A Feedforward Decoupling Control Method for Multi-ports DC Transformer

Hao Wu1, 2,*
1 Key laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, China
2 University of Chinese Academy of Sciences, Beijing, 100049, China

* Corresponding author e-mail: wuhao@mail.iee.ac.cn

Abstract. DC Transformer (DCT) is a new type of intelligent power electronic device using power semiconductors and high-frequency transformer to realize power conversion. Multi-ports DCT has broad applications in DC distribution networks. In this paper, the power transmission characteristics of the phase-shift controlled multi-ports DCT are analyzed. The non-linear coupling characteristics of the output power at different ports are also studied. The small-signal dynamic coupling model of the multi-ports DCT is established. On this basis, a feed-forward term is introduced and constructed in the closed-loop voltage control system. The theoretical analysis shows that the feedforward term can decouple the output voltage of different ports of the multi-ports DCT. The correctness of the feed-forward control method is verified by simulations.

1. Introduction

With the development of renewable energy technology, more and more distributed power sources and energy storage systems are included in distribution networks. For the distribution network with more distributed power supply and DC load, the connection mode of DC distribution network can reduce the intermediate link of new energy generation system and DC load access to the distribution network, which can reduce the cost of access to the distribution network and improve the efficiency and power density of the whole system. Besides, compared with the AC distribution network, the DC distribution network does not need to track the voltage and frequency of the grid in terms of control and protection. The controllability and reliability of the system are greatly improved, which is more suitable for the access of distributed power and load. In DC distribution network, the direct current transformer (DCT) is a kind of basic and important power conversion equipment. DCT can realize voltage transformation and energy transmission, and the voltage transformation and energy transmission present active control mode.

In recent years, the research focus on DCT mainly includes the circuit topology and control of multi-ports DCT. Multi-ports DC transformer can directly interconnect multiple DC power grids. The multi-ports DCT with complete galvanic isolation couples each port through a multi winding high-frequency transformer with a common core and the number of windings is the same as the number of ports, which is suitable for high voltage and high power applications. Figure 1 is a typical circuit topology of a three-ports DC transformer with a common core.
In reference [1], a multi-ports DCT suitable for railway locomotive electric traction field is studied, and three control methods are proposed, which can realize the power balance of the input port. Reference [2] studies the application of multi-ports DCT in the micro-grid with an energy storage battery pack. In reference [3], the phase-shifting modulation strategy and power control method of multi-ports DCT are studied. In reference [4], the performances of multi-ports DCT with H-bridge, neutral point clamp, flying capacitor, and T-type circuit are studied and compared. In reference [5, 6], the control strategy of the multi-ports DCT is studied, which can effectively control the power transfer between the windings. In reference [7], a double closed-loop control strategy for multi-ports DCT is proposed, but this method needs to collect the AC current of the transformer winding, and the calculation of the phase-shift angle is greatly affected by the excitation inductance and leakage inductance parameters of transformer. In reference [8], a hardware decoupling strategy is proposed. The leakage inductance of one winding is designed to be much larger than that of the other two windings, so as to realize the power decoupling control of three windings. In reference [9-12], two phase-shifting control strategies and their respective calculation methods of phase-shifting angle are studied. However, the control strategy is only applicable to specific situations: three ports are respectively connected to fuel cell, super capacitor, and load.

In this paper, the multi-ports DCT shown in Figure 1 is taken as the research object. Aiming at the problem of coupling between the output power of each port, a power decoupling strategy based on the feedforward term is studied and verified by simulation.

![Figure 1](image1.png)  
**Figure 1** Multi-ports DCT

![Figure 2](image2.png)  
**Figure 2** Y-type equivalent circuit and Δ-type equivalent circuit

2. Analysis of power transmission characteristics

The typical circuit topology of three-ports DCT is shown in Figure 1, which includes three H-bridge circuits and a three winding high frequency transformer. The operating frequency of each H-bridge circuit unit is fixed, and the square wave voltage \(V_1\), \(V_2\) and \(V_3\) are generated respectively. The phase shift angle between the H-bridge circuit unit connected by the power supply \(V_1\) and the H-bridge circuit unit voltage connected by \(V_2\) and \(V_3\) is defined as: \(\varphi_{12}\) and \(\varphi_{13}\), and the phase shift angle between the two H-bridge circuit unit voltages connected by \(V_2\) and \(V_3\) is \(\varphi_{23}=\varphi_{13}-\varphi_{12}\). The multi-windings transformer is equivalent to multiple reactors, and the H-bridge circuit is equivalent to square wave voltage source. At the same time, because the excitation inductance of the high-frequency transformer is independent of the power flow, it can be ignored to simplify the analysis. Figure 2 shows the Y-type equivalent circuit and Δ-type equivalent circuit of the multi-port DC transformer. The amplitude of the square wave voltage is determined by the original side voltage and transformer ratio. To realize soft switching, the selection of the transformation ratio of the port high-frequency transformer is generally consistent with the voltage ratio of the port DC bus, that is, the voltage transformation ratio is 1. It is assumed that the leakage inductance of three transformer windings after conversion is equal. According to the reference [13], the active power of the two ports full-bridge circuit without considering the duty cycle regulation (the duty cycle is always 0.5) can be expressed as follows:
Similarly, the power transmission equation between DCT ports can be expressed as follows:

\[
P_{12} = \frac{V_1 V_2}{\pi \omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|)
\]

\[
P_{23} = \frac{V_2 V_3}{\pi \omega L_{23}} \varphi_{23} (\pi - |\varphi_{23}|)
\]

\[
P_{13} = \frac{V_1 V_3}{\pi \omega L_{13}} \varphi_{13} (\pi - |\varphi_{13}|)
\]

Where, \( P_{12} \) represents the active power from port 1 to port 2, \( P_{23} \) represents the active power from port 2 to port 3, \( P_{13} \) represents the active power from port 1 to port 3, \( V_1 \), \( V_2 \), \( V_3 \) represent the effective value of voltage converted to port 1, and \( L_{12} \), \( L_{23} \), \( L_{13} \) represent the transformer leakage inductance values of ports 1-2, 2-3, and 1-3, respectively.

According to the law of conservation of energy, the active power transmitted by each port is:

\[
P_1 = P_{12} + P_{13} = \frac{V_1 V_3}{\pi \omega L_{13}} \varphi_{13} (\pi - |\varphi_{13}|) + \frac{V_2 V_3}{\pi \omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|)
\]

\[
P_2 = P_{12} - P_{23} = \frac{V_1 V_2}{\pi \omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|) - \frac{V_2 V_3}{\pi \omega L_{23}} \varphi_{23} (\pi - |\varphi_{23}|)
\]

\[
P_3 = P_{13} + P_{23} = \frac{V_1 V_3}{\pi \omega L_{13}} \varphi_{13} (\pi - |\varphi_{13}|) + \frac{V_2 V_3}{\pi \omega L_{23}} \varphi_{23} (\pi - |\varphi_{23}|)
\]

Where \( P_1 \), \( P_2 \), \( P_3 \) represent the active power transmitted by Ports 1, 2, and 3 respectively; the phase-shifting angles of the three square wave voltages satisfy the relation \( \varphi_{12} + \varphi_{23} = \varphi_{13} = 0 \). Therefore, there are only two independent phase-shifting angle variables in the power transmission equation. \( \varphi_{12} \) and \( \varphi_{23} \) are selected as the power transmission control variable.

### 3. Feedforward decoupling control algorithm

Port 1 is connected with DC power supply, and port 2 and port 3 are connected with the load. Define that the power flow direction of port 1 is positive in the direction of inflow to the multi-port DC transformer; the power flow direction of port 2 and port 3 is positive in the direction of outflow from the DC transformer. Under the condition that the power flows from port 1 to port 2 and port 3, the phase of \( V_1 \) is ahead of \( V_2 \) and \( V_3 \), that is, the phase shift angle \( \varphi_{12} > 0 \) and \( \varphi_{13} > 0 \), and \( \varphi_{23} = \varphi_{13} - \varphi_{12} \).

So, from formula (3):

\[
P_2 = \frac{V_2}{\omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|) - \frac{V_3}{\omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|)
\]

\[
P_3 = \frac{V_3}{\omega L_{13}} \varphi_{13} (\pi - |\varphi_{13}|) + \frac{V_3}{\omega L_{23}} \varphi_{23} (\pi - |\varphi_{23}|)
\]

Port 2 and port 3 are connected with resistance load, simplified (4) and (5):

\[
V_2 = \frac{R_{12} V_1}{\omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|) - \frac{R_{12} V_1}{\omega L_{12}} \varphi_{12} (\pi - |\varphi_{12}|)
\]

\[
V_3 = \frac{R_{13} V_1}{\omega L_{13}} \varphi_{13} (\pi - |\varphi_{13}|) + \frac{R_{13} V_2}{\omega L_{23}} \varphi_{23} (\pi - |\varphi_{23}|)
\]

When the output voltage or phase shift angle of port 2 changes, the output power of port 3 will also change, which will cause the fluctuation of output voltage of port 3. Port 3 is the same. The output power of port 2 and port 3 has a strong nonlinear coupling relationship. When there is load change or voltage fluctuation in one port, the voltage fluctuation of other ports should be minimized in the dynamic process. Therefore, it is necessary to study the port decoupling control strategy.
According to the definition of power and formula (6) and (7):

\[ C \frac{dV_2}{dt} = i_{2\_sec} - i_2 \]  
\[ C \frac{dV_3}{dt} = i_{3\_sec} - i_3 \]  

Taking the disturbance components \( \Delta V_2 \) and \( \Delta V_3 \) in (10) and (11) with \( i_{2\_sec}, i_{3\_sec} \) as examples, the voltage disturbance is not only related to \( \Delta \phi_{12} \) and \( \Delta \phi_{13} \) but also to \( \Delta \phi_{23} \) and \( \Delta \phi_{31} \).

\[ \Delta \phi_{23} = \frac{1}{\pi \omega L_{23}} (\Delta \phi_{23} - \Delta \phi_{31}) \]
\[ \Delta \phi_{31} = \frac{1}{\pi \omega L_{12}} (\Delta \phi_{31} - \Delta \phi_{12}) \]

\( G_{i_{2\_sec}} (s) = \frac{1}{\pi \omega L_{12}} (\pi - 2 \phi_{12}) \]
\( G_{i_{3\_sec}} (s) = \frac{1}{\pi \omega L_{13}} (\pi - 2 \phi_{13}) \]

To realize dynamic decoupling, the feedforward term is introduced into a voltage closed-loop control system. In the voltage closed-loop control system of \( V_2 \), a feedforward term consisting of the disturbance components \( \Delta V_2 \) and \( \Delta \phi_{13} \) of port 3 is added.

\[ \Delta \phi_{13} = \frac{G_{i_{2\_sec}} (s)}{G_{i_{3\_sec}} (s)} \Delta V_2 (s) - \frac{G_{i_{3\_sec}} (s)}{G_{i_{3\_sec}} (s)} \Delta \phi_{13} (s) \]

\[ V_2 \] is only related to the phase-shift angle disturbance \( \Delta \phi_{12} \) and the output current disturbance \( \Delta i_2 \), which realizes the dynamic decoupling of the output voltage. Similarly, in the voltage closed-loop control system of \( V_3 \), a feedforward term consisting of the disturbance components \( \Delta V_2 \) and \( \Delta \phi_{12} \) of port 2 is added.
\[
\Delta \phi_{13}'(s) = -\frac{G_{i_{12}}(s)}{G_{i_{13}}(s)} \Delta V_2(s) - \frac{G_{i_{12}}(s)}{G_{i_{13}}(s)} \Delta \phi_{12}(s)
\]  

(18)

\( V_3 \) is only related to the phase-shift angle disturbance \( \Delta \phi_{13} \) and the output current disturbance \( \Delta i_3 \), which realizes the dynamic decoupling of the output voltage.

Therefore, the schematic diagram of the dynamic decoupling control system with feedforward terms can be obtained, as shown in Figure 3.

![Figure 3. Dynamic decoupling control system with feedforward](image)

V2 compared with the given voltage \( V_2^* \), through PI controller, the output is \( \phi_{12} \). \( \phi_{12} \) and the sum of feedforward term as phase shift angle. \( V_3 \) compared with the given voltage \( V_3^* \), through PI controller, the output is \( \phi_{13} \). \( \phi_{13} \) and the sum of feedforward term as phase shift angle. Finally, according to the generated phase-shift angle, the delay between different ports is generated to drive the corresponding power semiconductor devices on and off.

4. Simulation results

To verify the correctness of the theoretical analysis, a simulation model of multi-ports DCT is built in PSIM software. The corresponding parameters are shown in Table 1. Among them, the DC power supply is the ideal power supply and the load is the resistance. The multi-ports DCT has three ports, among which port 1 is fixed as DC power supply and ports 2 and 3 are connected with resistance load. The simulation is carried out according to the following conditions:

For the first 0.25s, port 2 is connected with resistance load which is 12 Ω, and port 3 is connected with resistance load which is 18 Ω. At this time, the output power of port 2 is greater than that of port 3. After 0.25 s, port 3 is connected to resistance load which is 18 Ω in parallel. At this time, the two parallel 18 Ω load resistances of port 3 are equivalent to a 9 Ω load resistor. Port 2 is connected to resistance load which is 12 Ω and remains unchanged. The output power of port 3 is greater than that of port 2.

| Name of parameter                  | Values of parameters |
|-----------------------------------|----------------------|
| DC power supply Voltage           | \( V_1 = 40 \) V     |
| output load voltage               | \( V_2 = V_3 = 40 \) V |
| ratio of HFT                      | 1:1:1                |
| Leakage inductance of HFT         | \( L_1 = L_2 = L_3 = 40 \) µH |
| Output capacitance of DC side     | \( C_1 = C_2 = C_3 = 6.56 \) mF |
| Initial voltage of output capacitance of DC side | 40 V |
| switching frequency               | 5 kHz                |
| step time                         | 0.2 µs               |
Without decoupling control algorithm, the output DC voltage of port 2 is $V_2$, and the output DC voltage of port 3 is $V_3$. Their waveforms are shown in Figure 4. When decoupling control algorithm is adopted, the output DC voltage of port 2 is $\tilde{V}_2$, and the output DC voltage of port 3 is $\tilde{V}_3$, and their waveforms are shown in Figure 5.

![Figure 4](image1.png)

**Figure 4.** Without decoupling control algorithm, the output DC voltage of port 2 and port 3

![Figure 5](image2.png)

**Figure 5.** The output DC voltage of port 2 and port 3 when the decoupling control algorithm is adopted

In the dynamic process at 0.25 s load sudden change, the output voltage of ports 2 and 3 changes slightly by adopting the decoupling control strategy. The voltage variation of port 2 is 98.3% ~ 100.1% under the rated power, and that of port 3 is 99.55% ~ 100.05% of the rated value. Without a dynamic decoupling control strategy, the voltage variation of port 2 is 98.45% ~ 100.5% of the rated value, and that of port 3 is 97.6% ~ 100.5% of the rated value. The simulation results show that the decoupling control method with the feedforward term can realize dynamic decoupling control, reduce the amplitude of voltage fluctuation in the dynamic process, and improve the control performance of multi-port DCT.

5. **Conclusion**

This paper studied the dynamic control strategy of multi-port DCT. The small-signal model of DCT is established first. On this basis, the feedforward term is introduced and constructed in the voltage closed-loop control system. Simulation results show that the voltage variation range of the two ports is significantly reduced compared with the case without decoupling control.

**References**

[1] Gu C, Zheng Z, Li Y. A power electronic transformer (PET) with multiport bidirectional resonant DC-DC converters for electric traction applications[C]. 2015 IEEE Transportation Electrification Conference and Expo (ITEC), 2015: 1-6.

[2] Gunasekaran D, Umanand L. A multi-winding transformer based power converter topology for a growing DC micro-grid structure[C]. 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2012: 1-6.
[3] Gu C, Zheng Z, Li Y. Control strategies of a multiport power electronic transformer (PET) for DC distribution applications[C]. 2015 IEEE Electric Ship Technologies Symposium (ESTS), 2015: 135-139.

[4] Costa L F, Buticchi G, Liserre M. Comparison of basic power cells for quad-active-bridge DC-DC converter in smart transformer[C]. 2015 17th European Conference on Power Electronics and Applications (EPE’15 ECCE-Europe), 2015: 1-10.

[5] Jakka V N S R, Shukla A. A triple port active bridge converter based multi-fed power electronic transformer[C]. 2016 IEEE Energy Conversion Congress and Exposition (ECCE), 2016: 1-8.

[6] Yue Y, Masumoto K, Wada K, et al. Power flow control of a triple active bridge DC-DC converter using GaN power devices for a low-voltage DC power distribution system[C]. 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia), 2017: 772-777.

[7] Chattopadhyay R, Acharya S, Gohil G, et al. One switching cycle current control strategy for triple active bridge phase-shifted DC-DC converter[C]. 2017 IEEE Industry Applications Society Annual Meeting, 2017: 1-8.

[8] Liu R, Xu L, Kang Y, et al. Decoupled TAB converter with energy storage system for HVDC power system of more electric aircraft[J]. The Journal of Engineering, 2018, 2018(13): 593-602.

[9] Phattanasak M, Gavagsaz-Ghoachani R, Martin J, et al. Comparison of two nonlinear control strategies for a hybrid source system using an isolated three-port bidirectional DC-DC converter[C]. 2011 IEEE Vehicle Power and Propulsion Conference, 2011: 1-6.

[10] Phattanasak M, Gavagsaz-Ghoachani R, Martin J, et al. Flatness based control of an isolated three-port bidirectional DC-DC converter for a fuel cell hybrid source[C]. 2011 IEEE Energy Conversion Congress and Exposition, 2011: 977-984.

[11] Phattanasak M, Gavagsaz-Ghoachani R, Martin J, et al. Control of a hybrid energy source comprising a fuel cell and two storage devices using isolated three-port bidirectional DC-DC converters[C]. 2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER), 2013: 1-6.

[12] Phattanasak M, Gavagsaz-Ghoachani R, Martin J, et al. Control of a Hybrid Energy Source Comprising a Fuel Cell and Two Storage Devices Using Isolated Three-Port Bidirectional DC–DC Converters[J]. IEEE Transactions on Industry Applications, 2015, 51(1): 491-497

[13] Bai Hua, Nie Ziling, Chris C M. Experimental comparison of traditional phase-shift, dual-phase-shift, and model-based control of isolated bidirectional DC–DC converters[J]. IEEE Transactions on Power Electronics, 2010, 25(6): 1444-1449.