Bipolar Direct AC/AC Conversion-based Dual-bus Parallel Supply System and Its Flexible Regulation Characteristics

Yibo Wang, *Member*, *IEEE*, Yu Liu, Chuang Liu, *Member*, *IEEE*, Guowei Cai, Xinyi Zhang, Kaipu Liu, Yuan Wang, Chen Liu, and Zhanhui Du

***Abstract*—In the context of increasing demand for flexibility and controllability in distribution networks, this paper proposes a dual-bus parallel supply (DBPS) system based on bipolar direct AC/AC conversion. First, the topology of the DBPS system, which is composed of both conventional and flexible bus ports, is described. Then, through analyzing the principles of the DBPS system, the voltage flexible regulation range is obtained, and its superiority over a topological reciprocity system is achieved. Then, a control strategy for the DBPS system is proposed based on the theory of power flow regulation of distribution ring networks and the principles of flexible bus regulation of the DBPS system. Finally, simulation analyses on flexible control scenarios in different networking modes of the DBPS system verify the correctness and validity of the proposed theory.**

***Index Terms*—Bipolar direct AC/AC converter, dual-bus, flexible bus, flexible control.**

I. INTRODUCTION

The global energy crisis and environmental issues have made the distribution system a critical part of the power system. However, distribution systems face significant challenges and pressures, which also present opportunities to advance the development of modern distribution systems [1]–[3]. With the continuous development of the national economy, power users are displaying diverse trends, and the demand for power has gradually shifted from a focus on quantity to quality. However, the demands of power quality for different power users vary widely. Therefore, targeted power quality management has emerged as a promising approach to meet the diverse needs of power users. Furthermore, with the continuous maturation of power electronic technology and equipment, such techniques are increasingly being used by power users and distribution networks. Moreover, profound changes have occurred in the operation modes, morphological characteristics, and the evolution the paths of distribution systems [4]–[6]. From the perspective of the distribution network's operational mode, it is gradually shifting from the traditional "closed-loop design, open-loop operation" mode to a "closed-loop design, closed-loop operation" mode. The flexible regulation and interconnection technology of distribution networks based on power electronics technology and equipment will become indispensable for the differential management of power quality for users and the flexible regulation of distribution ring networks [7]–[9].

Recently, scholars have conducted extensive and in-depth research on power electronics technology and equipment for flexible distribution network regulation, yielding significant results [10], [11]. With the continuous reduction in the cost of power electronics, many innovations are gradually being applied in real-world applications, such as power electronic transformers (PET) [12], [13], VSC-BTB-based soft open points (SOP) [14], [15], the unified power flow controllers (UPFC) [16]–[19], etc. Moreover, these flexible primary devices [20] are all connected to the power grid through power electronic converters, typically using AC/DC or DC/DC converters. This indicates that research on these types of power conversion technology have matured.

However, the research and application of the AC/AC transformation technology, which is one of the four major power conversion technologies, still has great development potentials [21], [22]. Because there is no DC link in the direct AC/AC conversion technology, it does not need to assemble capacitors and energy storage devices with high volumes, weights, and costs. More-

Received: May 22, 2024
Accepted: November 20, 2024
Published Online: Online: May 1, 2025
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DOI: 10.23919/PCMP.2024.000072

over, the single-stage energy transformation structure from AC to AC leads to faster response speed and higher energy conversion efficiency than the other technologies [23]–[26]. Therefore, in AC distribution systems, the direct AC/AC transformation technology has recently received increasing attention. For example, the use of dynamic voltage restorers based on bipolar direct AC/AC conversion can better suppress the adverse effects of grid voltage fluctuations on sensitive loads; hybrid distribution transformers based on direct AC/AC conversion can reduce the adverse effects of voltage surges caused by uncertain factors in the distribution network on sensitive loads; and autotransformers based on bipolar direct AC/AC converters can better solve the difficult problem of regulating the voltage of the traditional autotransformer to satisfy the voltage transformation needs of the distribution network.

However, owing to the different topologies used in direct AC/AC conversion technology, there are some challenges in its operation, such as the unipolarity [23], commutation [24]–[27], and voltage imbalance of the flying capacitor [25]. For example, a novel direct AC/AC converter topology is proposed in [23]. However, due to its unipolar output characteristics, it is difficult to adapt this topology to bipolar voltage regulation in distribution networks. Therefore, a direct AC/AC converter topology with a bipolar voltage regulation function and its control strategy are proposed in [24]. However, the complexity of the control process to address the commutation problem during operation greatly reduces the applicability of the methods. Considering that the voltage balance of the flying capacitor has a significant influence on the safe and stable operations as well as the overall operational efficiency of the direct AC/AC converter [25], it is necessary to ensure that the blocking voltage of the device does not exceed its rated value during the design process. However, with increased number of levels, the difficulties in balancing the flying capacitor voltages increase significantly. To effectively address the problems of bipolarity, commutation, and flying capacitor voltage imbalance, reference [28] proposes an H-bridge direct AC/AC converter topology with bipolarity, no commutation problem, and common ground characteristics. Additionally, flexible voltage regulation of distribution networks is explored [29]. The findings provide a reference for subsequent research on distribution network flexible regulation technology based on the direct AC/AC transform as well as reveal the possibility of realizing the flexible regulation of the distribution network voltage and power flow. However, despite the continuous development of distribution networks, the application of direct AC/AC converters for flexible regulation of distribution networks has not been properly investigated [29].

Based on the above development background of distribution systems, the advantages of the bipolar direct AC/AC converter (BD-AC) topology and its applicability in flexible regulation of distribution systems, this paper proposes a dual-bus parallel supply (DBPS) system based on a BD-AC. The system contains not only a conventional bus output port but also a flexible one with both voltage amplitude and phase control ability. Differential management can be implemented for users with different voltage quality requirements according to load categories in the same power supply partition. In addition, in a distribution ring network, the flexible bus's ability to regulate voltage amplitude and phase angle enables flexible regulation of power flow in the loop network. First, the main topology of the DBPS system is described. Then, its structural characteristics are analyzed based on the operation principle of the DBPS system. The voltage regulation range of its flexible bus is obtained, and its advantages are compared with other topologies. Then, a flexible bus control strategy for the DBPS system after networking is proposed, and the effectiveness and rationality of the proposed theory are verified through the analyses of examples in different simulation scenarios.

II. BD-AC-BASED DBPS SYSTEM

Figure 1 illustrates the proposed topology of the BD-AC-based DBPS system.

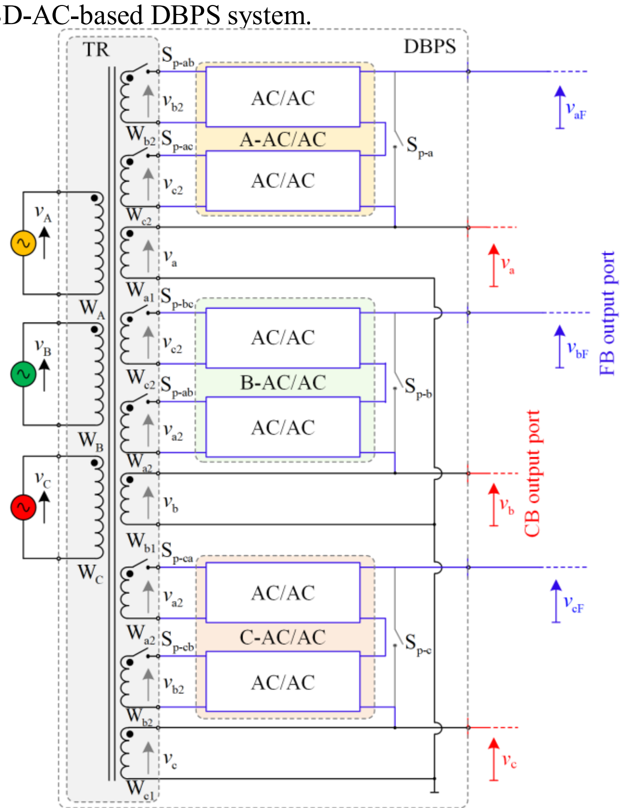

Fig. 1. System architecture of the BD-AC-based DBPS.

As shown, the main topology of a BD-AC-based DBPS comprises a three-phase/three-winding power frequency transformer (TR), and three groups of BD-AC modules (A-AC/AC, B-AC/AC, and C-AC/AC). The structure of the TR in Fig. 1 shows that W_A, W_B, and W_C are its primary windings, i.e., the input side of the DBPS system. The voltages of the three-phase input ports are represented by v_A, v_B, and v_C, while W_{a1}, W_{b1}, and W_{c1} are the secondary-side main windings of the TR. The voltages of the conventional bus output ports for the DBPS system are denoted by v_a, v_b, and v_c, while W_{a2}, W_{b2}, and W_{c2} are the secondary-side auxiliary windings of the TR. These components are drawn repeatedly in Fig. 1 to simplify the presentation. The corresponding voltages of the three auxiliary windings are characterized by v_{a2}, v_{b2}, and v_{c2}, which are connected to the BD-AC unit in the BD-AC module as the inputs of the BD-AC module. The topological connection relationship shows that the two BD-AC units corresponding to each phase of the BD-AC module are connected to the auxiliary windings of the other two phases of the TR. This indicates that the output voltage of each phase of the BD-AC module is supported by the other two phases. Furthermore, the output port of the BD-AC module is connected in series with the primary side main winding of the TR, to provides a flexible bus output port for the DBPS system, with the port voltages being (v_{aF}, v_{bF}, v_{cF}). To improve the operational reliability of the entire DBPS system, bypass switches are installed at the input and output ports of each group of the BD-AC modules. When the bypass switches are closed, the entire system changes from the DBPS mode to the conventional dual-bus output mode.

In summary, the DBPS system has two bus output ports: a conventional bus output port and a flexible bus output port. The conventional bus output port voltage is similar to the traditional bus port voltage supported by the TR secondary-side main winding, while the output voltage of the flexible bus port is supported by the TR secondary-side main winding and the BD-AC module. Therefore, based on the TR secondary-side main winding, a new flexible bus output port is formed and its voltage can be flexibly controlled by the BD-AC module.

III. Operational Principle and Application Scenario Analysis of the DBPS System

A. Operational Principle

From the topology, each phase of the BD-AC module in the DBPS system is regarded as a controlled source to facilitate the analysis of its operational principle, which can be simplified, as shown in Fig. 2.

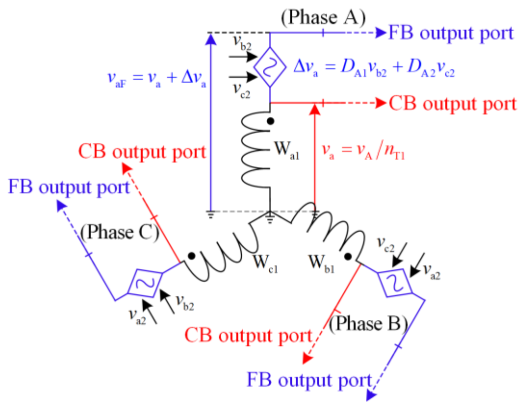

Fig. 2. Simplified diagram of the DBPS system output port.

In Fig. 2, the DBPS system has two output ports: a conventional bus and a flexible bus, whose output voltages are (v_a, v_b, v_c) and (v_{aF}, v_{bF}, v_{cF}), respectively, which can be calculated as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{n_{T1}} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{aF} \\ v_{bF} \\ v_{cF} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + \begin{bmatrix} \Delta v_a \\ \Delta v_b \\ \Delta v_c \end{bmatrix} \tag{2}$$

where n_{T1} is the turns ratio of the TR primary winding to its secondary main winding.

The flexible bus port voltages of the DBPS system (v_{aF}, v_{bF}, v_{cF}) depend on the conventional bus voltages (v_a, v_b, v_c) and the flexible regulation voltages of the BD-AC module $(\Delta v_a, \Delta v_b, \Delta v_c)$ According to the topological connection relation in Fig. 1 and (1), the flexible output voltages of the three-phase BD-AC module can be calculated as:

$$\begin{bmatrix} \Delta v_a \\ \Delta v_b \\ \Delta v_c \end{bmatrix} = \begin{bmatrix} 0 & D_{A1} & D_{A2} \\ D_{B2} & 0 & D_{B1} \\ D_{C1} & D_{C2} & 0 \end{bmatrix} \begin{bmatrix} v_{a2} \\ v_{b2} \\ v_{c2} \end{bmatrix} \tag{3}$$

where (D_{A1}, D_{A2}), (D_{B1}, D_{B2}), and (D_{C1}, D_{C2}) are the duty cycles of the BD-AC units installed in phases A, B, and C, respectively.

Similar to (1), there is:

$$\begin{bmatrix} v_{a2} \\ v_{b2} \\ v_{c2} \end{bmatrix} = \frac{1}{n_{T2}} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \tag{4}$$

where n_{T2} is the turns ratio of the TR primary-side winding to its secondary-side auxiliary winding.

In summary, the port voltages of the conventional and flexible buses of a DBPS system can be calculated and analyzed using (1) and (5), respectively.

$$\begin{bmatrix} v_{aF} \\ v_{bF} \\ v_{cF} \end{bmatrix} = \begin{bmatrix} \frac{1}{n_{T1}} & \frac{D_{A1}}{n_{T2}} & \frac{D_{A2}}{n_{T2}} \\ \frac{D_{B2}}{n_{T2}} & \frac{1}{n_{T1}} & \frac{D_{B1}}{n_{T2}} \\ \frac{D_{C1}}{n_{T2}} & \frac{D_{C2}}{n_{T2}} & \frac{1}{n_{T1}} \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \tag{5}$$

Moreover, equation (5) shows that each phase voltage of the flexible bus in the DBPS system is supported by the TR secondary side main winding and flexibly controlled by the BD-AC module. The flexible regulation voltage depends on the other two-phase voltages, i.e., the three-phase bus flexible control voltages in the DBPS system are supported by three others. Considering that the duty cycle $D(t)$ of the BD-AC unit is in the range $[-1, 1]$, the regulation principle (taking phase A as an example) and regulation range of the flexible bus port voltage of the DBPS system can be obtained, as shown in Fig. 3.

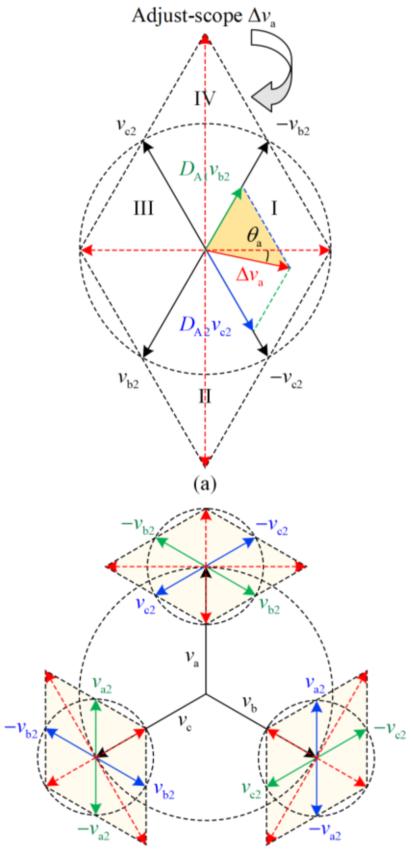

Fig. 3. Voltage regulation range of the DBPS flexible bus. (a) Schematic representation. (b) Control scope.

Figure 3(a) shows a schematic of the voltage phasor synthesis of the A-phase BD-AC module. As shown in the diagram, the regulating voltages provided by the B-phase and C-phase BD-AC units are $D_{A1}v_{b2}$ and $D_{A2}v_{c2}$, respectively, due to the 120° voltage difference between the B-phase- and C-phases. Furthermore, the flexible regulation voltage Δv_a provided by the BD-AC module in phase A is in the four regions from I to IV in Fig. 3(a). The duty cycle (D_{A1}, D_{A2}) values corresponding to the four regional boundaries are (−1, −1), (1, −1), (1, 1), and (−1, 1) respectively. Thus, the voltage regulation range of the three-phase DBPS system can be obtained, as shown in Fig. 3(b). From the above AC/AC unit voltage synthesis process and triangle corner theory, the AC/AC module has the voltage relationship as:

$$\frac{\Delta v_a}{\sin\left(\frac{\pi}{3}\right)} = \frac{D_{A1}v_{b2}}{\sin\left(\frac{\pi}{3}-\theta_a\right)} = \frac{D_{A2}v_{c2}}{\sin\left(\frac{\pi}{3}+\theta_a\right)} \tag{6}$$

where θ_a is the deviation angle between the output voltage of the A-phase AC/AC module and the corresponding voltage.

Therefore, the voltage relationship in the three-phase system is given as:

$$\begin{bmatrix}\Delta v_a\\ \Delta v_b\\ \Delta v_c\end{bmatrix} = \begin{bmatrix}M_{A1} & 0 & 0\\ 0 & M_{B1} & 0\\ 0 & 0 & M_{C1}\end{bmatrix}\begin{bmatrix}v_{b2}\\ v_{c2}\\ v_{a2}\end{bmatrix} = \begin{bmatrix}M_{A2} & 0 & 0\\ 0 & M_{B2} & 0\\ 0 & 0 & M_{C2}\end{bmatrix}\begin{bmatrix}v_{c2}\\ v_{a2}\\ v_{b2}\end{bmatrix} \tag{7}$$

Here:

$$\begin{bmatrix}M_{A1} & M_{A2}\\ M_{B1} & M_{B2}\\ M_{C1} & M_{C2}\end{bmatrix} = \begin{bmatrix}\frac{\sqrt{3}D_{A1}}{2\sin\left(\frac{\pi}{3}-\theta_a\right)} & \frac{\sqrt{3}D_{A2}}{2\sin\left(\frac{\pi}{3}+\theta_a\right)}\\ \frac{\sqrt{3}D_{B1}}{2\sin\left(\frac{\pi}{3}-\theta_b\right)} & \frac{\sqrt{3}D_{B2}}{2\sin\left(\frac{\pi}{3}+\theta_b\right)}\\ \frac{\sqrt{3}D_{C1}}{2\sin\left(\frac{\pi}{3}-\theta_c\right)} & \frac{\sqrt{3}D_{C2}}{2\sin\left(\frac{\pi}{3}+\theta_c\right)}\end{bmatrix} \tag{8}$$

where θ_b and θ_c are the deviation angles between the output voltages of phase B and C AC/AC modules and its own voltage, respectively.

Furthermore, when the value of the TR ratio is different, the voltage regulation range of the flexible bus in the DBPS system also changes. When n_{T1}/n_{T2} is larger, the voltage regulation range of the DBPS system is smaller, and vice versa. The above analysis shows that the flexible bus output port of the DBPS system realizes flexible regulation of not only the voltage amplitude but also the voltage phase angle.

B. Comparative Analysis of Topological Reciprocity

The above analysis shows that the flexible bus voltage of the DBPS system is mainly supported by the main winding of the TR secondary side. That is, the neutral grounding system is constructed by the main winding of the TR secondary side. When the BD-AC module in the DBPS system and the TR secondary-side main winding position are reciprocal, a simplified diagram of the output port can be obtained, as shown in Fig. 4.

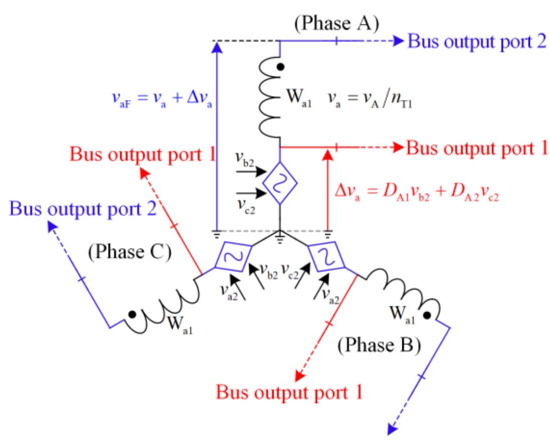

Fig. 4. Simplified diagram of the output port after topological reciprocity.

Figure 4 shows that in this topology, the voltages of the two groups of bus output ports of the DBPS system are $(\Delta v_a, \Delta v_b, \Delta v_c)$ and (v_{aF}, v_{bF}, v_{cF}), respectively. This means that the relationship between (2) and (3) holds once the topology becomes reciprocal. The voltages of the two groups of bus output ports are flexible and adjustable after topological reciprocity, and the voltages of bus output port 2, that is (v_{aF}, v_{bF}, v_{cF}), are the same as those before topological reciprocity. However, the voltage of bus output port 1 is equal to the output voltage of the BD-AC module. As shown in (3) and (4), the flexible bus voltages depend on n_{T2} and the duty ratio of the BD-AC unit. However, to ensure the voltage level and voltage quality of bus output port 2, the voltage level and voltage quality of bus output port 1 cannot be effectively guaranteed. After topological reciprocity, the system's dual-bus parallel supply flexibility is lost, limiting it to the construction of a single flexible bus. In summary, a DBPS system before topological reciprocity offers unique advantages and broader application prospects.

C. Application Scenario Analysis

An analysis of the operation principle of the DBPS system shows that the system contains two types of output ports: a conventional bus and flexible bus. The characteristics of the conventional bus output port are similar to those of the traditional substation bus system, while the flexible bus output port has the characteristics of flexible regulation of the voltage amplitude and phase angle. To facilitate the description and analysis of the application, this paper takes the traditional double bus connection (DBC) of a substation as an example to analyze the application scenario of the DBPS system, as shown in Fig. 5.

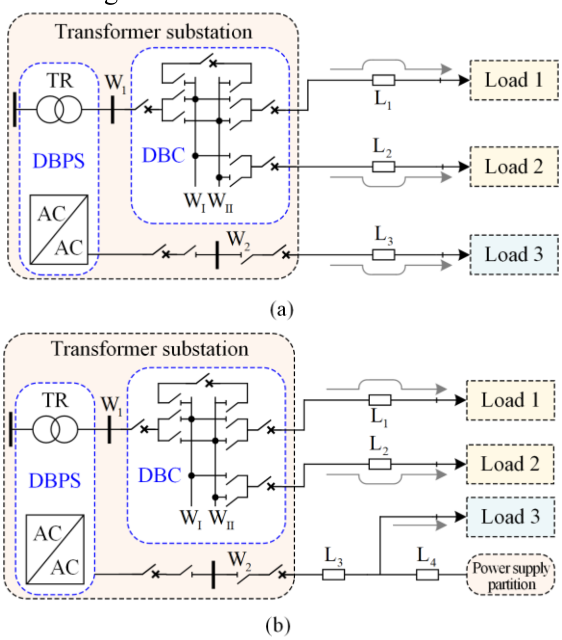

Fig. 5. Application scenario diagram of the DBPS system in its single-bus section connection mode. (a) Radial application scenario. (b) Ring network application scenario.

Figure 5 shows two application scenarios of the DBPS system under the DBC: a radial network application in Fig. 5(a) and a distribution ring network application in Fig. 5(b). In Fig. 5(a), the DBPS system adds a flexible bus W_2 to improve the voltage quality by maintaining the DBC (W_I and W_{II} are two buses connected by double buses) so that the substation can supply power to sensitive loads. This indicates that the DBPS system not only effectively integrates with traditional wiring forms but also provides differentiated management for users with different voltage quality requirements. The application scenario of the distribution ring network in Fig. 5(b) shows that loads 1 and 2 are supplied by L_1 and L_2, respectively, whereas load 3 is simultaneously supplied by L_3 and L_4. Thus, the DBPS system can construct a distribution ring network with a power supply partition. In this distribution ring network, by adjusting the voltage of the output flexible bus W_2 in the DBPS system, the power flow of the ring network can be flexibly regulated and optimized. This demonstrates the DBPS system's potential to regulate the power flow in the distribution ring network.

D. DBPS System Control Strategy

Because there is no substantial difference between the conventional bus output port of the DBPS system and that of a traditional bus, this study mainly considers the regulation of the flexible bus output port of the DBPS system in its parallel supply ring network connection mode. The power flow distribution under the regulation of the ring network power flow can be calculated and analyzed as:

$$S_{S1} = \frac{\sum_{i=1}^{n}\left(S_i \sum_{j=i+1}^{n+1} Z_j^*\right)}{Z_\Sigma^*} + \frac{v_N\left(v_{S1}^* + \Delta v^* - v_{S2}^*\right)}{Z_\Sigma^*} \tag{9}$$

$$S_{S2} = \frac{\sum_{i=1}^{n}\left(S_i \sum_{j=1}^{i} Z_j^*\right)}{Z_\Sigma^*} - \frac{v_N\left(v_{S1}^* + \Delta v^* - v_{S2}^*\right)}{Z_\Sigma^*} \tag{10}$$

where S_{S1}, S_{S2}, and S_i are the power of the two power supply points and load node i of the distribution ring network, respectively; Z_{L1}, $Z_{L2}, \cdots,$ Z_{Ln}, and Z_{Ln+1} are the impedance values of the different power lines in the loop; v_{S1}, v_{S2}, and v_N are the voltages of the two power supply points in the distribution ring network and the rated voltage of the network, respectively; and Δv is the compensation regulation voltage provided by the installed voltage regulation equipment.

According to (9) and (10), the power of the load nodes in the distribution ring network depends on the power users, and the power line parameters of the grid structure can be regarded as constant values. Therefore, the flexible regulation of network power flow can be realized by adjusting the voltage in the distribution ring network. Hence, when the DBPS system is connected and supplied to the ring network, it can realize flexible regulation of the voltage amplitude and phase angle of the flexible bus port, and has the potential to flexibly regulate the distribution ring network. Here, the target values of S_{S1} and S_{S2} are set as S_{1ref} and S_{2ref}, from which the expected value of the power flow regulation of the DBPS system can be calculated. Then, the target value of the DBPS system regulation voltage Δv_{ref} can be obtained from (9) or (10). Subsequently, the control strategy of the DBPS system can be obtained based on the voltage synthesis regulation principle of the DBPS system, as shown in Fig. 6.

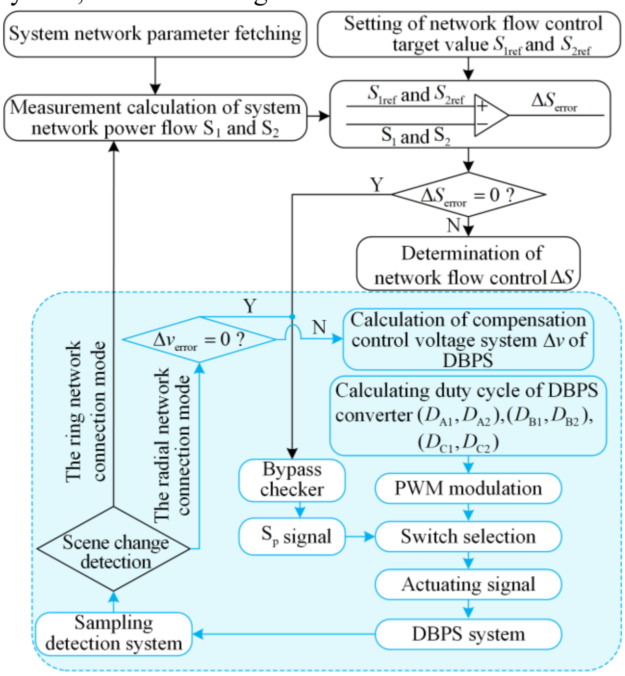

Fig. 6. DBPS system control strategy.

Thus, the flexible bus of the DBPS system can regulate the voltage amplitude and phase angle, and when connected in a distribution ring network, it can realize flexible power flow regulation of the distribution ring network. Moreover, networking in a radial distribution network can improve the voltage quality of the distribution network. Figure 6 shows the specific control strategy in blue, and demonstrates that, the DBPS system can realize differentiated flexible regulation and control of the distribution network according to different networking forms and specific regulation requirements.

IV. EXAMPLE ANALYSIS

A. Overview of Examples

To verify the correctness and effectiveness of the theoretical analysis described above, a DBPS system model was built on a PSIM simulation platform. Considering the advantages of the proposed direct AC/AC converter [28], such as its bipolarity, common ground, lack of a commutation problem, lack of bidirectional switching, and high operating efficiency, it is selected as the BD-AC unit of the DBPS system. Figure 7 illustrates the topology and modulation principles.

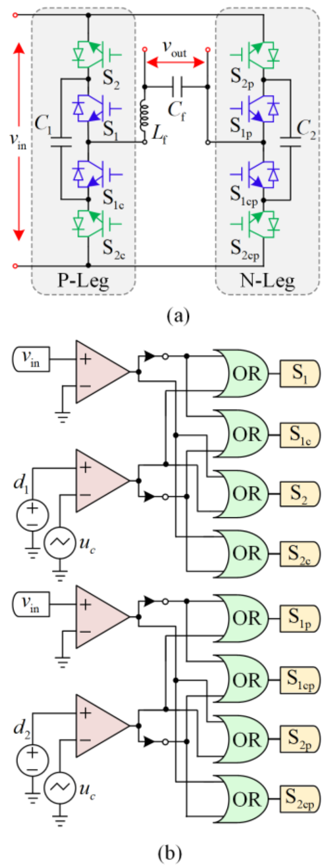

Fig. 7. Topology and modulation principles of the BD-AC unit. (a) BD-AC topology. (b) BD-AC modulation.

Figure 7(a) depicts the BD-AC unit topology and its H-bridge structure composed of two direct AC/AC chopper arms (P-Leg and N-Leg). Each arm contains four IGBTs (P-Leg: S_1, S_{1c}, S_2, and S_{2c}; N-Leg: S_{1p}, S_{1cp}, S_{2p}, and S_{2cp}) and a capacitor (P-Leg: C_1; N-Leg: C_2) to absorb the energy in the line stray inductance. Figure 7(b) shows the modulation principle of the BD-AC unit, where u_c represents the PWM triangular carrier. According to the modulation principle of the BD-AC unit, regardless of the polarity of the voltage $v_{in}(t)$ input to the BD-AC unit during its operation, two P-Legs and N-Legs are normally open every half-cycle. This means that the BD-AC unit has a maximum of four high-frequency IGBT switching, effectively reducing the switching losses. The relationship between the input voltage and output voltage $v_{out}(t)$ of the BD-AC unit is given by:

$$v_{out}(t) = D(t) v_{in}(t) \tag{11}$$

where $D(t)$ is the duty cycle of the BD-AC unit and has a value range of [−1, 1]. Moreover, equation (11) shows that the bipolar regulation of the voltage amplitude can be realized by adjusting the duty cycle of the BD-AC units.

In the simulation process, the selected rated input voltage of the TR primary side is 35 kV, and the rated output voltage of the TR secondary side main winding is 10 kV, indicating a turns ratio of the TR primary side winding to the secondary side main winding of $n_{T1} = 3.5$. In this simulation verification process, considering both the voltage quality standard of the medium-voltage distribution network in Chinese cities of 7% and the pressure-bearing capacities of the existing IGBTs in the market, a value of the turns ratio $n_{T2} = 20$ is selected. This results in the controllable voltage of the secondary auxiliary winding of 1.75 kV, while the switching frequency of the IGBTs is 15 kHz. The inductance and capacitance of the output filter are $L_f = 0.5$ mH and $C_f = 10$ μF, respectively, and the capacitances are $C_1 = C_2 = 10$ μF in the BD-AC unit. To verify the flexible regulation effect of the DBPS system in different operation scenarios, voltage flexible regulation in parallel supply and radiation connection modes as well as power flow regulation in parallel supply and ring network connection modes are simulated.

B. Verification of the Voltage Regulation in the Parallel Supply and Radiation Connection Modes

In the scenario of voltage regulation in the parallel supply and radiation connection mode, the system is set as a symmetrical load $\boldsymbol{Z}_{LOAD} = (20 + j5)\ \Omega$. Simultaneously, simulations of the DBPS system in different states are carried out to analyze the operation of the DBPS system during constant voltage, voltage drop, and sudden voltage rise. The simulation results are shown in Figs. 8 and 9 for scenarios 1 and 2, respectively.

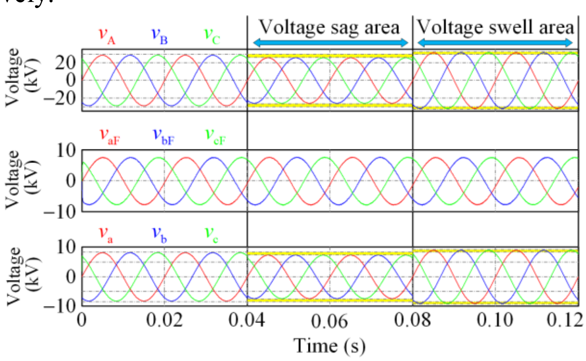

Fig. 8. Scenario 1: voltage regulation (sag-swell 7%).

Figure 8 shows the waveforms of the simulation results for the input port voltages (v_A, v_B, v_C), flexible bus port voltages (v_{aF}, v_{bF}, v_{cF}), and conventional bus port voltages (v_a, v_b, v_c) of the DBPS system. As seen, during the period from [0, 0.04] s, the network-side voltage of the DBPS system is constant, and the voltages of its conventional and flexible bus ports are both in a stable state. During the periods from [0.04, 0.08] s and [0.08, 0.12] s, the grid-side voltage of the DBPS system drops and suddenly rises, with a depth of 7%. During these periods, the flexible bus port voltage of the DBPS system remains in a constant state, whereas the conventional bus port voltage is dropped and then suddenly increased following the drop and sudden rise in the grid-side voltage. In summary, when the voltage on the network side fluctuates within 7%, although the parallel bus of the DBPS system can meet the network voltage quality requirements, the voltage quality of the conventional bus is noticeably reduced. Moreover, the voltage quality of the load connected to the flexible bus is guaranteed. This demonstrates that the DBPS system can meet the voltage quality requirements of the sensitive load and has good flexible voltage regulation ability.

To verify the voltage regulation ability of the flexible bus when the voltage on the grid side drops or rises by more than 7%, a 15% grid-side voltage drop-rise scenario simulated and the results are shown in Fig. 9.

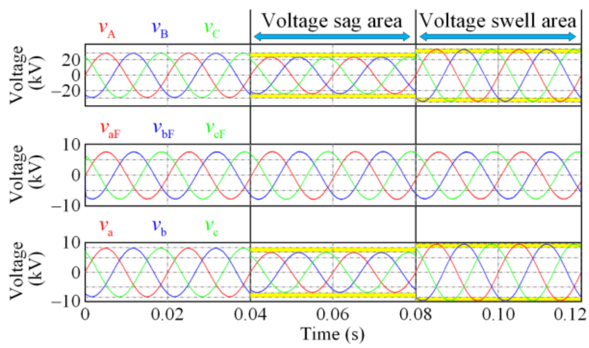

Fig. 9. Scenario 2: voltage regulation (sag-swell 15%).

As shown in Fig. 9, during the period from [0, 0.04] s, the grid-side voltage of DBPS system is constant, and the supplied dual-bus voltage is also constant. During the periods from [0.04, 0.08] s and [0.08, 0.12] s, the voltage on the network side of the DBPS system drops by 15% and rises sharply by 15% respectively. In this scenario, the flexible bus port of the DBPS system operate normally and its the voltage remains constant. In contrast, the voltage at the conventional bus port drops and rises sharply in proportion to the voltage on the network side. This demonstrates that the DBPS system retains the ability to maintain the load voltage quality during large and abrupt drop or rise of the grid side voltage .

C. Verification of Power Flow Regulation in the Parallel Supply and Ring Connection Mode

The power flow regulation scenario of the DBPS system is analyzed using the connection mode of the parallel supply ring network shown in Fig. 10.

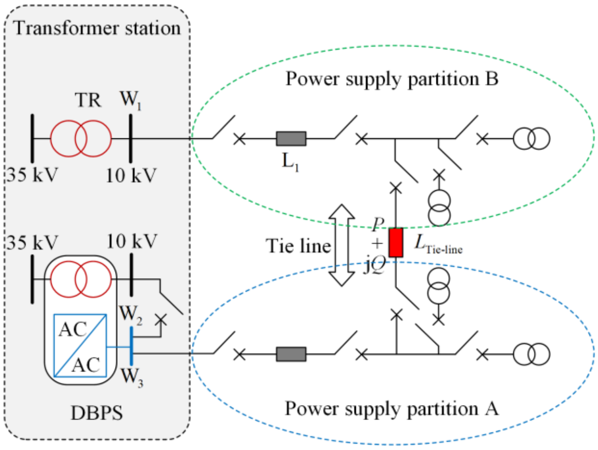

Fig. 10. Schematic of the parallel supply ring network connection mode.

In the parallel supply ring network connection mode, Figs. 11 and 12 show the simulation results under the same and different increasing and decreasing trends of the tie lines P and Q, respectively.

Figure 11 shows the waveforms of the power on the tie line $L_{\text{Tie-line}}$ (P, Q), output voltage of the conventional bus $W_2(v_a, v_b, v_c)$, output voltage of the flexible bus $W_3(v_{aF}, v_{bF}, v_{cF})$, output voltage of the bus $W_1(v_{W1a}, v_{W1b}, v_{W1c})$, voltage difference between the buses W_1 and $W_2(\Delta v_{A12}, \Delta v_{B12}, \Delta v_{C12})$, and voltage difference between the buses W_3 and $W_3(\Delta v_{A13}, \Delta v_{B13}, \Delta v_{C13})$, respectively.

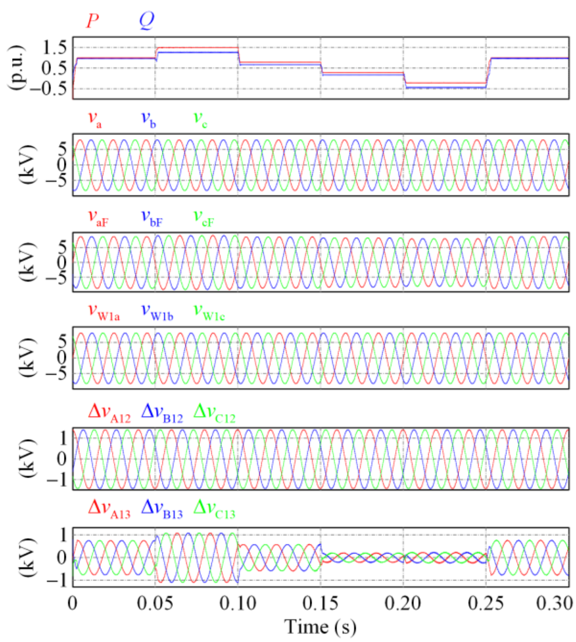

Fig. 11. Scenario 1: power flow regulation.

During the period from [0, 0.05] s, the DBPS system is in the state of "no regulation", and the power flow on the tie line $L_{\text{Tie-line}}$ is the natural distribution state of the load. Moreover, the active and reactive power at this time are regarded as the rated state of regulation, and the direction is from the power supply partition A to the power supply partition B. That is, $P = 1.0$ p.u. and $Q = 1.0$ p.u. During the period from [0.05, 0.10] s, the power supply partition B becomes overloaded, due to the centralized charging of a large number of electric vehicles. At this time, the power supply partition A coincides with the increase of the output of the distributed power supply. To satisfy the power demand of power supply partition B and consume the distributed power supply, a load transfer is realized through the regulation of the DBPS system at this time, i.e., from [0.05, 0.10] s, the power transmission of the tie line is $P = 1.5$ p.u. and $Q = 1.3$ p.u. It is assumed that during the period from [0.10–0.15] s, the load of power supply partition B is reduced and thus, there is no need for power supply partition A to support excessive power. At this time, through the regulation of the DBPS system, the power transmission of the tie line is reduced to $P = 0.8$ p.u. and $Q = 0.7$ p.u. Furthermore, during the period from [0.15, 0.20] s, the load demand of the power supply partition B is further reduced, and the transmission power of the tie line continues being lowered to $P = 0.3$ p.u. and $Q = 0.2$ p.u. Assuming the load in power supply partition A suddenly rises during [0.20, 0.25] s, the power supply in partition A becomes constrained, while the distributed power output in partition B significantly increases. Then, the power transmission mode of the tie line is changed by the regulation of the DBPS system, and the power transmission from the power supply partition B to partition A is $P = -0.2$ p.u. and $Q = -0.4$ p.u. During the period from [0.25, 0.30] s, the scenes of the power supply partitions A and B return to their original states as in [0, 0.05] s. At this time, the power transmission of the tie lines changes again and returns to its original state of $P = 1.0$ p.u. and $Q = 1.0$ p.u. The simulation results show that $(\Delta v_{A12}, \Delta v_{B12}, \Delta v_{C12})$ remain constant during the above changes, whereas $(\Delta v_{A13}, \Delta v_{B13}, \Delta v_{C13})$ change according to the power regulation requirements of the tie lines. Thus, the power flow regulation of the distribution ring network is realized based on the voltage regulation of the flexible bus W_3.

Figure 12 shows that during the period from [0, 0.05] s, power on the tie line $L_{\text{Tie-line}}$ flows from power supply partition A to partition B, with $P = 1.0$ p.u. and $Q = 1.0$ p.u. During the periods from [0.05, 0.10] s, [0.10, 0.15] s, [0.15, 0.20] s, [0.20, 0.25] s and [0.25, 0.30] s, the changes of the active and reactive power $(\Delta P, \Delta Q)$ are (−0.5, 0.2) p.u., (−0.5, −1.2) p.u., (−0.5, 0.5) p.u., (1.0, 0.5) p.u., respectively. Moreover, the active and reactive power (P, Q) of the tie line are (0.5, 1.2) p.u., (0, 0) p.u., (−0.5, 0.5) p.u., (−1.0, 0) p.u., and (0, 0.5) p.u., respectively. During the periods from [0.05, 0.10] s and [0.15, 0.20] s, the variation of active power in the tie line presents an opposite trend. In this process, the regulation effect of the distribution ring network is excellent. Furthermore, during the period of [0.10, 0.15] s, the active power and reactive power of the tie line are regulated to zero, indicating no power exchange between power supply partitions A and B. Simultaneously, Fig. 12 shows that the voltage of the flexible bus W_3 is equal to that of the conventional bus W_1. Through the above analysis, the flexible regulation of power flow in the distribution ring network can be realized using the DBPS system.

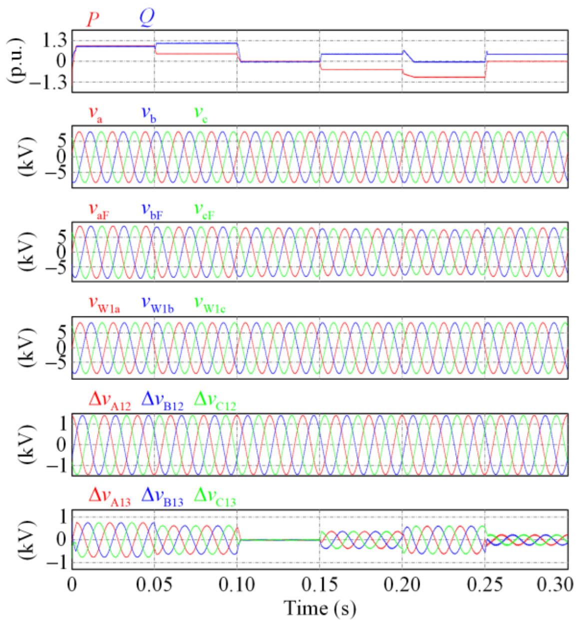

Fig. 12. Scenario 2: power flow regulation.

In summary, compared with traditional flexible distribution equipment (such as SOP based on MMC), the DBPS system based on direct AC/AC conversion not only has the basic functions of SOP but also realizes flexible regulation of power flow in the distribution ring network. Simultaneously, its dual-bus (conventional bus and flexible bus) parallel supply ability can be effectively integrated with the traditional substation bus connection mode to realize differentiated management of different power loads. The direct AC/AC conversion technology has single-stage power conversion characteristics that result in a DBPS system with a high operating efficiency. Finally, considering the topological connection between the power electronic module and TR in the DBPS system, the DBPS system can be changed from the conventional and flexible bus parallel supply mode to the conventional double-bus parallel supply mode in the case of power electronic module failure or maintenance, leading to high power supply reliability.

V. Conclusion

This study proposes a dual-bus parallel supply system based on bipolar direct AC/AC conversion to address the increasing demand for flexibility and controllability in distribution networks. By analyzing the topological structure and operation principles of the proposed DBPS system, this study highlights its advantages. The system has both conventional and flexible bus output ports, constituting a hybrid parallel bus system that can realize the functions of load voltage regulation in parallel supply and radiation connection modes as well as power flow regulation in parallel supply and ring connection modes. In this study, the flexible bus voltage control range of the DBPS system is analyzed, and its advantages over the topological reciprocity system are described. To satisfy the requirements of flexible regulation in different scenarios, a flexible regulation strategy suitable for the DBPS is presented. Finally, the correctness and rationality of the proposed theory are verified by case studies of voltage regulation scenarios in the parallel supply radiation connection mode and power flow regulation scenario in the parallel supply ring network connection mode.

In future research, the reliability of the DBPS will be analyzed in terms of AC/AC device losses, failure rate, redundant structuring, fault-tolerant control strategy, and distribution network protection, etc. Additionally, it is also necessary to consider how to protect the transformers and distribution networks when distribution line faults occur while ensuring coordinated regulation between the DBPS system and relay protection devices.

Acknowledgment

Not applicable.

Authors' Contributions

Yibo Wang: planning, design, and implementation of the entire research DBPS. Yu Liu: model building of DBPS. Chuang Liu: revision and review. Guowei Cai: conceiving and designing the scenario. Xinyi Zhang: formula derivation. Kaipu Liu: analyzing the data. Yuan Wang: software and simulations. Chen Liu: manuscript draft writing. Zhanhui Du: drawing graphics. All authors read and approved the final manuscript.

Funding

This work is supported in part by the National Natural Science Foundation of China (No. 52107182).

Availability of Data and Materials

Please contact the corresponding author for data material request.

DECLARATIONS

Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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