Research on the Topology and Control Strategy of a Novel Three-Port Converter

Tao Wang, Xiangqian Chen, Qiang Guo and Shan Li *

School of Electrical and Electronic Engineering, Technology of Chongqing University, Chongqing 400054, China
* Correspondence: lishan@cqut.edu.cn; Tel.: +86-13983022114

Abstract: A novel three-port converter (TPC) is proposed to meet the diversity of demand for electrical equipment in this paper. It interfaces a single input power port and two output ports. The proposed TPC can be viewed as two bidirectional DC-DC converters. With a different operation mode, the proposed TPC can output two DC voltages or a single DC and a single AC voltage. The topology and operation principal of the TPC is analyzed in detail. Moreover, the mathematic model of the TPC is derived. Then, by considering the dynamic response and disturbance suppression, a step by step PI and PR controller design process for TPC is also presented. Both the simulation and the experimental results validate the proposed method.

Keywords: three-port converter; PR controller; sustainable energy; DC-DC converter

1. Introduction

Sustainable energy is attracting more and more attention, due to environmental pol-
lution and the shortage of fossil fuel, [1–3]. With the different demands of electrical
equipment, the sustainable energy sources, such as photovoltaics, fuel cells, etc., [4–6],
need to be converted to appropriate voltage sources. Hence, several separate DC-DC and
DC-AC converters need to be used. However, multiple converters lead to high cost, low
efficiency, and difficulty in achieving centralized control [7].

Compared to multiple separate converters, such as DC-DC, AC-DC and DC-AC
converters, the three-port converter (TPC) has the advantages of fewer components, higher
efficiency, higher power density and a multivoltage level output [8]. It has been widely
used in industrial fields, such as aviation power supply [9], DC micro-grid [10] and electric
vehicles [11,12]. Currently, a number of topologies and control strategies for TPC have
been proposed. In [12], a TPC which consists of three bidirectional DC-DC converters
is presented for fuel-cell-powered hybrid vehicles. It deals with the power flow from
multisource on-board energy systems. Although the structure of the bidirectional DC-DC
converter in [12] is independent, it still needs a lot of switches. In [13], a new DC-DC
converter with three ports is proposed. Therein, only three controllable switches are used,
which reduces the number of switches. In [14], a new single stage three-input DC-DC
boost converter is proposed. It interfaces two unidirectional input ports and a bidirectional
port. Although high integration and high efficiency are realized, the number of power
devices is high and it needs bulky port filters. In [15], a three-port DC-DC converter is
proposed with an integrated magnetic technique, where the port ripple cancellation and
high-power density are realized by two magnetic devices. A three-port high-step-up/step-
down bidirectional DC/DC converter is proposed in [16]. It combines a high-step-up
converter by photovoltaic means and a battery charge/discharge bidirectional converter.
In order to improve the efficiency of a two-stage AC-DC power system, a single-phase
three-port PFC converter with sigma architecture is proposed in [17]. In addition, a novel
three-port three-phase rectifier without isolation transformer is proposed in [18]. The TPC
of [17,18] provides a low voltage DC load port, and a high voltage DC port. So far, nearly
all the three-port converters are either dual input port and single DC output port or single input port and dual DC output port. It cannot supply AC and DC loads at the same time.

With the increase in electrical equipment demands, the DC and AC output hybrid system is more and more popular. Therefore, a novel three-port converter is proposed in this paper. The proposed TPC interfaces a single input power port and two output ports. With different operation modes, the proposed TPC can output two DC voltages or a single DC and a single AC voltage. The paper is organized as follows. In Section 2, the topology, operation principle and mode of the proposed TPC are analyzed in detail, and the simulation results of open-loop control are exhibited. In Section 3, the small-signal model and control strategy of the proposed TPC are investigated when it outputs DC voltage. In Section 4, the large signal model and the optimization design method for a PR controller are investigated when it outputs AC voltage. Finally, the simulation and experimental verification are completed in Sections 5 and 6, respectively.

2. Topology and Operation Mode of Proposed TPC

The topology of the proposed TPC is shown in Figure 1. The DC-link capacitor is $C_{dc}$. $u_{dc}$ is the input voltage. $S_1$–$S_4$ are four switch pairs which consist of an IGBT with anti-parallel diode. $L_a$ and $L_b$ are output filter inductors. $C_a$ and $C_b$ are output filter capacitors. There are two operation modes for the proposed TPC, namely dual DC output and single DC and single AC output. These are analyzed in the next subsection.

Figure 1. Topology of the proposed DC/DC and DC/AC hybrid TPC.

2.1. Dual DC Output Mode

In the dual-DC-output mode, Port 13 and Port 23 are two independent DC output ports. As each leg is combined with a set of LC filters, the proposed TPC can be viewed as two bidirectional DC-DC converters. Taking branch a as an example, the equivalent circuit under different switching states is shown in Figure 2. When $S_1$ is ON and $S_4$ is OFF, the DC load is supplied by the DC voltage source. Here, $u_a = u_{dc}$. When $S_1$ is OFF and $S_4$ is ON, the DC load is supplied by inductor $L_a$ and capacitor $C_a$, and $u_a = 0$. Then, the $u_a$ is a PWM voltage and its average value equals the output port voltage $u_{13}$. 

Figure 2. Equivalent circuits under different switching states of leg-a: (a) $S_1$ is ON and $S_4$ is OFF; (b) $S_4$ is ON and $S_1$ is OFF.
Therefore, the output voltage of TPC in dual DC output mode is

\[
\begin{cases}
u_{13} = u_{dc}d_a \\ v_{23} = u_{dc}d_b
\end{cases}
\]

where \(d_a\) and \(d_b\) represent the duty cycle of \(S_1\) and \(S_2\), respectively. Then Port 12 is also a DC voltage, and equals:

\[
u_{12} = u_{dc}(d_a - d_b)
\]

where \(v_{12}, v_{13}\) and \(v_{23}\) are the voltage of the Port 12, Port 13 and Port 23, respectively. The two independent voltages can be obtained by controlling the duty cycles \(d_a\) and \(d_b\).

### 2.2. Single DC and Single AC Output Mode

In single DC and single AC output mode, Port 23 and Port 12 are DC and AC output ports, respectively. As Port 23 is a DC port, then the duty cycle of \(S_3\) needs to be controlled as a constant. Since the voltage of Port 12 is the voltage difference between Port 13 and Port 23, the duty cycle \(d_a\) should be controlled as follows:

\[
d_a = D + m \cos(\theta)
\]

where \(D\) is a constant and equals \(d_b\). \(m \cos(\theta)\) is the reference signal of Port 12. The range of \(m\) is:

\[
m \in (0, \min(D, 1 - D))
\]

Therefore, if the \(d_b\) is controlled as a constant and \(d_a\) is controlled as in (3), Port 23 and Port 12 can output a DC voltage and AC voltage, respectively.

### 2.3. Open Loop Simulation Results of TPC

In order to verify the voltage output capability of the TPC, the open loop simulation was carried out. The simulation parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter inductor (L_a) and (L_b) (mH)</td>
<td>2</td>
</tr>
<tr>
<td>Filter capacitor (C_a) and (C_b) ((\mu F))</td>
<td>15</td>
</tr>
<tr>
<td>Voltage of DC-bus (u_{dc}) (V)</td>
<td>100</td>
</tr>
<tr>
<td>Switching frequency (f_{sw}) (kHz)</td>
<td>10</td>
</tr>
<tr>
<td>Load of Port 12 (R_{12}) ((\Omega))</td>
<td>10</td>
</tr>
<tr>
<td>Load of Port 13 (R_{13}) ((\Omega))</td>
<td>20</td>
</tr>
<tr>
<td>Load of Port 23 (R_{23}) ((\Omega))</td>
<td>50</td>
</tr>
</tbody>
</table>

Firstly, in dual DC output mode, the duty cycles \(d_a\) and \(d_b\) are 0.7 and 0.4, respectively. The simulation results of output port voltages are shown in Figure 3. It is clear that each output port voltage is consistent with the results of (1) in steady state.

![Figure 3. Simulation waveform under open-loop control when the TPC operates dual DC output mode.](image-url)
Next, in single DC and single AC output mode, the duty cycles $d_a$ and $d_b$ are:

$$\begin{align*}
    d_a &= 0.5 + 0.3 \cos(100\pi t) \\
    d_b &= 0.5
\end{align*}$$

The load of DC Port $23 R_{23}$ is $20 \Omega$. The load of AC Port $12 R_{12}$ is set as $1 \Omega$, $5 \Omega$ and $10 \Omega$, respectively. Then the simulation results of $u_{23}$ and $u_{12}$ are shown in Figure 4. With the increase in AC load, a larger and larger AC component is superimposed on the DC output voltage $u_{23}$. Moreover, the amplitude and phase of the AC output voltage $u_{12}$ is affected by the change of AC load. Therefore, the controller should be carefully designed to eliminate the coupling between DC and AC output port. This is investigated in the next section.

![Simulation waveform under open-loop control when the TPC operates single DC and single AC output mode: (a) $u_{12}$, the voltage of AC-output port; (b) $u_{23}$, the voltage of DC-output port.](image)

**Figure 4.** Simulation waveform under open-loop control when the TPC operates single DC and single AC output mode: (a) $u_{12}$, the voltage of AC-output port; (b) $u_{23}$, the voltage of DC-output port.

### 3. Mathematical Modeling and Control Strategy of DC Output Port

As analyzed in Section 2, the DC output port of the TPC is actually the output of a bidirectional DC-DC converter whether in dual DC output mode or in single DC single AC mode. Taking DC Port $23$ as an example, the corresponding circuit is the combination of branch b and the LC filter. When $S_3$ is turned on, the state equation of $i_b$, $u_{23}$ and the input current $i_{dc}$ is as follows:

$$\begin{align*}
    L \frac{di_b(t)}{dt} &= u_{dc}(t) - u_{23}(t) \\
    C \frac{du_{23}(t)}{dt} &= i_b(t) - \frac{u_{23}(t)}{R} \\
    i_{dc}(t) &= i_b(t)
\end{align*}$$

where $L$, $C$, $R$ represent the value of inductor, capacitor, and load of output port, respectively. When $S_2$ is turned on, the state equation is as follows:

$$\begin{align*}
    L \frac{di_b(t)}{dt} &= -u_{23}(t) \\
    C \frac{du_{23}(t)}{dt} &= i_b(t) - \frac{u_{23}(t)}{R} \\
    i_{dc}(t) &= 0
\end{align*}$$

During a switching period, the average state equation is as follows:

$$\begin{align*}
    L \frac{di_b(t)}{dt} &= d_b(t) u_{dc}(t) - u_{23}(t) \\
    C \frac{du_{23}(t)}{dt} &= i_b(t) - \frac{u_{23}(t)}{R} \\
    i_{dc}(t) &= d_b(t) i_b(t)
\end{align*}$$
The average model in Formula (8) is equivalent to the superposition of the steady-state operating point and disturbed small signal, which includes the following forms:

\[
\begin{cases}
    i_b(t) = I_b + \hat{i}_b \\
    \dot{d}_b(t) = D_b + \dot{\hat{d}}_b \\
    u_{dc}(t) = U_{dc} + \hat{u}_{dc} \\
    u_{23}(t) = U_{23} + \hat{u}_{23} \\
    i_{dc}(t) = I_{dc} + \hat{i}_{dc}
\end{cases}
\]  

(9)

A small-signal state equation is constructed by substituting Equation (9) into Equation(7), which is shown as follows:

\[
\begin{cases}
    L \frac{d \hat{i}_b}{dt} = D_b \hat{u}_{dc} + U_{dc} \dot{\hat{d}}_b - \hat{u}_{23} \\
    C \frac{d \hat{u}_{23}}{dt} = \hat{i}_b - \frac{\hat{u}_{23}}{R} \\
    \dot{i}_{dc} = D_b \dot{\hat{i}}_b + I_{dc} \ddot{\hat{d}}_b
\end{cases}
\]  

(10)

The small-signal equivalent circuit model of Formula (10) is shown in Figure 5.

![Figure 5](image)

Figure 5. The small-signal equivalent circuit model of the TPC.

From Figure 5, the expressions of duty ratio–output voltage transfer function \(G_{d2u}(s)\), input voltage output voltage transfer function \(G_{u2u}(s)\) and output impedance transfer function \(Z_{out}(s)\) are derived as follows:

\[
\begin{align*}
    G_{d2u}(s) &= \frac{U_{23}R}{D_b(LCRs^2 + Ls + R)} \\
    G_{u2u}(s) &= \frac{D_bR}{LCRs^2 + Ls + R} \\
    Z_{out}(s) &= \frac{L_{Rs}}{LCRs^2 + Ls + R}
\end{align*}
\]  

(11)

Then, a PI controller is used to regulate the voltage of Port 23; the control block diagram is shown in Figure 6.

![Figure 6](image)

Figure 6. The control block diagram when the TPC outputs DC voltage.

The open loop transfer function \(H(s)\) can be derived as:

\[
H(s) = \frac{U_{23}(k_p1s + k_d)}{D_bU_{dc}s(LCRs^2 + Ls + R)}
\]  

(12)
where \( k_{p1} \) and \( k_{i1} \) are the proportional and integral coefficients of PI controller, \( \hat{u}_{23} \) can be expressed as:

\[
\hat{u}_{23}(s) = \frac{H(s)\hat{u}_{23}^*(s)}{1 + H(s)} + \frac{G_{u2a}(s)\hat{u}_{dc}^*(s)}{1 + H(s)} - Z_{out}(s)\hat{I}_{23}^*(s)
\]  

(13)

A series of steady-state operating points “\( U_{dc} = 100 \text{ V}, D_b = 0.5, U_{23} = 50 \text{ V}, \) and \( R = 10 \Omega \)” and substituted into (12) and (13). Then, with the sisotool box of MATLAB, the PI controller parameters of TPC are determined by the following principles.

1. The cutoff frequency of \( H(s) \) is near one-tenth of the switching frequency. Then, the balance between steady-state performance and dynamic performance can be realized;
2. In the low frequency band, the amplitude of \( Z_{out}(s)/(1 + H(s)) \) should be below 0 dB;
3. In the low frequency band, the amplitude of \( G_{u2a}(s)/(1 + H(s)) \) should also be below 0 dB.

In this paper, \( k_{p1} \) and \( k_{i1} \) are 1.5 and 20, respectively. At the same time, the bode plot of \( H(s) \) is shown as Figure 7. The cutoff frequency is 1.05 kHz, which satisfies the above principles. The phase margin is 35°. Then, the superior stability and disturbance rejection capability are realized.

![Figure 7](image1)

**Figure 7.** The bode plot of \( H(s) \) after PI compensation.

The bode plots of \( Z_{out}(s)/(1 + H(s)) \) and \( G_{u2a}(s)/(1 + H(s)) \) are shown as Figures 8 and 9, respectively. In the low frequency band, their amplitudes are all below the 0 dB, which satisfies the principle of design for PI controller parameters.

![Figure 8](image2)

**Figure 8.** The bode plot of \( Z_{out}(s)/(1 + H(s)) \) after PI compensation.
Figure 9. The bode plot of $G_{u2u}(s)/(1 + H(s))$ after PI compensation.

4. Control Strategy of AC Output Port

For the AC output port, the corresponding output voltage $u_{12}$ is affected by the AC load $R_{12}$. To solve this problem, the transfer function of AC output circuit is established in this section. Moreover, a proportional resonant (PR) controller is designed to regulate $u_{12}$. As analyzed in Section 2.2, the average value of PWM voltage $u_{ab}$ equals the output voltage $u_{12}$ as in (2). Then, the output voltage can be controlled by adjusting the duty cycles $d_a$ and $d_b$. Since the $d_b$ has already been controlled by a PI controller, only $d_a$ needs to be controlled for the AC port. Figure 10 shows the control block of the AC port.

Figure 10. The control block diagram of the AC port circuit.

The expression of the transform function of PR controller is shown as follows:

$$G_{PR}(s) = k_p + \frac{2k_c\zeta \omega_0 s}{s^2 + 2\zeta \omega_0 s + \omega_0^2}$$

(14)

where $\omega_0$ is the resonant frequency, and set to 100 $\pi$ rad/s, $\zeta$ is the damping ratio and set as 0.5, $k_p$ and $k_c$ are proportional coefficients and resonance coefficients, respectively. From Figure 10, the $u_{12}(s)$ can be expressed as:

$$u_{12}(s) = u'_{12}(s) \cdot G_{close}(s) + i_{12}(s) \cdot G_{i2u}(s)$$

(15)

where $G_{close}(s)$ represents the closed-loop transfer function of the system, and $G_{i2u}(s)$ represents the transfer function from load current to load voltage. The open loop transfer function $G_{open}(s)$ can be derived as:

$$G_{open}(s) = \frac{k_p s^2 + 2\zeta \omega_0 (k_p + k_c) s + k_p \omega_0^2}{(L_C s^2 + 1)(s^2 + 2\zeta \omega_0 s + \omega_0^2)(1 + 1.5Ts)}$$

(16)

The $G_{close}(s)$ and $G_{i2u}(s)$ can be rewritten as:

$$\begin{align*}
G_{close}(s) &= \frac{G_{open}(s)}{1 + G_{open}(s)} \\
G_{i2u}(s) &= \frac{k_p}{1 + G_{open}(s)(L_C s^2 + 1)}
\end{align*}$$

(17)

The order of the transfer function is too high to directly obtain the coefficients in the PR controller. Therefore, to optimize the coefficients $k_p$ and $k_c$, the amplitude–frequency characteristic curves of $G_{close}(s)$ and $G_{i2u}(s)$ under different values of $k_p$ and $k_c$ are plotted.
by MATLAB. Firstly, let $k_p = 1$ and $k_c$ gradually increases from 1 to 30, and the amplitude–frequency characteristic curves of $G_{close}(s)$ and $G_{i2u}(s)$ are shown in Figure 11. With the increase in $k_c$, the amplitude of $G_{close}(s)$ in the low frequency band gradually increases and approaches the 0 dB line. In the high frequency band, $k_c$ has little influence on the amplitude of $G_{close}(s)$. Meanwhile, the gain of $G_{i2u}(s)$ at 50 Hz decreases with the increasing of $k_c$, which indicates that the increasing of $k_c$ has a more obvious inhibition effect on the inhibition of port current.

![Figure 11](image1.png)

**Figure 11.** The Bode plot under different $k_c$: (a) $G_{close}(s)$; (b) $G_{i2u}(s)$.

Next, let $k_c = 5$ and $k_p$ gradually increases from 1 to 30. The amplitude–frequency characteristic curves of $G_{close}(s)$ and $G_{i2u}(s)$ are shown in Figure 12. The following performance at low frequency improves with the increase in $k_p$, but the steady-state errors cannot be eliminated. Meanwhile, the cutoff frequency of $G_{close}(s)$ increases as $k_p$ increases. the amplitude of $G_{i2u}(s)$ decreases as $k_p$ increases.

![Figure 12](image2.png)

**Figure 12.** The Bode plot under different $k_p$: (a) $G_{close}(s)$; (b) $G_{i2u}(s)$.

Based on the independent analysis of $k_p$ and $k_c$, the optimal parameters of the PR controller were obtained ($k_p = 8$ and $k_c = 21$) by using sisotool toolbox of MATLAB, and the Bode diagram of $G_{close}(s)$ is shown in the Figure 13. It shows a good steady-state characteristic in the low frequency band, and the cutoff frequency is 1.2 kHz, which is near one-tenth of the switching frequency, a fast dynamic response can also be obtained.
5. Simulation Results

To verify the effectiveness of the proposed TPC and control strategy, simulations were carried out.

5.1. Simulation Results of Dual DC Output Mode

In dual DC output mode, the reference of $u_{12}$, $u_{13}$ and $u_{23}$ were 40, 90 and 50 V respectively. The simulation results of $u_{12}$, $u_{13}$ and $u_{23}$ are shown in Figure 14a. It is clear that the actual output voltage could accurately track the reference voltage without steady-state error, and the ripple of the voltage of all ports was within the range of $[-1\%, 1\%]$.

![Figure 14](image)

**Figure 14.** The simulation waveforms under close-loop control when the TPC operates dual DC output mode: (a) steady-state; (b) $u_{dc}$ step from 100 V to 120 V at the time of 10 ms.

Figure 14b shows the voltage of each output port when the input voltage $u_{dc}$ step from 100 V to 120 V at the time of 10 ms. The results shown in Figure 14 demonstrate the effectiveness of the proposed controller.

5.2. Simulation Results of Single DC and Single AC Output Mode

In single DC and AC output mode, the reference of $u_{23}$ was 50 V, and the reference of amplitude and frequency of $u_{12}$ set as 25 V and 50 Hz, respectively. The corresponding results are shown in Figure 15 when the AC load was 5 $\Omega$. Compared to the open loop results shown in Figure 4b, the amplitude of the 50 Hz AC component in $u_{23}$ reduced from 3.05 V to 0.03 V.

![Figure 15](image)
Figure 15. The steady-state simulation waveforms under closed loop control when the TPC operates single DC and single AC output mode.

Figure 16 shows the simulation results of $u_{12}$ and $i_a$ when AC load changed from 20 $\Omega$ to 5 $\Omega$ at the time of 0.03 s. It is obvious that a load step perturbation had no effect on $u_{12}$. When the reference of frequency dropped from 50 Hz to 25 Hz, the simulation result of $u_{12}$ is shown in Figure 17. From Figures 15–17, it is clear that the coupling phenomenon between AC port and DC port was suppressed significantly with the proposed PR controller.

Figure 16. The dynamic simulation waveform under closed loop control when $R_{12}$ changes from 20 $\Omega$ to 5 $\Omega$.

Figure 17. The dynamic simulation waveforms under closed loop control when frequency drops from 50 Hz to 25 Hz.

6. Experimental Results

The experiment was also carried out to validate the proposed TPC and its control strategy. The TPC prototype is shown in Figure 18 and its parameters are listed in Table 2. The controller is TMS320F28335.
6.2. Experimental Results under Single DC and Single AC Output Mode

Figure 19a shows the steady experimental results of $u_{12}$, $u_{13}$ and $u_{23}$ when their reference signals were 40, 90 and 50 V, respectively. When a step disturbance occurred in input voltage $u_{dc}$, the experimental results of $u_{23}$ are shown in Figure 19b. It is clear that the output of TPC in dual DC output mode had good steady and transient responses with the proposed controller from Figure 19.

Figure 19. The experimental waveforms under close-loop control when the TPC operates dual DC output mode: (a) steady state; (b) $u_{dc}$ step from 100 V to 120 V.

6.2. Experimental Results under Single DC and Single AC Output Mode

Figure 20a shows the experimental results under single DC and single AC output mode. Therein, the reference signal of $u_{23}$ was 50 V, and the reference of amplitude and frequency of $u_{12}$ were 25 V and 50 Hz, respectively. The FFT results of $u_{12}$ are shown in Figure 20b. With the proposed PR controller, the THD of $u_{12}$ was only 2.86%. From Figure 20a, the DC output voltage $u_{23}$ did not contain the AC component. From Figure 20b, the low order harmonic component in AC output voltage $u_{12}$ was well suppressed with
proposed PR controller. Figure 21 shows the experimental waveforms of \( u_{12} \) and \( u_{23} \) when the AC load \( R_{12} \) changed from 20 \( \Omega \) to 5 \( \Omega \). The results shown in Figures 20 and 21 demonstrate that the output of TPC in single DC and single AC output mode had good steady and transient responses with the proposed controller.

Figure 20. The steady-state experimental waveforms under close-loop control when the TPC operates single DC and single AC output mode: (a) \( u_{12} \) and \( u_{23} \); (b) FFT results of \( u_{12} \).

Figure 21. The dynamic experimental waveforms under close-loop control when \( R_{12} \) changes from 20 \( \Omega \) to 5 \( \Omega \).

7. Conclusions

The simulation and experimental results proved the feasibility and correctness of the topology and control strategy of the proposed TPC in this paper. Several conclusions are summarized as follows.

1. A novel and simple three-port converter is proposed. It interfaces a single input power port and two output ports.
2. The proposed TPC has two operation modes. It can output two DC voltages with different levels or output a single AC voltage and a single DC voltage at the same time.
3. With the proposed control scheme, the coupling between the DC and AC output ports in TPC could be suppressed, significantly.
4. In the single DC and single AC output mode, the maximum of AC output voltage is half of the input voltage.

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S.L.; project administration, S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

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