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RESEARCH ARTICLE

A Power Flow Calculation Method for Multi-Voltage Level DC Power Grid Considering the Control Modes and DC/DC Converter

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ABSTRACT Compared with traditional DC power flow analysis; multi-voltage level DC grid power flow analysis is more complex due to its diverse operation methods. This article proposes the power flow calculation method in multi-voltage level DC grid considering the control modes. To take into account the control mode of the different AC/DC and DC/DC converter stations, the basic control characteristic of multi-voltage level DC grid is studied at first. After obtaining the DC transformers' influence in power flow analysis, the multi-voltage level DC grid is then partitioned in different sub-grids according to different converter's and DC transformer's control modes. Based on such method, the steady-state equivalent model of the multi-voltage level DC grid can be established for power flow calculation. Finally, the node admittance matrix and power flow equation are established through Newton Iterative method. To verify the proposed method, a three-voltage level DC grid with 13 terminals are established in PSCAD software. Based on such model, the correctness of the method is verified and the impact of the DC transformers is also analyzed.

INDEX TERMS Control method, dc grid, multiple voltage levels, power flow calculation.

I. INTRODUCTION

Due to the rapid economic growth, there is an urgent need to address issues such as uneven energy distribution, renewable energy grid connection, and scarce transmission corridors in China's power grid. Therefore, the Voltage Source Converter Multi-terminal DC System (VSC-MTDC) based on modular multi-level converters (MMC), which can effectively address these difficulties, is expected to be established as the development direction of the future power grid [1], [2], [3], [4], [5]. The VSC-MTDC system is composed of at least three VSCs connected in series, parallel or mixed connection, which can realize multi-power supply, and can flexibly, conveniently, and reliably control power flow changes. It is more suitable for new energy grid connections and urban DC power distribution while solving the problem of traditional DC commutation failure and has become a research hotspot in recent years [6].

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Building a future DC power grid faces some key technical challenges [7]. On the one hand, the development of key equipment, including high-voltage DC circuit breakers and DC/DC converters, is a key core issue that must be addressed in the DC power grid [8]. On the other hand, due to the small response time constant of the DC power grid, new and higher requirements have been put forward for the simulation of the DC power grid system [9], the operation control and protection technology of the DC power grid, and the rapid fault detection technology of the DC power grid.

Based on such situation, power flow problem becomes one of the most fundamental problems in power system analysis, and the research on DC power grid power flow analysis and control technology is also an important foundation for the research of the above problems. In recent years, the issue of DC power grid power flow has attracted the attention of many scholars.

In the study of power flow in DC power grids, the most fundamental issue is the analysis and control technology of power flow in DC power grids. At present, based on the connections between different converter stations, the VSC-MTDC control method is mainly divided into two types: communication type control (master slave control) and non-communication type control (margin control, droop control) -. According to the existing results, lots of related adaptive control strategies are also invented. Such as the adaptive droop control strategy suitable for power sharing among various converter stations [10], the adaptive droop control strategy to avoid DC voltage deviation exceeding the limit [11], and the adaptive droop control strategy considering the reduction of total generation cost [10]. As the control strategies of each converter station change, the power flow model of VSC hybrid power grid will also change accordingly. the equivalent model of power droop and current droop control strategies in power flow calculation has been studied [12], and the unified power flow method for VSC hybrid power grids considering fixed coefficient droop control strategies is also proposed [13].

Compared to constant coefficient droop control, the droop coefficient value in adaptive droop control strategy will change with the transmission power and DC voltage of VSC, resulting in existing power flow calculation methods not being suitable for VSC hybrid power grids with adaptive droop control strategy. Moreover, existing literature usually studies the power flow calculation methods of VSC hybrid power grids based on simplified converter station models. For example, the model proposed in references [13] and [14] ignores the station filter busbar, and the model in reference [15] ignores the station step-up transformer. This simplified processing method often leads to inaccurate power flow calculation results. In addition, modulation, as an important control variable of VSC, can not only change the AC side voltage of VSC, but also affect the optimal pulse width modulation (PWM) mode of VSC [16], the anti-harmonic ability of VSC AC side to DC voltage [17], and the optimal power flow of VSC-HVDC [18]. Moreover, if overmodulation occurs, it can also lead to low order voltage harmonics in the AC system. Therefore, it is necessary to further solve the power flow calculation problem of VSC hybrid power grid under different control systems.

With a large number of DC power grids connected to the existing AC power grid, it has had a certain impact on the operation of equipment, relay protection, and safety and stability of the system. Therefore, it is necessary to conduct research on the power flow calculation of AC and DC power grids to prevent problems such as overload and voltage exceeding limits [19].

The power flow calculation of AC/DC hybrid power grid not only needs to consider the AC power flow model and DC power flow model, but also needs to consider the inverter power flow model connected to the AC/DC power grid appropriate improvements and supplements in the system power flow algorithm can be applied to AC/DC power flow calculation [20]. The calculation methods for AC/DC power flow are mainly divided into unified iteration method and

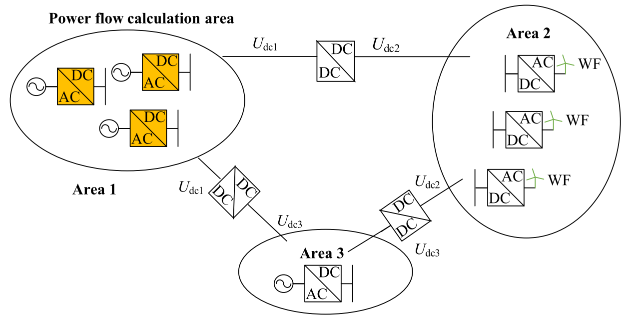

FIGURE 1. The multi-voltage level DC grids.

alternating iteration method. The unified iterative method has fast convergence and iteration fewer generations; The alternating iteration method iteratively solves the AC power flow and DC power flow separately, making it easy to expand [21].

Due to the use of fully controlled power electronic devices, VSC can independently control active and reactive power, select the optimal reference value of the converter station, and make it easier to achieve DC power flow control based on the optimal power flow, making the research on the optimal power flow of DC power grid more practical [18]. At present, many scholars have conducted some research on the optimal power flow problem of AC/DC systems containing VSC. The AC/DC power grid based on flexible DC transmission technology faces optimization issues such as power balance constraints, power flow distribution, and economic operation [22], [23], [24].

However, with the rise of VSC-MTDC voltage level and the complexity of system topology, the requirements for DC systems with DC transformers are needed, it increases the difficulty of system control. However, the above research has paid little attention to such area. And the power flow of DC grids with multi-voltage level has neither studied thoroughly.

To solve such problem, this paper establishes a steady-state equivalent model of the multi-voltage level DC power grid. The model considers the control methods of DC transformers and converter stations. Based on the definition and classification of DC power grid nodes, the node admittance matrix and power flow equation are established. By use of the Newton Iterative method, and the power flow calculation method of DC power grid is deduced. Finally, a three-voltage level DC power grid based on PSCAD was constructed, and the effectiveness and correctness of the proposed calculation method are verified.

The organization of the paper is as follow. Section II studies the steady state equivalent model of DC power grid with multiple voltage levels; Section III establishes the power flow calculation model for multi-voltage level DC power grid; Section IV constructs the simulation and verifications and Section V concludes the paper.

II. STEADY STATE EQUIVALENT MODEL OF DC POWER GRID WITH MULTIPLE VOLTAGE LEVELS

A. THE DC POWER GRID WITH MULTIPLE VOLTAGE LEVELS

The basic topology of a multi-voltage level flexible DC power grid is shown in Figure 1, which includes DC buses with different voltage levels. Each DC bus has multiple MMCs of the same voltage level, which can operate in constant DC voltage control, constant power control, or constant AC voltage control modes. It should be noted that in practice, only one fixed DC voltage control MMC is allowed to exist on each bus. However, for modeling uniformity, multiple fixed DC voltage control MMC are still defined here. The DC bus is connected through a DC voltage converter. In theory, the active power can flow from the high-voltage side to the low-voltage side, as well as from the low-voltage side to the high-voltage side. However, a reasonable situation should be for the power to flow from the high-voltage side to the low-voltage side.

For a DC grid with fixed voltage level, there is only one station control the DC voltage at DC side, such that for the other stations they can just control their active power, namely the current, rather than DC voltage.

B. STEADY STATE EQUIVALENT MODEL OF DC POWER GRID WITH MULTIPLE VOLTAGE LEVELS

The equivalent model of the converter station mainly includes a mathematical model based on the switch function, the AC/DC power exchange law of the converter station, and the controller model. MMC operates by continuously switching sub-modules to achieve power transmission, and the switching state of the sub-modules is used to study the switching mathematical model of MMC. The control method of inverters is an important guarantee for achieving AC/DC power exchange. The control methods of voltage source inverters mainly include the indirect current control method and direct current control method. The indirect current control process is relatively simple and mainly applied in early VSC-type DC transmission technology. However, due to the lack of current feedback, its dynamic response time is longer, and changes in system parameters have a significant impact on control stability. In the DC transmission technology based on MMC, the DC current control method using *d-q* coordinate system and PI control algorithm is widely used. Active external loop controllers mainly include constant active power control, constant DC voltage control, and constant AC frequency control.

In the study of mathematical models and controller design, it is assumed that the active power p injected into MMC is equal to the sum of the DC side power P_{dc} and the loss P_{loss}.

$$p = P_{\mathrm{dc}} + P_{loss} \tag{1}$$

The functional relationship between the loss of the converter station and the transmission power can be approximated to the form of a Quadratic function, in which the secondary loss is mainly generated by the equivalent resistance on the AC side, the primary loss is mainly generated by the on-state loss caused by the IGBT holding voltage, and the constant loss is mainly generated by the transformer excitation loss, filter, equivalent inductance on the AC side, etc. The relationship between converter station loss and transmission power is approximately a Quadratic function, so the converter station loss P_{loss} is

$$P_{loss} = a * P_{dc}^2 + bP_{dc} + c \tag{2}$$

In the formula, a, b, and c are the loss coefficients.

From the perspective of steady-state power flow calculation, DC systems can ignore parameters such as inductance and capacitance in the line, and only consider resistance parameters. Based on the method of graph theory, the DC side outlet of the converter station is first compared to the generator node in the AC system. It is assumed that the current injected into the DC system by converter station i is I_{di}, the voltage at the DC outlet of converter station i is U_{di}, the line resistance between node i and node j is represented by r_{ij}, and the line conductivity between node i and node j is represented by G_{ij}; Based on Kirchhoff's law in circuit principles, the relationship between the node voltage U_{di} of the converter station and the node injection current I_{di} is

$$I_{di} = \sum_{j=1}^{n} G_{ij} U_{dj} \tag{3}$$

In the formula (3), n represents the number of nodes in the DC power grid. And the elements of the node admittance matrix G are defined as

$$\begin{cases} G_{ii} = \sum\limits_{\substack{j=1,\\ i \neq j}}^{n} 1/r_{ij} \\ G_{ij} = 1/r_{ij} \end{cases} \tag{4}$$

C. DC/DC STEADY-STATE MODEL AND MULTI-VOLTAGE LEVEL DC POWER GRID PARTITIONING METHOD

This section focuses on the steady-state equivalent model of DC-DC converters used in high-voltage and high-power DC power grids. In multi-voltage level DC power grids, in order to have a certain ability to block DC faults, the MMC two-port isolated DC-DC converter topology structure shown in Figure 2 is often used.

To ensure effective power transmission, one side of this MMC-isolated DC transformer must adopt *Vf* control mode to establish a stable AC voltage; The *d*-axis control on the other side can adopt constant DC voltage control, constant active power control, or droop control. Therefore, this type of DC transformer generally has three control modes, namely: 1) *Vf* control/ constant DC voltage control; 2) *Vf* control/ constant active power control; 3) *Vf* control/droop control.

As shown in Figure 3, it is assumed that the *j*-side of the DC transformer is under *Vf* control, and the *i*-side is one of constant power control, constant voltage control, or droop

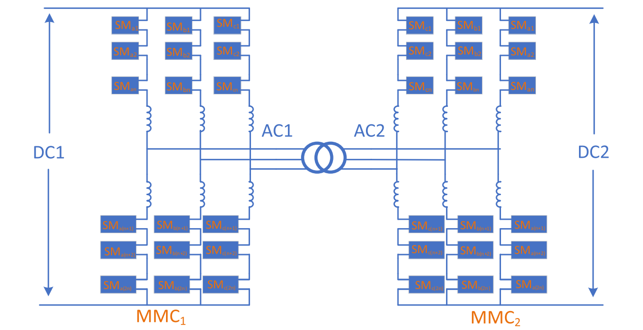

FIGURE 2. Isolated DC-DC topology based on MMC.

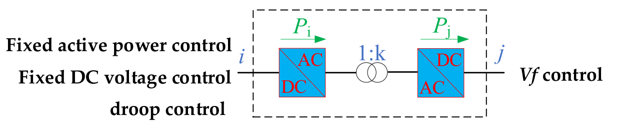

FIGURE 3. DC Transformer equivalent model.

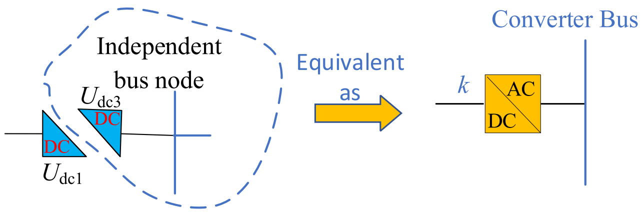

FIGURE 4. The DC transformer is connected to the independent bus node.

control. Due to the fact that the *Vf* control method takes the frequency and voltage of the AC side as the control objects and has no control ability over the active power or voltage of the DC side, considering the internal losses of the DC transformer, the power P_i and P_j on both sides are obtained by (5). Such that the DC transformer can be equivalent to a converter station.

$$P_i = P_j + P_{loss} \tag{5}$$

Usually, the DC transformer is located at an independent bus node in the power grid or in parallel with the converter station on the same bus node. When located at an independent bus node, the DC transformer is equivalent to the converter station k, and the control method depends on the i-side control method, as shown in Figure 4.

When connected in parallel to the same bus node as the converter station, the DC transformer and converter station can be equivalent to a converter station k, and the control method depends on the i-side converter station and converter station a, as shown in the figure 5.

And the control methods of station j are mainly divided into 9 situations as shown in Table 1.

Taking Figure 6 as an example, due to the relationship between the power P_i and P_j on both sides of the DC transformer as shown in (5), the multi-voltage level DC power grid can be divided according to the voltage level.

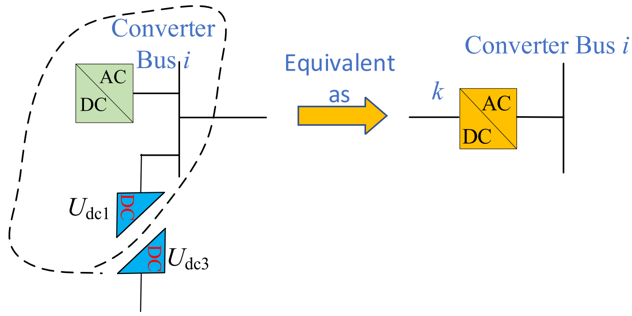

FIGURE 5. The DC transformer is connected to the busbar node of the converter station.

TABLE 1. Converter station control mode.

DC transformer control Mode	Converter a	Converter j
constant power control	constant power control	constant power control
	constant DC voltage control	constant DC voltage control
	droop control	droop control
droop control	constant power control	droop control
	constant DC voltage control	constant DC voltage control
	droop control	droop control
constant DC voltage control	constant power control	constant DC voltage control
	constant DC voltage control	-
	droop control	constant DC voltage control

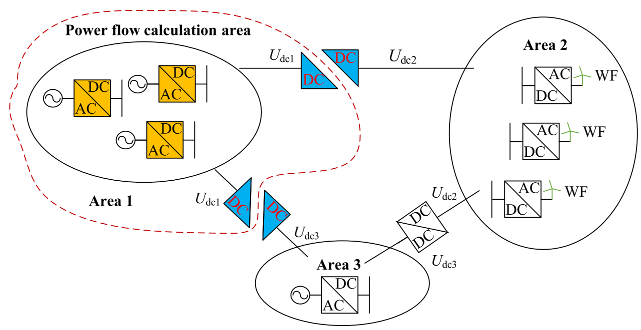

FIGURE 6. Power flow calculation area.

The power flow calculation results of Zone 1 can be substituted into Zone 2 and Zone 3 for relevant power flow calculations.

III. POWER FLOW CALCULATION MODEL FOR MULTI-VOLTAGE LEVEL DC POWER GRID

A. DEFINITION AND CLASSIFICATION OF DC POWER GRID NODES

In a DC power grid, each DC bus can also be considered a node. However, the MMC converter that provides voltage and injected power to the connected busbar can independently control its injected active and reactive power, which is one of the characteristics completely different from the AC system. Similar to AC system power flow calculation, nodes are divided into PQ nodes, PV nodes, and $V\theta$ Nodes in the DC power grid can be divided into three categories based on the different control methods of MMC, in order to use different power flow equations. The DC nodes are divided into three categories: Type I is the fixed AC active power node and the fixed DC power node, which maintains the P tracking reference value; Type II is a fixed DC voltage node, where the DC voltage U_{d} is always constant; Type III is a droop control node that maintains a specific slope relationship between P_{d} and U_{d}.

The coordinated control of the DC power grid is mainly reflected in the mutual coordination of active power control among various converter stations, in order to ensure system power balance and DC voltage stability. The DC power grid must contain at least one power control class (Class I or III) node, and at most one DC voltage control class (Class II) node.

Currently, the two widely used coordinated control methods are master-slave operation and droop operation.

B. NODE ADMITTANCE MATRIX AND POWER FLOW EQUATION

In the DC power grid, the connected energy storage unit can also be regarded as a power source or load, such as the photovoltaic array connected through DC/DC, which can be regarded as a DC power source. Nodes directly connected to DC loads or power sources are treated as constant power nodes, and their power correction equation is

$$\Delta P_{di} = U_{di}\sum_{j=1}^{n} G_{ij}U_{dj} + P_{loss} - P_{dcLi} \tag{6}$$

where, ΔP_{di} is the DC power imbalance value, and P_{dcLi} is the DC power of the DC load or power supply.

The power correction equation for intermediate DC nodes that are not directly connected to DC loads or power sources, and those that are not directly connected to MMC is

$$\Delta P_{di} = U_{di}\sum_{j=1}^{n} G_{ij}U_{dj} + P_{loss} \tag{7}$$

The steady-state power flow model of DC power grid can be expressed by n-node power correction equations. The power flow calculation is to solve the nonlinear equations under the given DC voltage, node power and droop coefficient. The Newton-Raphson method can be used for iterative solutions. The power flow correction equation for the DC power grid is

$$\Delta P_d = J_{\mathrm{dc}}\Delta U_d \tag{8}$$

$$U_d^{(k+1)} = U_d^{(k)} + \Delta U_d^{(k)} \tag{9}$$

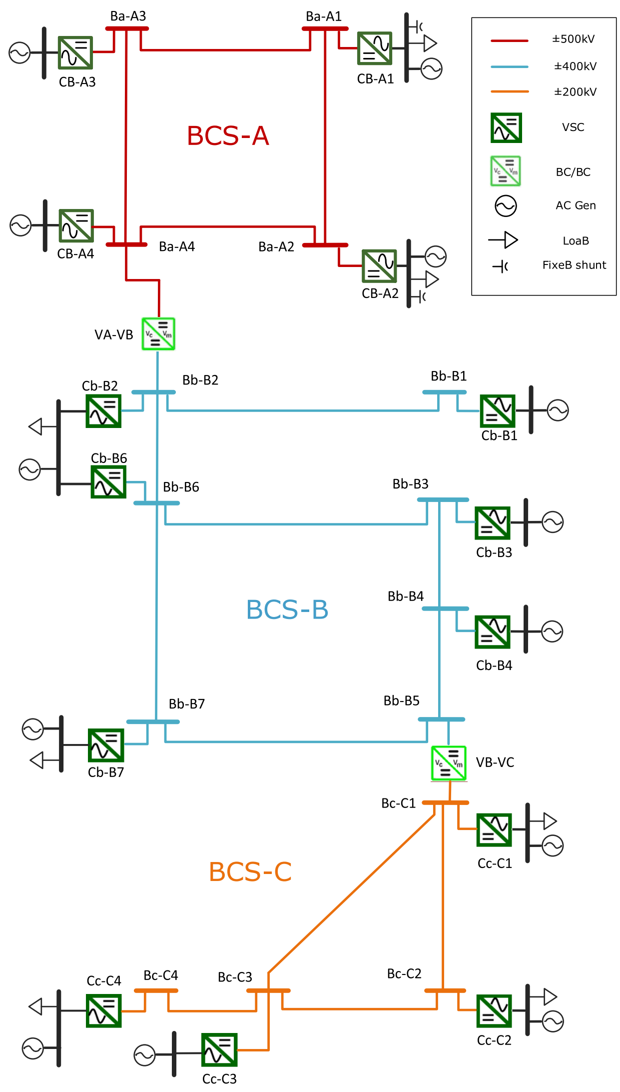

FIGURE 7. 13-terminal multi-voltage level DC grid topology.

where, ΔP_{d} is the DC node power increment vector, ΔU_{d} is the DC node power increment vector, and J_{dc} is the Jacobian matrix of the DC power grid.

When using master-slave control, the power correction equation of the slave converter station node is

$$\Delta P_{di} = U_{di}\sum_{j=1}^{n_c} G_{ij}U_{dj} + P_{loss} - P_{dcLi} \tag{10}$$

When using droop control, the node power correction equation is

$$\Delta P_d = P_d + P_{loss} - P_{d\mathrm{ref}} + K(U_d - U_{d\mathrm{ref}}) \tag{11}$$

In the formula, K is the droop coefficient of the droop control system.

Expand the n multivariate functions in the above formula into Taylor series near the initial value, and omit the terms of the second order and higher order of ΔU to get the following

TABLE 2. Converter station control parameters.

Converter	Control Modes	Control Parameters
CB-A1	Constant active power control	Psref=-900MW
CB-A2	Constant DC voltage control	Udref=1000kV
CB-A3	Constant active power control	Psref=1200MW
CB-A4	Constant active power control	Psref=1200MW
Cb-B1	Constant active power control	Psref=-400MW
Cb-B2	Constant active power control	Psref=600MW
Cb-B3	Droop control	Psref=-600MW, Udref=800kV，K=6
Cb-B4	Constant DC voltage control	Udref=800kV
Cb-B5	Constant active power control	Psref=1200MW
Cb-B6	Constant active power control	Psref=600MW
Cb-B7	Droop control	Psref=500MW, Udref=800kV，K=7
Cc-C1	Constant active power control	Psref=-180MW
Cc-C2	Constant DC voltage control	Udref=400kV
Cc-C3	Constant active power control	Psref=200MW
Cc-C4	Droop control	Psref=-150MW, Udref=400kV，K=6

TABLE 3. DC transformer control mode.

DC transformer	High voltage side	Low voltage side
DC/DC1	Vf control	Droop control (Psref=300MW，Udref=800kV，K=6)
DC/DC2	Vf control	Droop control (Psref=100MW，Udref=400kV，K=8)

formula

$$\begin{cases} \Delta P_{d1} = \dfrac{\partial P_{d1}}{\partial U_{d1}}\Delta U_{d1} + \dfrac{\partial P_{d1}}{\partial U_{d2}}\Delta U_{d2} + \ldots + \dfrac{\partial P_{d1}}{\partial U_{dn}}\Delta U_{dn} \\ \Delta P_{d2} = \dfrac{\partial P_{d2}}{\partial U_{d1}}\Delta U_{d1} + \dfrac{\partial P_{d2}}{\partial U_{d2}}\Delta U_{d2} + \ldots + \dfrac{\partial P_{d2}}{\partial U_{dn}}\Delta U_{dn} \\ \ldots \\ \Delta P_{dn} = \dfrac{\partial P_{dn}}{\partial U_{d1}}\Delta U_{d1} + \dfrac{\partial P_{dn}}{\partial U_{d2}}\Delta U_{d2} + \ldots + \dfrac{\partial P_{dn}}{\partial U_{dn}}\Delta U_{dn} \end{cases} \tag{12}$$

Write the above equation in matrix form as shown in (8), where the Jacobian matrix and determinant $\boldsymbol{J}_{\mathrm{dc}}$ is shown in

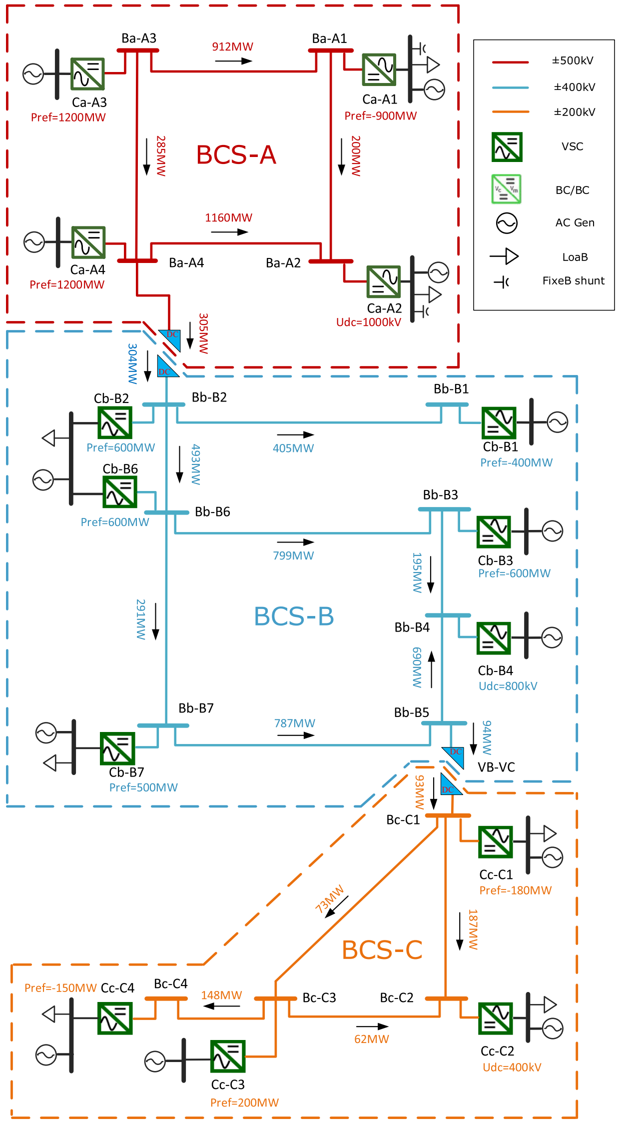

FIGURE 8. Power flow calculation partition model.

the following equation

$$J_{dc} = \begin{bmatrix} \dfrac{\partial P_{d1}}{\partial U_{d1}} & \dfrac{\partial P_{d1}}{\partial U_{d2}} & \cdots & \dfrac{\partial P_{d1}}{\partial U_{dn}} \\ \dfrac{\partial P_{d2}}{\partial U_{d1}} & \cdots & & \\ \cdots & & & \\ \dfrac{\partial P_{dn}}{\partial U_{d1}} & \cdots & \dfrac{\partial P_{dn}}{\partial U_{dn}} & \end{bmatrix} \tag{13}$$

The elements of Jacobian matrix and determinant are defined as follows

$$J_{dcij} = \begin{cases} U_{di} \cdot G_{ij} i \neq j \\ \sum_{k=1}^{i-1} G_{ik} \cdot U_{dk} + 2G_{ii} \cdot U_{di} \; i = j \end{cases} \tag{14}$$

Among them, J_{dcij} represents the element in the i-th row and jth column of J_{dc}.

The main converter station with constant DC voltage is the power balance station, whose DC voltage is constant and does

TABLE 4. The comparison between the calculation results of the power flow of the line and the simulation value.

Line	Calculated value/MW	Simulation value/MW	error
A3-A1	912	895	1.86%
A3-A4	285	284	0.35%
A4-A2	1160	1139	1.81%
A1-A2	200	198	1.00%
B2-B1	405	406	-0.25%
B2-B6	493	495	-0.41%
B6-B3	799	797	0.25%
B6-B7	291	289	0.69%
B7-B5	787	790	-0.38%
B3-B4	195	197	-1.03%
B5-B4	690	681	1.30%
C1-C2	187	188	-0.53%
C1-C3	73	72	1.37%
C3-C2	62	63	-1.61%
C3-C4	148	145	2.03%

not need to be added to the iteration, so the Jacobian matrix and determinant J_{dc} needs to be reduced by one order and the row and column elements corresponding to the nodes of the constant DC voltage station are deleted.

When using droop control, the corresponding elements of the Jacobian matrix are defined as follows

$$J_{dcij} = \begin{cases} U_{di} \cdot G_{ij} i \neq j \\ \sum_{k=1}^{i-1} G_{ik} \cdot U_{dk} + 2G_{ii} \cdot U_{di} + \mathrm{K} i = j \end{cases} \tag{15}$$

C. POWER FLOW CALCULATION METHOD FOR DC POWER GRID

The flow chart of power flow calculation method based on Newton Iterative method is studied in this paper, The calculation process can be summarized as follow.

(1) Input the original data of the system;

(2) Divide the DC power grid with multiple voltage levels and construct a partition node admittance matrix; Set the initial value of node voltage;

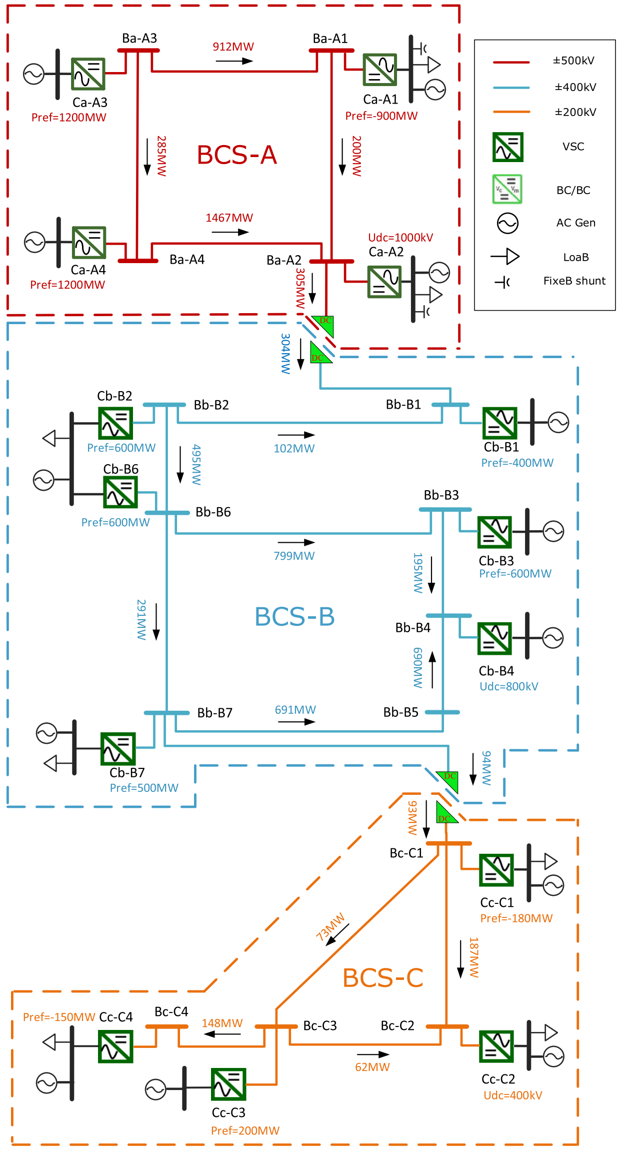

FIGURE 9. Power flow calculation partition model.

(3) Calculate the imbalance of the power correction equation ΔP_{d};

(4) Determine whether the corresponding variable meets the convergence requirements; Yes, output the result and the calculation is completed. Otherwise, continue to the next step;

(5) Calculate the iterative Jacobian matrix J_{dc}. And voltage correction amount ΔU_{d};

(6) Return to step (3) and continue with the calculation.

IV. SIMULATION VERIFICATION

In order to verify the correctness of the above multi-voltage level DC power flow calculation method, a three-voltage level flexible DC power grid model is constructed based on PSCAD simulation software, as shown in Figure 7.

TABLE 5. The comparison between the calculation results of the power flow of the line and the simulation value.

Line	Calculated value/MW	Simulation value/MW	error
A3-A1	912	902	1.10%
A3-A4	285	281	1.40%
A4-A2	1467	1444	1.57%
A1-A2	200	196	2.00%
B2-B1	102	102	0.00%
B2-B6	495	490	1.01%
B6-B3	799	789	1.25%
B6-B7	291	286	1.72%
B7-B5	691	684	1.01%
B3-B4	195	195	0.00%
B5-B4	690	677	1.88%
C1-C2	187	186	0.53%
C1-C3	73	72	1.37%
C3-C2	62	61	1.61%
C3-C4	148	146	1.35%

A. THE POWER FLOW CALCULATION METHOD SIMULATIONS

The control parameters of each converter station are shown in Table 2, and the control parameters of DC transformers are shown in Table 3. According to the multi-voltage level DC power grid zoning method, Figure 7 is divided into three zones, as shown in Figure 8. According to the equivalent method of the converter station nodes connected to the DC transformer, the converter stations MA-4, MB-1, MC-2 are directly connected to the DC transformer, and the DC/DC2 high-voltage side is connected to the independent busbar BB-4. The corresponding control methods and parameters of the equivalent converter station are shown in Table 2 and Table 3.

The comparison between the power flow calculation results of this power flow calculation method and the PSCAD simulation values is shown in Table 4. From Table 4, it can be seen that the difference between the calculated results of the line power flow and the simulated values is within 1%. The main reason for the error is that the losses of the converter and DC transformer are obtained by fitting functions, which have a certain error with the actual losses; Secondly, Newton Iterative method also has inherent truncation error. However, its considerable agreement with simulation values verifies the correctness of the proposed power flow calculation method for multi-voltage level DC power grids.

B. THE DC/DC TRANSFORMER IMPACTS SIMULATIONS

To further verify the correctness of the proposed method and also study the DC/DC transformer's impacts on the DC grid's power distribution, the previous PSCAD model is adjusted by moving the DC transformer's location.

The adjusted model is shown in Figure 9, it can be seen that DC transformer 1 and 2 are located in different position of the model. The Table 5 presents the comparison and simulation results.

From the simulation and comparison results, it can be concluded that the proposed power flow method is correct and of accuracy in different multi-voltage DC grid system. Moreover, the changes of the DC transformers also indicates that the power flow of the DC grid is impacted only with the nearby converters and DC lines. The faraway power flow distribution situation is basically not influenced.

V. CONCLUSION

This article studies the power flow calculation method of multi-voltage level DC grid. Based on the study above, the following conclusions can be obtained.

1) The DC transformer can be split into different voltage level when the multi-voltage level DC grid's power flow is calculated. It is convenient and effective when DC transformer's control modes are correctly considered.
2) Based on the proposed multi-voltage DC power grid zoning method, the node admittance matrix and power flow equation can be established based on the Newton Iterative method, and the DC power flow can be calculated easily in different sub-grids with traditional DC power flow calculation method.
3) The simulations implemented on a three-voltage level DC grid in PSCAD software verifies the correctness of the proposed method, and the DC transformer's impact on the power flow is also analyzed. The simulation results and calculation results comparison prove the accuracy of the proposed method.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHORS CONTRIBUTIONS

Conceptualization: Shifeng Ye, Jianxiang Xie, and Jia Jun Ou; methodology: Ruhai Huang; software: Shifeng Ye, Jianxiang Xie, and Jia Jun Ou; validation: Shifeng Ye, Jianxiang Xie, and Jia Jun Ou; writing—original draft preparation: Shifeng Ye; writing—review and editing: Ruhai Huang; supervision: Ruhai Huang and Jianxiang Xie; modification: Shifeng Ye, Jianxiang Xie, and Jia Jun Ou. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY

Not applicable.

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