in this paper. The proposed topologies are three-phase cascaded H-bridge MLI topology, three-phase cascaded...
voltage-source inverter topology using inductors, and three-phase cascaded voltage-source inverter topology using coupled transformers. The proposed configurations are based on the AC module topology in which only one PV module is connected to one DC-DC isolated Ćuk converter for optimal MPPT achievement. In addition, galvanic isolation is included per module to eliminate leakage current due to parasitic capacitance and to decouple the second harmonic voltage ripple. The SIMULINK environment has been used to simulate the presented topologies. The simulation results show that the presented topologies are functioning well in improving power grid quality. The proposed control schemes are functioning well to keep the DC-link voltages at their reference voltages. The control methods can generate a sinusoidal grid current in phase with the grid voltage, and the THD of grid current is within the acceptable range. Experimental implementation of the proposed topologies has been achieved in this paper. Data acquisition and the control are achieved with the help of MicroLabBox, produced by dSPACE. Comparison of the three topologies has been achieved in this paper, by simulation and by experiment. The comparison of the proposed configurations shows that the efficiency of the three-phase cascaded VSI using inductors is higher than the efficiency of the cascaded H-bridge. In addition, the three-phase cascaded VSI using coupled transformers has the worst efficiency due to the presence of three coupled transformers in the configuration. However, the THD of the generated voltage and the grid current of the three-phase cascaded VSI using coupled transformers are the lowest compared to those of the other two topologies. The simulation and experimental results and comparisons are presented to verify the proposed topologies’ effectiveness and reliability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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