Multi–Port High–Frequency AC–Link and Indirect Matrix Converters: A Generalized Structure

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Abstract

Conventional multi-stage AC/DC/DC, AC/DC/AC, DC/DC/DC, and DC/DC/AC converters are two ports converters used to connect a resource or load to an AC or DC grid. To connect several loads or resources to a grid, these converters can easily be extended to a multi-port converter through a common DC-link, with simplified control and a reduced number of active switches. However, DC-link huge energy storage component increases the converter volume and cost and reduces its lifetime and reliability. On the other hand, most of the resources with these types of converters have fault ride–through problems and the DC-link voltage increases during the grid-side faults. The indirect matrix converter is a two-port high-frequency AC-link (HFAC) converter without any intermediate energy storage component, which can be used to connect just a single source or load to a grid. In this paper, a generalized extension of a two-port indirect matrix converter (and the other HFAC converters) to a multi-port converter is proposed. The modulation method, voltage and current gains, and the reactive power limitation of the proposed structure are also presented. Performances of the proposed structure and its modulation strategy are verified through simulation in MATLAB/SIMULINK environment.

Keywords — AC/DC grid connection, high-frequency AC-link converter (HFAC), indirect matrix converter, modulation method, multi-port converter.
1 Introduction

Distributed generators (DGs) are connected to the AC or DC grids via conventional multi-stage AC/DC/AC, DC/DC/AC, AC/DC/DC, or DC/DC/DC converters, as presented in Fig. 1(a). These converters are a back-to-back connection of two voltage source converters through a common DC-link capacitor. In a hybrid system with two or more DGs and storages, these converters can be easily extended to a multi-port converter with the back-to-back connection of multiple voltage source converter through their common DC-link capacitor, as shown in Fig. 1(b) [1–5].

The intermediate DC-link capacitor simplifies the converter control through independent control of the DG-side and grid-side converters. The DG-side DC/DC or AC/DC converter controls the DG power and boosts its low voltage to a desirable level for the grid-side converter. The grid-side DC/AC or DC/DC converter controls the DC-link voltage by delivering generated power to the AC or DC grid. The DC/AC converter can also generate reactive power to meet the AC grid or load reactive power requirements [6].

Although the DC-link capacitor facilitates the converter control, it increases the converter volume, reduces its reliability, and causes grid-side fault ride-through problems [7]. When a fault occurs on the grid side, the grid-side converter voltage and power decrease, while the DG power cannot be decreased rapidly due to the independent control of the DG-side and grid-side converters. Therefore, the DC-link voltage increases due to its input and output power inequality. Two types of methods are proposed in the literature to solve this problem: adding an external system such as energy storage or a brake resistor, or improving the control structure of the DG-side converter by getting feedback from the DC-link or grid-side voltage. Both of these methods lead to the complexity of the converter structure or control [8–10]. For this purpose, direct and indirect matrix converters are proposed in the literature without any intermediate energy storage component. These all-silicon converters are more reliable and compact compared with the conventional multi-stage AC/DC/AC back-to-back frequency converters [11–13].

Due to the lack of an intermediate energy storage component, it is difficult to extend this two-port matrix converter to a multi-port one, and except for a few special and non-expandable three-port cases [14–22], most of the matrix converters proposed in the literature are two-port converters used to connect a single resource or load to an AC or DC grid. Therefore, to connect several resources or loads the grid, unlike extendable multi-stage back-to-back converters, several matrix converters are required which increases the system complexity and cost. In this paper, a generalized structure for multi-port indirect matrix converters is proposed which can be used to connect multiple DGs or storage to an AC or DC grid or load. The presented generalized structure can also be applied to the other HFAC converters.

For this purpose, in Section II, the basic indirect matrix converter and its modulation method are investigated. The voltage and current gains of this converter are also presented in this section.
In Section III, the generalized structure of a multi–port indirect matrix converter is presented which can be used to connect multiple DC or AC DGs and storage to an AC or DC grid or load. Modulation and commutation methods of the proposed structure, and the voltage and current gains are also presented. Finally, the proposed generalized structure is verified through simulation in MATLAB/SIMULINK environment for different cases and conditions in Section IV.

2 Indirect Matrix Converter

The indirect matrix converter is a three–phase to three–phase high–frequency AC–link (HFAC) converter without any intermediate energy storage component. The basic structure of a three–phase to three–phase indirect matrix converter is depicted in Fig. 2. As presented in this figure, this converter is a back–to–back connection of two current source and voltage source converters with bidirectional four–quadrant switches. Although conventional indirect matrix converters are sparse counterparts of this basic topology with fewer active switches, in this manuscript just the basic topology is considered whose principles are applicable to all sparse topologies [23]. Due to the lack of huge energy storage components, these all–silicon converters are more compact and reliable compared with conventional back–to–back converters [24,25].

2.1 Modulation Method

Since an indirect matrix converter is a back–to–back connection of a voltage source converter with a current source converter, one of the most complete modulation methods proposed for this converter is indirect space vector modulation [25,26]. In this modulation method, at first, it is supposed
that the voltage source and current source converters of the indirect matrix converter are controlled independently by their conventional space vector modulation (SVM) methods and their switching states and times are calculated. Finally, calculated switching times and states are combined in the indirect SVM to control the indirect matrix converter the same as the back-to-back connection of a voltage source converter and a current source converter.

### 2.1.1 Space Vector Modulation of the Voltage Source Converter

The voltage source converter of an indirect matrix converter is specified in Fig. 2 which its voltage source value is $v_{pn}$. To control this voltage source converter, conventional space vector modulation (SVM) is used which its switching states and vectors are presented in Table 1 and Fig. 3(a). Two of these vectors (i.e. $\vec{V}_7$ and $\vec{V}_8$) are zero vectors and the other remaining 6 vectors split $\alpha\beta$ plane into 6 sectors.

The desired output voltage vector $\vec{V}_{o,ref}$ in each sector of $\mathcal{J}$ can be constructed by the two adjacent vectors of this sector as presented in Figs. 3(b). Hence, as depicted in Fig. 3(c), for $Dv_j$ portion of each switching period $T_s$ vector $\vec{V}_j$, for $Dv_{j+1}$ portion of $T_s$ vector $\vec{V}_{j+1}$ and for the rest of the switching period vector $\vec{V}_0$ are applied. $Dv_j$, $Dv_{j+1}$ and $Dv_0$ can be obtained as follows:
\[(a)\]

\[(b)\]

\[(c)\]

Figure 3: The voltage source converter space vectors in the \(\alpha\beta\) reference frame and its SVM pattern

\[
\begin{align*}
Dv_j &= m_v \sin \left( \frac{\pi}{3} - \theta_v \right) \\
Dv_{j+1} &= m_v \sin (\theta_v) \\
Dv_0 &= 1 - Dv_j - Dv_{j+1}
\end{align*}
\] (1)

where, \(m_v\) is the voltage source converter modulation index which controls the converter voltage gain as follows.

\[
m_v = \sqrt{3} \frac{V_{o,ref}}{v_{pn,ave}}
\] (2)

\(V_{o,ref}\) is the desired output phase to neutral voltage amplitude, and \(v_{pn,ave}\) is the DC–link averaged voltage. The modulation index can be selected as \(0 \leq m_v \leq 1\), and the maximum phase to neutral voltage amplitude which can be constructed with this modulation method is \(\frac{v_{pn,ave}}{\sqrt{3}}\). The averaged output voltage and DC–link current of this voltage source converter is as follows:

\[
\vec{V}_{o,ave} = Dv_j \vec{V}_j + Dv_{j+1} \vec{V}_{j+1} + Dv_0 \vec{V}_0 = \vec{V}_{o,ref}
\] (3)
The current source converter space vectors in the $\alpha\beta$ reference frame and its SVM pattern

\[
i_{pn,ave} = \frac{3}{2v_{pn}} \left\{ Dv_j \vec{V}_j \vec{I}_0 + Dv_{j+1} \vec{V}_{j+1} \vec{I}_o \right\} = \frac{\sqrt{3}}{2} m_v I_o \cos \varphi_o \tag{4}
\]

where, $I_o$ and $\varphi_o$ are the instantaneous output current amplitude and phase angle with respect to the output voltage.

### 2.1.2 Space Vector Modulation of the Current Source Converter

The current source converter of an indirect matrix converter is specified in Fig. 2 which its current source value is $i_{pn}$. To control this current source converter, conventional space vector modulation (SVM) is used which its switching vectors are presented in Table 2 and Fig. 4(a). Three of these vectors (i.e. $\vec{I}_7$, $\vec{I}_8$ and $\vec{I}_9$) are zero vectors and the other remaining 6 vectors split $\alpha\beta$ plane into 6 sectors.

The desired input current vector $\vec{I}_{i,ref}$ in each sector of $k$ can be constructed by the two adjacent vectors of this sector as presented in Figs. 4(b). Hence, as depicted in Fig. 4(c), for $Di_k$ portion of each switching period $T_s$ vector $\vec{I}_k$, for $Di_{k+1}$ portion of $T_s$ vector $\vec{I}_{k+1}$, and for the rest of the switching period vector $\vec{I}_0$ are applied. $Di_k$, $Di_{k+1}$ and $Di_0$ can be calculated as follows:
Table 2: The Current Source Converter Switching States and Space Vectors

<table>
<thead>
<tr>
<th>Vector Name</th>
<th>Switching State</th>
</tr>
</thead>
<tbody>
<tr>
<td>I₁</td>
<td>Saₚ, Scₙ</td>
</tr>
<tr>
<td>I₂</td>
<td>Sbₚ, Scₙ</td>
</tr>
<tr>
<td>I₃</td>
<td>Sbₚ, Saₙ</td>
</tr>
<tr>
<td>I₄</td>
<td>Scₚ, Saₙ</td>
</tr>
<tr>
<td>I₅</td>
<td>Scₚ, Sbₙ</td>
</tr>
<tr>
<td>I₆</td>
<td>Saₚ, Sbₙ</td>
</tr>
<tr>
<td>I₀</td>
<td></td>
</tr>
<tr>
<td>I₇</td>
<td>Saₚ, Saₙ</td>
</tr>
<tr>
<td>I₈</td>
<td>Sbₚ, Sbₙ</td>
</tr>
<tr>
<td>I₉</td>
<td>Scₚ, Scₙ</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
D_{ik} &= m_c \sin \left( \frac{\pi}{3} - \theta_i \right) \\
D_{ik+1} &= m_c \sin (\theta_i) \\
D_{i0} &= 1 - D_{ik} - D_{ik+1}
\end{align*}
\] (5)

where, \( m_c \) is the current source converter modulation index which controls the converter current gain as follows.

\[
m_c = \frac{I_{i,ref}}{i_{pn,ave}}
\] (6)

\( I_{i,ref} \) is the desired input current amplitude, and \( i_{pn,ave} \) is the DC–link averaged current. The modulation index can be selected as \( 0 \leq m_c \leq 1 \), and the maximum current amplitude which can be constructed with this modulation method is \( i_{pn,ave} \). The averaged output current and the DC–link voltage of this current source converter is as follows:

\[
\vec{I}_{i,ave} = D_{ik} \vec{I}_k + D_{ik+1} \vec{I}_{k+1} + D_{i0} \vec{I}_0 = \vec{I}_{i,ref}
\] (7)

\[
v_{pn,ave} = \frac{3}{2i_{pn}} \left\{ D_{ik} \vec{I}_k \vec{V}_i + D_{ik+1} \vec{I}_{k+1} \vec{V}_i \right\}
\]

\[
= \frac{3}{2} m_c V_i \cos \varphi_i
\] (8)

where, \( V_i \) and \( \varphi_i \) are the instantaneous input phase–neutral voltage amplitude and phase angle with respect to the input current.

2.1.3 Space Vector Modulation of the Indirect Matrix Converter

Space vector modulation of an indirect matrix converter is a combination of voltage source and current source converters modulations. To construct the desired output voltage vector \( \vec{V}_{o,ref} \) in the sector \( j \) and desired input current vector \( \vec{I}_{i,ref} \) in the sector \( k \), vectors \( \vec{V}_j \) and \( \vec{V}_{j+1} \) in the voltage
source converter, and vectors $\vec{I}_k$ and $\vec{I}_{k+1}$ in the current source converter are used. For this purpose, as presented in Fig. 5, $D_{jk}$ portion of the switching period vectors $\vec{V}_j$ and $\vec{I}_k$, $D_{j(k+1)}$ portion of the switching period vectors $\vec{V}_j$ and $\vec{I}_{k+1}$, $D_{(j+1)k}$ portion of the switching period vectors $\vec{V}_{j+1}$ and $\vec{I}_k$, and $D_{(j+1)(k+1)}$ portion of the switching period vectors $\vec{V}_{j+1}$ and $\vec{I}_{k+1}$ are applied. And for the last remaining part of the switching period (i.e. $D_0$), vectors $\vec{V}_0$ and $\vec{I}_0$ are applied. Where $D_{jk}$, $D_{j(k+1)}$, $D_{(j+1)k}$, $D_{(j+1)(k+1)}$ and $D_0$ are calculated form (1) and (5) as presented in (9). Similar to Figs. 5(a) and 5(b), order of applying input, output and zero vectors can be changed arbitrary to reduce the switching frequency and loss or the output voltages and input currents distortion and THD.

$$
\begin{align*}
D_{jk} &= Dv_j Di_k = m_t \sin \left( \frac{\pi}{3} - \theta_o \right) \sin \left( \frac{\pi}{3} - \theta_i \right) \\
D_{j(k+1)} &= Dv_j Di_{k+1} = m_t \sin \left( \frac{\pi}{3} - \theta_o \right) \sin (\theta_i) \\
D_{(j+1)k} &= Dv_{j+1} Di_k = m_t \sin (\theta_o) \sin \left( \frac{\pi}{3} - \theta_i \right) \\
D_{(j+1)(k+1)} &= Dv_{j+1} Di_{k+1} = m_t \sin (\theta_o) \sin (\theta_i) \\
D_0 &= 1 - D_{jk} - D_{j(k+1)} - D_{(j+1)k} - D_{(j+1)(k+1)}
\end{align*}
$$

where $m_t = m_c m_v$ is the total matrix converter modulation index which can be selected as $0 \leq m_t \leq 1$.

### 2.2 Voltage and Current Gains

With the indirect modulation strategy presented in Fig. 5, for the $Di_k$ portion of the time duration applying $\vec{V}_j$ in the output converter, $\vec{I}_k$ is applied in the input converter, and for the remaining $Di_{k+1}$ part of this time $\vec{I}_{k+1}$ is applied in the input converter. Also, for the $Di_k$ portion of the time
duration applying $\vec{V}_{j+1}$ in the output converter, $\vec{I}_k$ is applied in the input converter, and for the remaining $D_{i_k+1}$ part of this time $\vec{I}_{k+1}$ is applied in the input converter. Therefore, the averaged DC–link voltage during applying $\vec{V}_j$, $\vec{V}_{j+1}$ and also the whole of the switching period is the same as (8), and with respect to (2), the averaged output phase–neutral voltage vector which can be obtained by the indirect modulation strategy is:

$$V_{o,ave} = \frac{\sqrt{3}}{2} m_t V_i \cos \phi_i \approx 0.866 m_t V_i \cos \phi_i$$  \hspace{1cm} (10)$$

It can be seen that the maximum output phase–neutral voltage which can be constructed with the indirect matrix converter depends on the input power factor of the converter. When the input power factor is one the maximum output phase–neutral voltage is 0.866 of the input phase–neutral voltage.

Similarly, as presented in Fig. 5, for the $D_{v_j}$ portion of the time duration applying $\vec{I}_k$ in the input converter, $\vec{V}_i$ is applied in the output converter, and for the remaining $D_{v_{j+1}}$ part of this time $\vec{V}_{i+1}$ is applied in the output converter. Also, for the $D_{v_j}$ portion of the time duration applying $\vec{I}_{k+1}$ in the input converter, $\vec{V}_j$ is applied in the output converter, and for the remaining $D_{v_{j+1}}$ part of this time $\vec{V}_{j+1}$ is applied in the output converter. Therefore, the averaged DC–link current during applying $\vec{I}_k$, $\vec{I}_{k+1}$ and also the whole of the switching period is the same as (4), and with respect to (6), the averaged input current vector which can be obtained by the indirect modulation strategy is:

$$I_{i,ave} = \frac{\sqrt{3}}{2} m_t I_o \cos \phi_o \approx 0.866 m_t I_o \cos \phi_o$$  \hspace{1cm} (11)$$

### 3 Generalized Multi–Port Indirect Matrix Converter

The indirect matrix converter is a two–port high frequency AC–link (HFAC) converter. However, in a hybrid system a multi–port converter is required to connect two or more AC or DC power resources to an AC or DC grid or load. As presented in Fig. 1, conventional back–to–back converters can easily be extended to a multi–port converter by connecting multiple voltage source converter through their common DC link. However, except for a few cases [14–22], most of the matrix and HFAC converters proposed in the literature are two–port converters which can be used to connect a single DG or storage to an AC or DC grid. In this Section, a generalized structure of a multi–port indirect matrix converter is proposed which can be used to connect several AC or DC resources to an AC or DC grid or load in a hybrid system.

The single–phase equivalent circuit of a two–port indirect matrix converter is presented in Fig. 6. As presented in Fig. 2, the input filter of the current source converter is a capacitive filter which is a voltage source element. Therefore, the output port of this converter is also a controllable voltage source with the value presented in (8). Since two voltage sources with different voltages cannot be
paralleled, the output port of this converter must be connected to a current source. In a similar manner, the output filter of the voltage source converter is an inductive filter which is a current source component. Therefore, the input port of this converter is also a controllable current source with the value presented in (4). Since two current sources with different currents cannot be serried, the input port of this converter must be connected to a voltage source.

Since two or more current sources with different currents can be paralleled, or two or more voltage sources with different voltages can be serried, to extend an indirect matrix (or HFAC) converter to a multi-port converter several voltage source converters can be paralleled in the output stage or several current source converters can be serried in the input stage of an indirect matrix converter. The single-phase equivalent circuit of these multi-port converters are presented in Fig. 7 for three-port samples.

Therefore, as presented in Fig. 7(a), in a single-input multi-output matrix converter two or more voltage source converters are connected in parallel in the output stage, and as presented in Fig. 7(b), in a multi-input single-output matrix converter two or more current source converters are connected in series in the input stage. Where, the voltage and current source converters can be a three-phase, single-phase or a DC converter of Figs. 8 and 9 respectively.

3.1 Modulation Method

To control a multi-port indirect matrix converter the same as a two-port indirect matrix converter indirect space vector modulation method is proposed in which, the voltage and current source converters are controlled with the conventional SVM method for the three-phase converters or PWM method for single-phase and DC converters. Then, switching states of these converters are combined such that the desired averaged output voltage and input current achieved. This process is described for a single-input multi-output matrix converter and multi-input single-output matrix converters in the two following separate subsections.
Figure 7: Three–port indirect matrix converters equivalent circuit a: Single–input multi–output indirect matrix converter equivalent circuit b: Multi–input single–output indirect matrix converter equivalent circuit

Figure 8: a: Three–phase current source converter, b: single–phase and DC current source converters, and c: their single–phase equivalent circuit
Figure 9: a: Three-phase voltage source converter, b: full-bridge single-phase and DC voltage source converters, c: half-bridge DC voltage source converter, and d: their single-phase equivalent circuit

3.1.1 Single-input multi-output matrix converter modulation method

To simplify the single-input multi-output matrix converter control and modulation, modulation index of the input current source converter (i.e. \( m_c \)) is selected as one and the output voltage source converter modulation indexes (i.e. \( m_{v1}, m_{v2}, \ldots, m_{vn} \)) are changed to control the output voltage and input current of the multi-port matrix converter as follows:

\[
\begin{align*}
m_c &= \frac{I_{i,ref}}{i_{pn,ave}} = 1 \\
v_{pn,ave} &= \frac{3}{2} m_c V_i \cos \varphi_i = \frac{3}{2} V_i \cos \varphi_i \\
i_{pn,ave} &= \sum_{l=1}^{n} \frac{\sqrt{3}}{2} m_{vl} I_{ol} \cos \varphi_{ol} \\
m_{vl} &= \frac{\sqrt{3} V_{ol,ref}}{v_{pn,ave}}, \quad l = 1, \ldots, n
\end{align*}
\]

(12)

For the DC outputs, the converters’ duty cycles are calculated in a similar manner to achieve desirable output voltages. It can be seen from (12) that the same as an indirect matrix converter, the input and outputs power factor limit the multi-output converter voltage and current gains. After calculating modulation indexes and duty cycles, switching times of each vector of the input and output converters are calculated using (1) and (5), and the switching states and times of the
multi–port converter is calculated by combining the input and each output switching states and times with respect to (9) and Fig. 10(a).

With respect to Fig. 7(a), in the single–input multi–output matrix converter, the input current source converter is common between the output voltage source converters. Therefore, as depicted in Fig. 10(a), for the input converter, at the first $D_i k$ part of the switching period $\vec{I}_k$, the next $D_i 0$ part of the switching period $\vec{I}_0$, and at the last $D_i k+1$ part of the switching period $\vec{I}_{k+1}$ of the input converter are applied. Since each output converter works independent of the other ones, its switching diagram is completely similar to the two–port matrix converter presented in Fig. 5(a).

Therefore, for the typical converter which is in sector $j$, at the first $D_{kj}$ part of the switching period $\vec{V}_j$, the next $D_{k(j+1)}$ part of the switching period $\vec{V}_{j+1}$, the next $D_{0 kj}$ part of the switching period $\vec{V}_0$, the next $D_{(k+1)j}$ part of the switching period $\vec{V}_{j+1}$, and at the last $D_{(k+1)j}$ part of the switching period $\vec{V}_j$ of the input converter are applied. With this modulation method, each output port operates with the input port similar to a two–port matrix converter.

### 3.1.2 Multi–input single–output matrix converter modulation method

In a similar manner, to control the multi–input single–output matrix converter simply, modulation index of the output voltage source converter (i.e. $m_v$) is selected as one and the input current source converter modulation indexes (i.e. $m_{c1}, m_{c2}, ..., m_{cn}$) are changed to control the output voltage and inputs current of the matrix converter as follows:
\[ m_v = \sqrt{3} \frac{V_{o,ref}}{v_{pn,ave}} = 1 \]
\[ i_{pn,ave} = \frac{\sqrt{3}}{2} m_v I_o \cos \varphi_o = \frac{\sqrt{3}}{2} I_o \cos \varphi_o \]
\[ u_{pn,ave} = \sum_{l=1}^{n} \frac{3}{2} m_{cl} V_{il} \cos \varphi_{il} \]
\[ m_{cl} = \frac{I_{il,ref}}{i_{pn,ave}}, l = 1, ..., n \] (13)

For the DC inputs, the converters duty cycles are calculated in a similar manner to achieve desirable input. It can be seen from (13) that the same as an indirect matrix converter, the inputs and output power factor limit the multi–input converter voltage and current gains. After calculating modulation indexes and duty cycles, switching times of each vector of the input and output converters are calculated using (1) and (5), and the switching states and times of the multi–port converter is calculated by combining the input and each output switching states and times with respect to (9) and Fig. 10(b).

With respect to Fig. 7(b), in the multi–input single–output matrix converter, the output voltage source converter is common between the input current source converters. Therefore, as depicted in Fig. 10(b), for the output converter, at the first \( Dv_j \) part of the switching period \( \vec{V}_j \), the next \( Dv_0 \) part of the switching period \( \vec{V}_0 \), and at the last \( Dv_{j+1} \) part of the switching period \( \vec{V}_{j+1} \) of the output converter are applied. Since each input converter works independent of the other ones, its switching diagram is completely similar to the two–port matrix converter presented in Fig. 5(b).

Therefore, for the typical converter which is in sector \( k \), at the first \( D_jk \) part of the switching period \( \vec{I}_k \), the next \( D_{j(k+1)} \) part of the switching period \( \vec{I}_{k+1} \), the next \( D_{0jk} \) part of the switching period \( \vec{I}_0 \), the next \( D_{(j+1)k(k+1)} \) part of the switching period \( \vec{I}_{k+1} \), and at the last \( D_{(j+1)k} \) part of the switching period \( \vec{I}_k \) of the input converter are applied. With this modulation method, each input port operates with the output port similar to a two–port matrix converter.

4 Simulation Results

In this section, the proposed generalized structure is evaluated through simulation in the MATLAB/SIMULINK software environment. For this purpose, a single–input multi–output and a multi–input single–output indirect matrix converter are considered in the two following subsections.

4.1 Single–input multi–output indirect matrix converter

A single–input multi–output indirect matrix converter can be used to connect different three–phase, single–phase, or DC systems to each other. In these simulations, three single–input multi–output
converters are simulated in three cases. The first one connects a three-phase input system to the two different three-phase output systems, the second one is used to connect a three-phase input system to a three-phase and a DC output systems, and finally, the third one is used to connect a three-phase input system to the three different three-phase output systems. The general scheme of the simulated systems and their control structure is presented in Fig. 11. Circuit diagram of the three-phase input current source converter is presented in Fig. 8(a), and the circuit diagram of the output three-phase and DC voltage source converters are presented in Figs. 9(a) and 9(b) respectively. The parameters of the input and output stages are presented in Table 3.

### 4.1.1 Single-input double-output AC→AC-AC converter

In this case, to examine the converter performance, at time 0.025s the input power factor is changed from 1 to 0.8, and at time 0.05s the AC output 2 voltage is increased 50% and simulation results for this converter is presented in Fig. 12.

### 4.1.2 Single-input double-output AC→AC-DC converter

Similar to the previous case, in this case, at time 0.025s the input power factor is changed from 1 to 0.8, and at time 0.05s the DC output 2 voltage is increased 50% and simulation results of this
Table 3: Simulation parameters of the single–input multi–output indirect matrix converters

<table>
<thead>
<tr>
<th></th>
<th>AC input</th>
<th>AC output 1</th>
<th>AC output 2 (case 1 &amp; case 3)</th>
<th>AC output 3 (case 3)</th>
<th>DC output 2 (case 2)</th>
<th>Switching frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_i$</td>
<td>400V</td>
<td>$V_o$</td>
<td>100V</td>
<td></td>
<td></td>
<td>$f_s$ 20kHz</td>
</tr>
<tr>
<td>$f_i$</td>
<td>50Hz</td>
<td>$f_o$</td>
<td>75Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\cos \phi_i$</td>
<td>1</td>
<td>$Z_{Load}$</td>
<td>$R_{Load}$ 5Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{fi}$</td>
<td>500µH</td>
<td>$L_{fo}$</td>
<td>5mH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{fi}$</td>
<td>20µF</td>
<td>$C_{fo}$</td>
<td>1µF</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AC input

AC output 1

AC output 2 (case 1 & case 3)

DC output 2 (case 2)

AC output 3 (case 3)

Switching frequency

Figure 12: Simulation results of single–input double–output AC→AC-AC converter. $I_{in}$: AC input current $V_{out1}$: AC output 1 line-to-line voltage $V_{out2}$: AC output 2 line-to-line voltage.
Figure 13: Simulation results of single–input double–output AC→AC-DC converter. $I_{in}$: AC input current $V_{out1}$: AC output line-to-line voltage $V_{out2}$: DC output voltage

converter is also presented in Fig. 13.

### 4.1.3 Single–input triple–output AC→AC-AC-AC converter

Similar to the two previous cases, at time 0.025s the input power factor is changed from 1 to 0.8, and at time 0.05s the AC output 2 voltage is increased 50% and simulation results for this converter is presented in Fig. 14.

### 4.2 Multi–input single–output indirect matrix converter

Similarly, a multi–input single–output indirect matrix converter can be used to connect different three–phase, single–phase, or DC systems to each other. In these simulations, three multi–input single–output converters are simulated in three cases which, the first one connects two different three–phase input systems to a three–phase output system, the second one is used to connect a three–phase and a DC input systems to a three–phase output system, and finally, the third one is used to connect three different three–phase input systems to a three–phase output system. The general scheme of the simulated systems and their control structure is presented in Fig.15. Circuit diagram of the three-phase and DC input current source converters are presented in Figs. 8(a) and 8(b) respectively, and the circuit diagram of the output three–phase voltage source converters is presented in Fig. 9(a). The parameters of the input and output stages are presented in Table 4.
Figure 14: Simulation results of single–input triple–output AC→AC-AC-AC converter. \( I_{\text{in}} \): AC input current \( V_{\text{out1}} \): AC output 1 line-to-line voltage \( V_{\text{out2}} \): AC output 2 line-to-line voltage \( V_{\text{out3}} \): AC output 3 line-to-line voltage
Figure 15: The general scheme of the simulated multi-input single-output converters and their control structure

Table 4: Simulation parameters of the multi-input single-output indirect matrix converters

<table>
<thead>
<tr>
<th></th>
<th>AC input 1</th>
<th>AC input 2 (case 1 &amp; case 3)</th>
<th>DC input 2 (case 2)</th>
<th>AC input 3 (case 3)</th>
<th>AC output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, $V_i$</td>
<td>400V</td>
<td>150V</td>
<td>100V</td>
<td>75V</td>
<td>200V</td>
</tr>
<tr>
<td>Frequency, $f_i$</td>
<td>50Hz</td>
<td>75Hz</td>
<td>50Hz</td>
<td>50Hz</td>
<td>60Hz</td>
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<tr>
<td>Power factor, $\cos \phi_i$</td>
<td>1</td>
<td>0.85</td>
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<td>0.75</td>
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<tr>
<td>Inductance, $L_{fi}$</td>
<td>500$\mu$H</td>
<td>500$\mu$H</td>
<td>500$\mu$H</td>
<td>500$\mu$H</td>
<td></td>
</tr>
<tr>
<td>Capacitance, $C_{fi}$</td>
<td>20$\mu$F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC output</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage, $V_o$</td>
<td>200V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency, $f_o$</td>
<td>60Hz</td>
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<tr>
<td>Load resistance, $R_{Load}$</td>
<td>10Ω</td>
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<tr>
<td>Inductance, $L_{fo}$</td>
<td>5mH</td>
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<tr>
<td>Capacitance, $C_{fo}$</td>
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<tr>
<td>Switching frequency, $f_s$</td>
<td>20kHz</td>
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</tr>
</tbody>
</table>
4.2.1 Double–input single–output AC–AC→AC converter

In this case to examine the converter performance, to decrease the AC input 1 power at time 0.025s its power factor is changed from 1 to 0.8, and at time 0.05s the AC output voltage is increased 50% and simulation results for this converter is presented in Fig. 16.

4.2.2 Double–input single–output AC–DC→AC converter

Similar to the previous case, in this case to decrease the DC input 2 power at time 0.025s its modulation index is changed from 1 to 0.8, and at time 0.05s the AC output voltage is increased 50% and simulation results of this converter is also presented in Fig. 17.

4.2.3 Triple–input single–output AC–AC–AC→AC converter

In this case, similar to the two previous cases, to decrease the AC input 1 power at time 0.025s its power factor is changed from 1 to 0.8, and at time 0.05s the AC output voltage is increased 50% and simulation results for this converter is presented in Fig. 18.
5 Conclusions

To connect multiple DGs and storages to an AC or DC grid or load a multi-port converter is required. Conventional back-to-back converters can easily be extended to a multi-port converter by connecting several voltage source converters through their common DC link. Bulky DC link capacitor simplifies converter control and extension, but increases the system volume and reduces its lifetime. Common high frequency AC-link converters such as indirect matrix converters are two-port converters. In this paper a general structure for a multi-port indirect matrix converter is proposed which can be used to connect several DC or AC resources to an AC or DC grid or load. The proposed structure can be used to extend every HFAC converter to a multi-port converter. The modulation method and voltage and current gain of the proposed converter are also presented.

References


Figure 18: Simulation results of triple-input single-output AC-AC-AC→AC converter. $I_{in1}$: AC input 1 current $I_{in2}$: AC input 2 current $I_{in3}$: AC input 3 current $V_{out}$: AC output line-to-line voltage


**Biography**

**Hossein Hojabri** was born in Kerman, Iran, in 1982. He received the B.Sc. degree in electrical engineering from Isfahan University of Technology, Isfahan, Iran, in 2004, and the M.Sc. and Ph.D. degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, in 2006 and 2013, respectively. He is currently an Assistant Professor with the Department of Electrical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran. His research interests include application of power electronics in power systems, microgrids, power quality, and renewable energy systems.