Steady-state output characteristics of a three-port bidirectional DC-DC converter with dead time

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Abstract. This paper introduces a transformer-coupled three-port three-bridge half-bridge bidirectional DC-DC converter with dead time phase shift control. The converter consists of a high-frequency three-winding transformer and three independent half-bridge circuits. The half bridge is coupled through a transformer to provide galvanic isolation for all power ports. The converter uses phase shift control to achieve energy flow control through pulse width modulation (PWM). By controlling the gate pulse by PWM, the control of the dead time is realized, and the dead time can effectively suppress the straight-through phenomenon of the switch in the multi-port system, which can reduce power consumption and protect the power device. Through mathematical derivation, a detailed theoretical analysis of the three-port steady-state output characteristics with dead time is carried out. A typical application of the proposed converter is an electric vehicle auxiliary power supply system with a photovoltaic cell/auxiliary battery/power battery. The effectiveness of the proposed converter was verified by MATLAB simulation software.

1. Introduction

The energy crisis and environmental problems brought about by traditional fossil energy are becoming more and more serious, but the demand for electricity and economic development is growing. The three-port DC-DC converter effectively combines the power supply end with the energy storage component to overcome the inherent problems of randomness and separability of the renewable energy power generation system. The energy of the power supply is transmitted to the output at a faster speed and smaller size, so that the entire circuit module can be miniaturized and lightened [1].

One practical way to implement a three-port system is to use a transformer with multiple secondary windings to provide multiple inputs [2] or outputs [3]. A current-type multi-port DC-DC converter topology is described in [4]. This topology connects two current sources through the full bridge to the same three-winding transformer. The two input current sources provide power to the load simultaneously or in a time-sharing manner.

The active three-port bridge topology in the dual active bridge topology [5-9] has the following characteristics: Since all ports have a bridge structure, the energy flow is bidirectional, and the power flow between the three ports can be managed by a phase shift bridge [10]. The use of the delta model of the transformer network facilitates system analysis [11]. However, the main disadvantage of the three-port converter is that it does not maintain soft switching in the case of a wide operating voltage at the port. In the literature [12], an MCCI-type isolated three-port three-half bridge (THB) bidirectional DC-DC converter is proposed. The circuit consists of three half-bridge topologies and a
three-winding isolating transformer, where both inputs are combined boost half-bridge topology units and the output is a voltage-type half-bridge topology unit.

This paper describes a three-port half-bridge DC-DC converter consisting of three half-bridges. The three-port energy flow with dead time is studied, and the steady-state output characteristics of multi-port are analyzed theoretically based on the dead time.

2. Topological analysis
If the isolated multi-port converter is applied to an electric vehicle auxiliary power supply system, the output port is generally the charging port of the electric vehicle, and the charging voltage of the charging interface can be set to be the same or different. In order to absorb photovoltaic energy, input ports often need to be integrated. These renewable energy input ports generally only require their output energy and do not require energy absorption. Therefore, these ports can be used as one-way ports. In the introduction of renewable energy, the system will inevitably be affected by the intermittent and volatility characteristics of its power supply. The input power may not meet the system load requirements at certain moments. In order to alleviate this deficiency, the system port can introduce energy storage devices such as auxiliary batteries and power batteries, which provide the remaining energy when the photovoltaic energy transmission power is insufficient, and can store excess energy when the photovoltaic energy transmission power is greater than the load demand. Therefore, the port connecting the energy storage device needs to have the ability to flow in both directions. The general topology of the isolated multi-port converter for electric vehicle auxiliary power supply system can be as shown in figure 1 below:

Figure 1. General purpose topology for isolated three-port converters for electric vehicles.

This paper takes the isolated voltage type half-bridge three-port converter as an example. The topology is shown in figure 2.

As shown in figure 2, the circuit consists of three input combined half-bridge circuits, a three-winding high frequency transformer. Bidirectional power flow between each input and output can be achieved. The converter adopts phase shift control, wherein the primary side power supply \( U_{i1} \) is connected to the half bridge topology unit, and the phase shift angles between the secondary side power sources \( U_{i2}' \) and \( U_{i3}' \) are respectively \( \phi_{12} \) and \( \phi_{13} \), and the phase shift angle between the secondary half circuit circuits is \( \phi_{23} (= \phi_{13} - \phi_{12}) \). When the primary side is used as a reference, a square wave voltage \( u_1 \) is generated on the primary side of the transformer. The half-bridge circuit on the secondary side generates two square wave voltages \( u_2' \) and \( u_3' \) on the secondary side of the transformer. The theoretical analysis below shows that the magnitude and direction of the transmitted power between the three ports can be changed by controlling the phase shift angles \( \phi_{12} \), \( \phi_{13} \), and \( \phi_{23} \) of the drive signals between the transform units on both sides of the transformer, and it is possible to transmit power separately or simultaneously between any ports.
This converter has the following advantages over the other multiport DC converters mentioned in the literature above:

- The use of a half-bridge structure can reduce the number of components, can effectively reduce costs, and can greatly reduce the volume of the converter in places where space such as electric vehicles is limited;
- Soft switching can be realized in a large load range without an auxiliary device and a resonant circuit;
- The converter can eliminate power fluctuations caused by intermittent photovoltaic power generation;
- The voltage type input terminal can provide continuous current, which is suitable for connecting energy storage components such as batteries and super capacitors. By controlling the input leakage current, the power distribution between each port can be accurately realized.
- The introduction of dead time control can effectively suppress the straight-through phenomenon of power devices.

3. Three-port equivalent circuit analysis

Multi-winding transformers play a very important role in the converter circuit topology, and their functions include the following three aspects: (1) combining different DC input power sources by means of magnetic coupling; (2) providing storage Electrical isolation between the energy component and the load (inverter); (3) boosting from the low voltage side (LVS) to the high voltage side (HVS). The transformer leakage inductance is used here as an energy transfer element between the input and output loads. The equivalent circuit of the three-winding transformer given in [13] is shown in figure 3(a), where \( L_m \) is the effective magnetizing inductance. \( T_1 \) and \( T_2 \) are two ideal transformers with a turns ratio of \( 1:n_2 \) and \( 1:n_3 \). Where \( L_1', L_2' \) and \( L_3' \) respectively represent the leakage inductance of each winding of the primary and secondary sides. In the case of ignoring the magnetizing inductance, the three-half bridge DC-DC converter shown in figures 3(b) and 3(c) can be obtained. Simplified circuit models in which each half-bridge circuit is replaced by an equivalent voltage source, and the three-winding transformer is represented by a "Y" and "Δ" shaped circuit model.
Figure 3. (a) Equivalent circuit of a three-winding transformer. (b) Y-type primary equivalent circuit of a three-port system. (c) Delta type primary equivalent circuit of a three-port system.

The power flow in the converter is determined by the square wave voltage sources $u_1$, $u_2'$, $u_3'$ and the duty cycle $D$ shown in figure 3(a). $i_1$, $i_2'$, $i_3'$ are the leakage inductance currents of each winding. In the transformer "Y" shape of Figure 3(b), $i_1$ is the primary current, $i_2$ and $i_3$ are the secondary currents, $u_1$ is the primary voltage, $u_2$ and $u_3$ are the secondary voltages, $V_1$, $V_2$, $V_3$, $V_4$, $V_5$ and $V_6$ are capacitor voltages that are converted to the primary side. Since the transformer $Tr$ leakage inductance is used as the energy transfer element between the three ports during the operation of the converter, the leakage inductance can be used instead of the transformer when performing circuit simplification analysis. It can be seen from figures 3(a) and 3(b) that

\[ L_2 = L_2' \frac{n_2}{n_2}, L_3 = L_3' \frac{n_3}{n_3}, i_1 = i_2', n_2 = i_3', n_3 = u_2' / n_2, u_3 = u_3' / n_3 \]

is satisfied between the inductance, the voltage and the current.

In the "Y" shape of the transformer, the leakage inductance of each winding is the equivalent leakage inductance with reference to the primary side. By applying "Y-Δ" conversion, the "Δ" of the transformer shown in figure 3(c) can be obtained. where $L_{12}$, $L_{13}$ and $L_{23}$ respectively represent the leakage inductance between the windings of the "Δ" shape model, which are combined with "The following conversion relationships are satisfied between the leakage inductances in the Y-shaped model:

\[ L_{23} = \frac{L_1}{L_3} \cdot L_2 + L_1 \cdot L_3 \cdot L_2, L_{13} = \frac{L_1}{L_2} \cdot L_3 + L_1 \cdot L_3 \cdot L_2, L_{12} = \frac{L_1}{L_3} \cdot L_2 + L_1 \cdot L_3 + L_2 \cdot L_3 \]

Where $i_{12}, i_{13}, i_{23}$ indicates the leakage current of $L_{12}, L_{13}, L_{23}$.

The "Δ" shape model is suitable for mathematical modeling of the converter, while the "Y" shape model is suitable for both commutation and soft switching condition analysis. The converter can be conceptually viewed as an inductive network driven by a square wave voltage source, where the voltage sources are controlled by phase shifts between each other.

4. Steady-state analysis with dead time

In the half-bridge circuit, due to the existence of parasitic capacitance of the power tube, there is a delay in the switching process of the power tube, and the switching operation cannot be completed instantaneously. Therefore, it is possible to cause the high-voltage side power tube and the low-voltage
side power tube in the half-bridge circuit to simultaneously turn on the burn-in circuit. In order to avoid this, the signals of the high-voltage side MOS tube and the low-voltage side MOS tube cannot be completely synchronized, and it is necessary to insert a period of time therein, which is also called dead time. Since the operating efficiency of the circuit varies with dead time, the dead time of the highest operating efficiency depends on different applications, input or load conditions, external components, and so on. Therefore, the control circuit of the half-bridge circuit can have better applicability if a programmable dead time is added [14, 15]. In this paper, the dead-time phenomenon is suppressed by the dead time, and the dead time setting is realized. The delay signal is generated by the high-low side signal, and the driving signal with the dead time delay is obtained by the logical operation with the original signal.

Figure 4 analyzes the ideal voltage and current waveforms on both sides of the transformer with dead time. The amount of energy transmitted across the transformer is determined by the phase shift angle between the square wave voltages. The current waveform is determined by the phase shift angle and the voltage relationship between $V_1$, $V_2$, $V_3$, $V_4$, $V_5$ and $V_6$, and will be demonstrated in detail below. The analysis of the steady-state characteristics of the output of the three-half bridge DC-DC converter with dead time is based on the equivalent circuit with reference to the primary side and the ideal voltage and current waveform of the transformer shown in figure 4.

As can be seen from figure 4, the converter has eighteen modes during one switching cycle. The transformer currents $i_{12}$, $i_{13}$ and $i_{23}$ are all functions of $\theta(=\omega t)$, where $\omega=2\pi f$, $f$ is the switching frequency. The square wave length in the positive half cycle of a cycle is $\phi=2\pi D$. The following analysis shows the case of leakage inductance current $i_{12}$ when the duty ratio is 0.5, and the leakage inductance currents $i_{13}$ and $i_{23}$ can be similarly introduced. Table 1 lists the expression of the leakage inductance current $i_{12}$ of the transformer for each operating mode.
Figure 4. Ideal voltage and current waveforms on both sides of the transformer with dead time when referenced to the primary side.
### Table 1. Expression of transformer leakage current $i_{12}$.

| Converter mode | Three-winding transformer leakage current $i_{12} (\theta)$ |
|----------------|----------------------------------------------------------|
| Mode 1 $(0 < \theta \leq \Delta \theta)$                  | $\frac{V_1 - \theta + i_{12} (0)}{\omega L_{s2}}$         |
| Mode 2 $(\Delta \theta < \theta \leq \phi_{12} - \Delta \theta)$ | $\frac{V_1 + V_1 (\theta - \Delta \theta) + i_{12} (\Delta \theta)}{\omega L_{s2}}$ |
| Mode 3 $(\phi_{12} - \Delta \theta < \theta \leq \phi_{12})$ | $\frac{V_1}{\omega L_{s2}} (\theta - \phi_{12} + \Delta \theta) + i_{12} (\phi_{12} - \Delta \theta)$ |
| Mode 4 $(\phi_{12} < \theta \leq \phi_{12} + \Delta \theta)$ | $\frac{V_1 - V_1 (\theta - \phi_{12} - \Delta \theta) + i_{12} (\phi_{12} + \Delta \theta)}{\omega L_{s2}}$ |
| Mode 5 $(\phi_{12} + \Delta \theta < \theta \leq \phi_{13} - \Delta \theta)$ | $\frac{-V_1}{\omega L_{s2}} (\theta - \phi + \Delta \theta) + i_{12} (\phi - \Delta \theta)$ |
| Mode 6 $(\phi_{13} - \Delta \theta < \theta \leq \phi_{13})$ | $\frac{-V_2 - V_1 (\theta - \phi - \Delta \theta) + i_{12} (\phi + \Delta \theta)}{\omega L_{s2}}$ |
| Mode 7 $(\phi_{13} < \theta \leq \phi_{13} + \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi + \Delta \theta) + i_{12} (\phi + \phi_{12} + \Delta \theta)$ |
| Mode 8 $(\phi < \theta \leq \phi + \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi + \Delta \theta) + i_{12} (\phi + \phi_{12} - \Delta \theta)$ |
| Mode 9 $(\phi - \Delta \theta < \theta \leq \phi)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi - \Delta \theta) + i_{12} (\phi + \phi_{12})$ |
| Mode 10 $(\phi < \theta \leq \phi + \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi - \Delta \theta) + i_{12} (\phi + \phi_{12} + \Delta \theta)$ |
| Mode 11 $(\phi + \Delta \theta < \theta \leq \phi_{12} + \phi - \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi - \Delta \theta) + i_{12} (\phi + \phi_{12})$ |
| Mode 12 $(\phi_{12} + \phi - \Delta \theta < \theta \leq \phi_{12} + \phi)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi + \Delta \theta) + i_{12} (\phi + \phi_{12} + \Delta \theta)$ |
| Mode 13 $(\phi_{12} + \phi < \theta \leq \phi_{13} + \phi + \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi + \Delta \theta) + i_{12} (\phi + \phi_{12} - \Delta \theta)$ |
| Mode 14 $(\phi_{12} + \phi + \Delta \theta < \theta \leq \phi_{13} + \phi - \Delta \theta)$ | $\frac{-V_2}{\omega L_{s2}} (\theta - \phi - \phi_{12} - \Delta \theta) + i_{12} (\phi + \phi_{12} - \Delta \theta)$ |
| Mode 15 $(\phi_{13} + \phi - \Delta \theta < \theta \leq \phi_{13} + \phi)$ | $\frac{V_1}{\omega L_{s2}} (\theta - 2\pi + \Delta \theta) + i_{12} (2\pi - \Delta \theta)$ |
| Mode 16 $(\phi_{13} + \phi < \theta \leq \phi_{13} + \phi + \Delta \theta)$ | $\frac{V_1}{\omega L_{s2}} (\theta - \phi - \Delta \theta) + i_{12} \psi(2\pi - \Delta \theta)$ |
| Mode 17 $(\phi_{13} + \phi + \Delta \theta < \theta \leq 2\pi - \Delta \theta)$ | $\frac{V_1}{\omega L_{s2}} (\theta - 2\pi + \Delta \theta) + i_{12} (2\pi - \Delta \theta)$ |
| Mode 18 $(2\pi - \Delta \theta < \theta \leq 2\pi)$ | $\frac{V_1}{\omega L_{s2}} (\theta - 2\pi + \Delta \theta) + i_{12} (2\pi - \Delta \theta)$ |

From the 18 working modes in Table 1, the following conclusions can be analyzed:
The volt-second value of the positive and negative half cycles of the transformer should be balanced in one cycle. Therefore, the initial condition of the transformer current $i_{12}$ should satisfy the following boundary conditions:

$$
\begin{align*}
\Delta \theta \quad & \quad i_{12}(\Delta \theta) = \frac{V_4}{\omega L_{t2}} \cdot (\Delta \theta) + i_{12}(0) \\
\phi_{12} - \Delta \theta \quad & \quad i_{12}(\phi_{12} - \Delta \theta) = \frac{V_1 + V_4}{\omega L_{t2}} \cdot (\phi_{12} - 2 \Delta \theta) + i_{12}(\Delta \theta) \\
\phi_{12} + \Delta \theta \quad & \quad i_{12}(\phi_{12} + \Delta \theta) = \frac{V_1}{\omega L_{t2}} \cdot (2 \Delta \theta) + i_{12}(\phi_{12} - \Delta \theta) \\
\pi - \Delta \theta \quad & \quad i_{12}(\pi - \Delta \theta) = \frac{V_1 - V_3}{\omega L_{t2}} \cdot (\pi - \phi_{12} - 2 \Delta \theta) + i_{12}(\phi_{12} - \Delta \theta) \\
\pi + \Delta \theta \quad & \quad i_{12}(\pi + \Delta \theta) = \frac{V_3}{\omega L_{t2}} \cdot (2 \Delta \theta) + i_{12}(\pi - \Delta \theta) \\
\phi_{12} + \pi - \Delta \theta \quad & \quad i_{12}(\phi_{12} + \pi - \Delta \theta) = \frac{V_2 - V_3}{\omega L_{t2}} \cdot (\phi_{12} - 2 \Delta \theta) + i_{12}(\pi + \Delta \theta) \\
\phi_{12} + \pi + \Delta \theta \quad & \quad i_{12}(\phi_{12} + \pi + \Delta \theta) = \frac{V_2}{\omega L_{t2}} \cdot (2 \Delta \theta) + i_{12}(\phi_{12} - \Delta \theta) \\
\pi - 2 \Delta \theta \quad & \quad i_{12}(\pi - 2 \Delta \theta) = \frac{-V_2 + V_1}{\omega L_{t2}} \cdot (\pi - \phi_{12} - 2 \Delta \theta) + i_{12}(\phi_{12} + \Delta \theta) \\
\pi + 2 \Delta \theta \quad & \quad i_{12}(\pi + 2 \Delta \theta) = \frac{V_1}{\omega L_{t2}} \cdot (\pi + \phi_{12} + \Delta \theta) + i_{12}(2 \pi - \Delta \theta)
\end{align*}
$$

Equation (2) combined with the boundary condition formula (3), the initial conditions of $i_{12}$ can be obtained:

$$
\begin{align*}
i_{12}(0) = i_{12}(2\pi) \\
i_{12}(\Delta \theta) = i_{12}(\phi_{12} + \pi - \Delta \theta) = -i_{12}(\phi_{12} - \Delta \theta) = -i_{12}(\pi + \Delta \theta) \\
i_{12}(\phi_{12} + \Delta \theta) = i_{12}(\pi - \Delta \theta) = -i_{12}(\pi + \phi_{12} + \Delta \theta) = -i_{12}(2\pi - \Delta \theta)
\end{align*}
$$

Equation (4) can be simplified as:

When the voltages of the three ports match, the capacitor voltages $V_1$, $V_2$, $V_3$, $V_4$, $V_5$ and $V_6$ converted to the primary side are equal in size. Assume $V_1 = V_2 = V_3 = V_4 = V_5 = V_6 = V_a$, and equation (4) can be simplified as:
\[
\begin{align*}
  i_{12}(0) &= i_{12}(2\pi) = -\frac{V_d}{\omega L_{i2}} (\phi_{12} - \Delta \theta) \\
  i_{12}(\Delta \theta) &= i_{12}(\phi_{12} + \pi - \Delta \theta) = -i_{12}(\phi_{12} - \Delta \theta) = -i_{12}(\pi + \Delta \theta) = -\frac{V_d}{\omega L_{i2}} (\phi_{12} - 2\Delta \theta) \\
  i_{12}(\phi_{12} + \Delta \theta) &= i_{12}(\pi - \Delta \theta) = -i_{12}(\pi + \phi_{12} + \Delta \theta) = -i_{12}(2\pi - \Delta \theta) = \frac{V_d}{\omega L_{i2}} (\phi_{12})
\end{align*}
\] (5)

Similarly, the initial conditions of \( i_{13} \) and \( i_{23} \) are available:
\[
\begin{align*}
  i_{13}(0) &= i_{13}(2\pi) = -\frac{V_d}{\omega L_{i3}} (\phi_{13} - \Delta \theta) \\
  i_{13}(\Delta \theta) &= i_{13}(\phi_{13} + \pi - \Delta \theta) = -i_{13}(\phi_{13} - \Delta \theta) = -i_{13}(\pi + \Delta \theta) = -\frac{V_d}{\omega L_{i3}} (\phi_{13} - 2\Delta \theta) \\
  i_{13}(\phi_{13} + \Delta \theta) &= i_{13}(\pi - \Delta \theta) = -i_{13}(\pi + \phi_{13} + \Delta \theta) = -i_{13}(2\pi - \Delta \theta) = \frac{V_d}{\omega L_{i3}} (\phi_{13})
\end{align*}
\] (6)

\[
\begin{align*}
  i_{23}(0) &= i_{23}(\phi_{23} - \Delta \theta) = i_{23}(\phi_{23} + \pi + \Delta \theta) = i_{23}(2\pi) = -i_{23}(\phi_{23} + \Delta \theta) \\
  = -i_{23}(\phi_{23} + \pi - \Delta \theta) = \frac{V_d}{\omega L_{i3}} (\phi_{23} - \phi_{12} - 4\Delta \theta) \\
  i_{23}(\phi_{23} + \Delta \theta) &= i_{23}(\phi_{23} + \pi - \Delta \theta) = -i_{23}(\phi_{23} - \Delta \theta) = -i_{23}(\phi_{23} + \pi + \Delta \theta) \\
  = \frac{V_d}{\omega L_{i3}} (\phi_{23} - \phi_{12} - 2\Delta \theta)
\end{align*}
\] (7)

As can be seen from table 1 and equations (5)-(7), the leakage currents \( i_{12}, i_{13} \) and \( i_{23} \) are linearly related to the capacitor voltages \( V_1, V_2, V_3, V_4, V_5 \), and \( V_6 \).

The transmission power of the power source \( U_{i1} \) to the power source \( U_{i2} \) is \( P_{12} \), the transmission power of the power source \( U_{i2} \) to the power source \( U_{i3} \) is \( P_{23} \), the transmission power of the power source \( U_{i3} \) to the power source \( U_{i1} \) is \( P_{13} \), the output power of the power source \( U_{i1} \) is \( P_1 \), and the output power of the power source \( U_{i2} \) is \( P_2 \). The output power of the power source \( U_{i3} \) is \( P_3 \). The output power of the power supply \( U_{i1} \) can be obtained by the expressions of \( i_{12} \) and \( i_{13} \):

\[
P_1 = \frac{1}{2\pi} \int_0^{2\pi} i_{12}(\theta) \cdot u_i(\theta) d\theta = P_{12} + P_{13} = \frac{1}{2\pi} \int_0^{2\pi} i_{13}(\theta) \cdot u_i(\theta) d\theta + \frac{1}{2\pi} \int_0^{2\pi} i_{12}(\theta) \cdot u_i(\theta) d\theta
\] (8)

Where \( u_i(\theta) \) is the piecewise function shown by equation (9):

\[
u_i(\theta) = \begin{cases} 
  V_1 & (0 < \theta < \phi) \\
  -V_2 & (\phi < \theta < 2\pi)
\end{cases}
\] (9)

To meet the conditions:

\[
U_i = (1-D) \cdot U_{i1} \\
V_2 = D \cdot U_{i1}
\] (10)
From table 1 and equations (5), (8), (9) and (10), the output power of the power source $U_i$ can be obtained:

$$P_i = P_{12} + P_{13} = \frac{V_o^2 \cdot [\phi_{12} \cdot (\pi - |\phi_{12}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{12}} + \frac{V_o^2 \cdot [\phi_{13} \cdot (\pi - |\phi_{13}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{13}}$$  \hspace{1cm} (11)

Similarly, the output power of power supplies $U_i$ and $U_i$ can be derived:

$$P_2 = -P_{12} + P_{23} = -\frac{V_o^2 \cdot [\phi_{12} \cdot (\pi - |\phi_{12}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{12}} + \frac{V_o^2 \cdot [\phi_{23} \cdot (\pi - |\phi_{23}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{23}}$$ \hspace{1cm} (12)

$$P_3 = -P_{13} - P_{23} = -\frac{V_o^2 \cdot [\phi_{13} \cdot (\pi - |\phi_{13}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{13}} - \frac{V_o^2 \cdot [\phi_{23} \cdot (\pi - |\phi_{23}|) - 2(\Delta \theta)^2]}{2\pi^2 fL_{23}}$$ \hspace{1cm} (13)

It can be derived from equations (11)-(13):

$$P_1 + P_2 + P_3 = 0$$ \hspace{1cm} (14)

From equations (11)-(13), it can be seen that an inductor with a smaller value can achieve a higher power flow, and when the output power remains unchanged, this causes a phase shift. The angle is reduced and a large current stress can be applied to the switching device. Therefore, consideration should be made to ensure that the current stress of the switching device is within the safe range and that the required output power level should also be met.

Combining the power transfer formulas of (11)-(14), the relationship between the power transmission direction between ports and the phase shift angles can be drawn. Where $\phi_{23} = \phi_{13} - \phi_{12}$, as shown in figure 5.

![Figure 5. Power transfer mode of a three-port converter.](image)

As can be seen from figure 5, there are eight basic power flows between the three ports:

- When $\phi_{12} > 0, \phi_{13} > 0$ and $\phi_{23} > 0$. At this time, $P_{12} > 0, P_{13} > 0, P_{23} > 0$, so port 1 transmits power to port 2 and port 3, and port 2 transmits power to port 3.
- When $\phi_{12} > 0, \phi_{13} > 0$ and $\phi_{23} < 0$. At this time, $P_{12} > 0, P_{13} > 0, P_{23} < 0$, so port 1 transmits power to port 2 and port 3, and port 3 transmits power to port 2.
- When $\phi_{12} > 0, \phi_{13} < 0$ and $\phi_{23} > 0$. At this time, $P_{12} > 0, P_{13} < 0, P_{23} > 0$, so port 1 delivers power to port 2, port 2 delivers power to port 3, and port 3 delivers power to port 1.
When \( \phi_{12} > 0, \phi_{13} < 0 \) and \( \phi_{23} < 0 \). At this time, \( P_{12} > 0, P_{13} < 0, P_{23} < 0 \), so port 3 delivers power to port 1, port 2, and port 1 delivers power to port 2.

When \( \phi_{12} < 0, \phi_{13} > 0 \) and \( \phi_{23} > 0 \). At this time, \( P_{12} < 0, P_{13} > 0, P_{23} > 0 \), so port 2 delivers power to port 1, port 1 delivers power to port 3, and port 2 delivers power to port 3.

When \( \phi_{12} < 0, \phi_{13} > 0 \) and \( \phi_{23} < 0 \). At this time, \( P_{12} < 0, P_{13} > 0, P_{23} < 0 \), so port 2 delivers power to port 1, port 1 delivers power to port 3, and port 3 passes power to port 2.

When \( \phi_{12} < 0, \phi_{13} < 0 \) and \( \phi_{23} > 0 \). At this time, \( P_{12} < 0, P_{13} < 0, P_{23} > 0 \), so port 2 delivers power to port 1, port 3 delivers power to port 1, and port 2 delivers power to port 3.

When \( \phi_{12} < 0, \phi_{13} < 0 \) and \( \phi_{23} < 0 \). At this time, \( P_{12} < 0, P_{13} < 0, P_{23} < 0 \), so port 2 delivers power to port 1, port 3 delivers power to port 1, and port 3 delivers power to port 2.

There is energy transfer between the three ports, and the energy between the three ports is only related to the phase shift angles \( \phi_{12} \) and \( \phi_{13} \) between port 1 and port 2 and port 3 in the case where the voltages at the respective terminals are determined. These two phase shift angles can be used to control the energy distribution of the three ports. The size of \( \phi_{12} \) and \( \phi_{13} \) determines the amount of energy transferred by each port, and the signs of \( \phi_{12}, \phi_{13} \) and \( \phi_{23} \) determine the flow direction between the energy of each port. It is worth noting that since the total output power of each port is the sum of the output powers of the other two ports, if a port delivers energy to one of the ports exactly equal to the energy delivered by the last port to the port, then The other two ports outside this port have a total output power of zero. In other words, in this case the port is equivalent to an intermediate link of the energy transfer of the other two ports, and the entire three-port converter system as a whole can be seen as only two ports participating in the energy transfer process. Taking port 1 as an example, the energy transmitted to port 2 and port 3 is \( P_{12} \) and \( P_{13} \), respectively. If \( \phi_{12} \) and \( \phi_{13} \) are controlled, the equation satisfies \( P_1 = P_{12} + P_{13} = 0 \). According to the law of conservation of power, \( P_2 + P_3 = 0 \) at this time, that is, the total output power of port 2 and port 3 is 0. For the entire system, the power delivered by port 2 is equal to the power absorbed by port 3. It can be seen that port 1 is equivalent to the medium for energy transfer between port 2 and port 3, and port 3 does not consume power as a whole. The power flow at this time can be represented by figure 6 below:

![Figure 6. Schematic diagram of power transfer when \( P_1 = P_{12} + P_{13} = 0 \).](image)

5. **Control strategy**

According to the above equations (1)-(14), different control schemes can be implemented. In this paper, the dual loop control strategy is applied to a three-port system. One loop is a voltage loop that keeps the voltage at each port constant. The other loop is a current loop that controls the direction of power flow between the different ports and maximizes the output power. To achieve the above
objectives, the control scheme shown in figure 7 employs two PI controllers. Where $i_1$ and $v_1$ are the feedback current and voltage of the first input stage; $i_2$ and $v_2$ are the feedback current and voltage of the second input stage; $i_3$ and $v_3$ are the feedback current and voltage of the third stage.

![Three-port half-bridge control scheme](image)

**Figure 7.** Three-port half-bridge control scheme.

6. Simulation
The steady-state performance of working mode 1 of the dead-time three-half bridge DC-DC converter in figure 4 above was simulated using MATLAB. The converter-related simulation parameters are listed in table 2.

| Table 2. Simulation parameter.                  |
|------------------------------------------------|
| Input voltage $U_{i_1}$ | 100V                   |
| Input voltage $U_{i_2}$ | 100V                   |
| Input voltage $U_{i_3}$ | 400V                   |
| Divided capacitor $C_1, C_2, C_3, C_4$ | 4mF                    |
| Divided capacitor $C_5, C_6$ | 500µF                  |
| Voltage stabilizing capacitor $C_{1q} \sim C_{3q}$ | 10mF                   |
| Transformer ratio $n_1 : n_2 : n_3$ | 1:1:4                  |
| Transformer leakage inductance $L_{12}, L_{33}$ | 1.3µH                  |
| Transformer leakage inductance $L_{23}$ | 20.8µH                 |
| Resonant capacitor $C_{r1}, C_{r2}, C_{r3}, C_{r4}$ | 0.5µF                  |
| Resonant capacitor | 0.05µF                 |
When the phase shift angle is $\phi_2 = 0.25\pi$ and the phase shift angle is $\phi_3 = 0.375\pi$, the voltages $u_1$, $u_1'$ and $u_1''$ on both sides of the transformer can be obtained, and the leakage current of each winding of the transformer is $i_1$, $i_1'$, and $i_1''$, and the average power $P_1$, $P_2$ and $P_3$ of the output of the port is obtained. The simulation waveform is shown in figures 8 and 9. It can be seen from figure 8 that the simulation waveforms of the voltage and winding leakage current on both sides of the transformer are consistent with the analysis results of the steady-state characteristics. The phase of the primary side voltage $u_1$ leads the secondary side voltages $u_1'$ and $u_1''$, and the port 1 transmits to the port 2 and port 3. Port 1 is in the output power state. The phase of the secondary voltage $u_2$ leads the secondary
voltage $u_3'$, and the port 2 transmits power to the port 3. By changing the magnitude of the phase shift angle between the primary side secondary square wave voltages, the amount of energy transmitted by the converter can be varied. The power calculation results obtained by bringing the parameters into equations (11)-(13) are in agreement with the simulation results in figure 9.

Figure 10 shows a three-dimensional plot of the functional relationship between output powers $P_1$, $P_2$, and $P_3$, where the range of $\phi_{12}$ and $\phi_{13}$ is defined at $[0, \pi]$.

![Figure 10](image)

**Figure 10.** Three-dimensional graph of the relationship between output power $P_1$, $P_2$, and $P_3$ and phase shift angles $\phi_{12}$ and $\phi_{13}$.

In figure 10, the abscissa indicates $\phi_{12}$ and $\phi_{13}$, respectively, and the ordinate indicates the output power of each port. Above the zero plane, it indicates that the output power of the port is positive and the power is emitted. Below the zero plane, the output power of the port is negative and the power is absorbed. As can be seen from the figure, when $\phi_{12} = \phi_{13} = 0.5\pi$, the output power of port 1 is the largest.

When the three-port converter is used in an electric vehicle integrated system, port 1 can be connected to a renewable energy source such as photovoltaics, port 2 can be connected to an auxiliary battery of an electric vehicle, and port 3 can be connected to a power battery of an electric vehicle, and the battery charging voltage level can be the same. It can also be different. When there is photovoltaic participation in the multi-port integrated system of the isolated electric vehicle, it can first provide the maximum power that the auxiliary battery of the electric vehicle can emit, and the power of the electric vehicle when the maximum power still cannot satisfy the charging of the electric vehicle. The battery replenishes the remaining power. When the photovoltaic can fully satisfy the auxiliary battery energy, it can charge the power battery of the electric vehicle; when there is no light, the auxiliary battery power is completely provided by the power battery. Using the power transfer relationship of
each port, under the condition that each port voltage is known, the values of $\phi_1$ and $\phi_2$ in different cases can be obtained to realize port energy management under each condition.

7. Conclusions
In this paper, a three-port converter with dead time is used to analyze the working principle, commutation process and energy flow of the three-port steady-state output in detail. Based on the structure of the three-half bridge, the steady-state characteristics of the converter are analyzed by mathematical expressions. The effects of phase shift angles $\phi_1$ and $\phi_2$ on the energy flow of the converter are studied. The gate pulse is controlled by PWM to control the dead time. For multi-port structure, the dead time can suppress the straight-through phenomenon of the switch. Reduce power consumption and protect power devices. Maximum power and constant output voltage are achieved by using phase-shifted PWM and dual PI control schemes. Finally, the feasibility of the three-half bridge DC-DC converter is verified by MATLAB simulation software.

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