



Article Coordinated Control Strategy of CU-MTDC under Abnormal Conditions Considering Power Supply Security

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Abstract: The coastal urban multi-terminal DC (CU-MTDC) is a prospective solution for enhancing the power supply security of the coastal urban power (CUP) grid and integrating the large-scale offshore wind farm. However, the large DC disturbances may significantly impact the CUP power supply security. The existing DC unbalanced power distribution methods are difficult to be applied in the CU-MTDC because of the complicated optimization process and the expansion of the influence range of a DC fault. To solve the above problems, this paper proposes a coordinated control strategy of CU-MTDC under abnormal conditions. First, calculation principles for the active power reference of center coastal urban power (CCUP) grid converters are proposed. Second, a DC unbalanced power coordinated distribution strategy under abnormal conditions is used based on the dynamic priority control to ensure power supply security of the critical AC lines. Third, the controller parameters of CCUP grid converters are calculated. Through a simple control process, the number of the regulation converters is dynamically scheduled according to the DC unbalanced power. The DC fault influence range on the urban power grid can be limited in a sufficiently small area. Simulation verified the effectiveness of the proposed control strategy.

Keywords: coastal urban multi-terminal DC (CU-MTDC); power supply security; offshore wind farm; coordinated control strategy under abnormal conditions; dynamic priority control

1. Introduction

With the rapidly increasing urban power load, the security of coastal urban power (CUP) supply is facing challenges [1] because of the shortage of transmission corridors and limitation of short circuit capacity [2,3]. Meanwhile, the CUP grid security has further deteriorated as a result of the large scale integration of offshore wind power [4,5]. High voltage direct current based on voltage source converter (VSC-HVDC) technology is recognized as an advanced approach for efficient and stable operation in future CUP grid [2], due to their high transmission capability [6,7], the flexibility of power dispatch and no short circuit current limitation et al. [2,8].

Up to now, several point-to-point VSC-HVDC projects [2,3,9] have been in operation or planned for the CUP grid. With the enlargement of the CUP grid, more than one point-to-point VSC-HVDC systems in different areas will be put into operation in the same CUP grid. To improve system flexibility and reliability, VSC-HVDC systems can be interconnected and developed into a coastal urban multi-terminal DC (CU-MTDC) system.

When MTDC is applied in the CUP grid, the main control objective is to relieve the transmission stress of the critical AC lines and improve the power supply security. Meanwhile, to realize the local absorption, offshore wind power further affects the security of the power supply to the CUP grid. Therefore, taking the power supply security into account, coordinated control strategies of the CU-MTDC are very important.

In recent years, as a new research field, some researchers have begun to pay attention to the application of VSC-HVDC in the urban power grid. In [10], the authors proposed



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). a locating and sizing method of interconnected converter stations. According to the method, the optimum location and capacity of the converter station are well determined. However, the control strategy of the DC system is not involved. On the basis of the [10], the detailed control strategy of a back-to-back VSC-HVDC interconnected two load areas of the urban power grid is proposed in [11]. In this paper, the proposed method includes load-balanced control, emergency support control and static voltage control. The results verify the effectiveness of the proposed control strategy. In [12], a coordinative control model that combines the load transfer capability of the HVDN and flexible and precise control of VSC is proposed to alleviate the urban transmission congestion. Although the above two papers have studied the control of VSC-HVDC in the urban power grid, the research project is the two-terminal DC system, and the multi-terminal DC system is not mentioned. Reference [13] focuses on a multi-voltage urban DC system and proposes a comprehensive control strategy that included free operation mode, limit operation mode and layer operation mode. Based on [13], a coordinated operation strategy for DC grids applied to the multi-regional urban power grid is studied in reference [14], and the coordination between multiple DC subsystems is analyzed. However, the influence of the AC system is not considered in the proposed coordinated control strategy, especially the power supply security. Based on the above analysis, the research on urban MTDC needs further attention.

Compared with the research on urban MTDC, considering the influence of the AC system, the coordinated operation mode and control strategy of MTDC in large power systems have been extensively studied, which can be used for reference. In [15], the paper considers the OPF of a meshed AC/DC system with MTDC networks. The OPF problem is formulated to minimize the transmission loss of the whole AC/DC network. In [16], an extended OPF model with a detailed MTDC is proposed. And then, a cost-benefit analysis approach using the model is proposed to determine the economy of the VSC project. In [17], the paper focuses on the frequency security of the AC system after DC fault and proposes a distribution method of DC unbalanced power. The simulation results show the method can effectively reduce the frequency fluctuation. The above research optimized the operation mode of MTDC through different control objectives. However, the power supply security of the AC system has not been given special attention and is usually introduced into the optimization process only as an inequality constraint. Therefore, considering the power supply security, a better-optimized operation mode of MTDC is obtained by the security-constrained optimal power flow (SCOPF) method. In [18], improved corrective security-constrained OPF for a meshed AC/DC power grid is proposed. The security constraints of N-1 contingencies for both AC and DC networks are fully considered. The results show that this method can be applied to middle and long-term schedules. In [19], a hierarchical SCOPF model is proposed for an AC/DC system. The MTDC system could provide support for the AC system by redistributing power flow across the entire grid. Through the above methods, the power supply security of the AC/DC system is fully considered. However, due to the large-scale power grid and too many optimization factors, this kind of method cannot be applied in real-time control because of the complicated calculation process. Therefore, a more direct calculation method is proposed for real-time control in [20]. In this paper, active power sensitivity is used to calculate the redistribution of DC unbalanced power after DC fault. The methods can guarantee power supply security by distributing the DC unbalanced power among all the normal converters. However, the influence area of DC fault on the AC system is expanded. In addition, the detailed coordinated control strategy is not proposed to cooperate with the calculation method, and parameter design of controllers is not involved.

In general, the drawbacks of the existing approaches are described as follows:

(1) The DC unbalanced power distribution method usually adopts an optimized calculation method using global data. There are generally many optimization factors in this kind of calculation method, and the calculation process is very complicated. Therefore, it is difficult to apply the existing approaches to real-time control; (2) The DC unbalanced power distribution strategies usually adopt all the normal converters to participate in the regulation, which inevitably leads to the expansion of the influence range of a DC fault on the AC system.

To solve the problems in the exiting approaches, a novel coordinated control strategy of CU-MTDC under abnormal conditions is proposed in this paper. Compared with traditional methods, the proposed method offers the following features and improvements:

- Based on the priority control idea, the control thresholds of different priorities are determined by the magnitude of the DC unbalanced power value and the maximum regulation capacity of the converter. The calculation and control process is very simple, which is easy to realize real-time control;
- (2) The number of the regulation converters is dynamically scheduled according to the DC unbalanced power value, instead of all the converters involved in control. With the proposed method, the influence range of DC faults on the urban power grid can be limited in a sufficiently small area;
- (3) Moreover, the parameter design of controllers is proposed to cooperate with the distribution strategy, which is very friendly to practical engineering realization.

The rest of this paper is organized as follows: Section 2 describes the basic system structure of CU-MTDC. In Section 3, the coordinated control strategy of CU-MTDC under abnormal conditions is proposed. The results of the simulations are performed in Section 4. Finally, Section 5 concludes the paper.

2. Basic System Structure of CU-MTDC

2.1. System Structure of CU-MTDC

A general VSC-MTDC system used for the coastal urban power system is adopted in this paper, as shown in Figure 1.



Figure 1. System structure of coastal urban multi-terminal DC (CU-MTDC).

As shown in Figure 1, the coastal urban power system is divided into N center load area and M non-center load area. The characteristic of the center load area is having heavy load and fewer sources, which causes the critical AC line in this area to have a larger possibility of power supply security problem. The characteristic of the non-center load area has a light load, and the inner source in the non-center load area is sufficient. Therefore, in order to realize better power flow distribution, increasing the offshore wind power integrating and enhancing the power supply security, a VSC-MTDC system is proposed and embedded into the coastal urban power system.

The proposed VSC-MTDC system has N inverter converters, which are named the center of coastal urban power grid (CCUP) converters and are directly connected with the center load area. In addition, there are M rectifier converters connected with non-center load areas or other power systems with higher voltage. The Wind-farm converter (WFVSC) aims at realizing integrating with wind power.

2.2. Control Structure of CU-MTDC

The control structure of CU-MTDC is introduced in detail and is depicted in Figure 2. Hierarchical control [21] is adopted in this paper to realize the unbalanced power distribution and real-time control.



Figure 2. The control structure of CU-MTDC.

2.2.1. Calculation Layer of the Operation Modes

When CU-MTDC is in operation, the main responsibility of this layer is twofold:

- (1) Operation mode calculation under normal condition. Under this condition, the active power reference value of the CCUP grid converter should be calculated since the reference value is relative to the droop coefficient calculation and affects the control directly. In addition, the reference value should ensure the N-1 security criterion and offshore wind power integration;
- (2) Operation mode calculation under abnormal condition. Under this condition, the active power output of the CCUP grid converter should be calculated to ensure the power supply security and avoid cascading failures of interconnected critical lines. Moreover, the influence of offshore wind farms is also considered.

It should be noticed that only CCUP grid converters are considered during the calculation procedure because the active power variation of other converter has little influence on the power flow of the critical AC line of the center CUP grid (less than 1%). In order to simplify the calculation process, it can be neglected.

2.2.2. Calculation Layer of Controller Parameters

In this layer, the controller parameters of converters should be calculated according to the calculated value from the upper layer. Meanwhile, DC network parameters, coordination mechanism of primary control are also considered during the calculation procedure.

2.2.3. Primary Control Strategy

The master-auxiliary control strategy [22] is adopted in this paper as the primary control, which is shown in Figure 3. Compared with traditional methods, master-auxiliary control is more suitable for CU-MTDC applications due to its better effectiveness of DC voltage control and accurate active power control (APC) of the APC converter under normal conditions. As shown in Figures 1 and 3, the rectifier converters are the master converter and auxiliary converter. The master converter is set to keep constant DC voltage control under normal conditions. The auxiliary converter is set to assist the DC voltage control. The CCUP grid converters are APC stations. The APC converters should turn into droop control under abnormal conditions. In this paper, constant active power control is used in the wind farm converter to simulate wind power variations.



Figure 3. U_{dc} -*P* characteristics of the master-auxiliary control strategy. (a) U_{dc} -*P* characteristics of the master converter. (b) U_{dc} -*P* characteristics of the auxiliary converter. (c) U_{dc} -*P* characteristics of the active power converter. (d) U_{dc} -*P* characteristics of the wind farm converter.

As shown in Figure 3, U_{dc} is the DC voltage of the converter, P is the active power of the converter on the AC side. P_{MAX} and P_{MIN} are the maximum and minimum active power of the converter, respectively. U_{dch} and U_{dcl} are the maximum and minimum DC voltage when the converter is under droop control, respectively. U_{dcH} and U_{dcL} are the DC voltage when the converter turns into droop control, respectively. U_{dcref} is the reference value of the DC system. U_H and U_L are the DC limit values of converters. P_{refn} and P_n are the active power reference value and the actual active power output value of the APC converter n, respectively. k_{aux} and k_{apc} are the droop coefficients of the auxiliary converter and APC converter, respectively. For all the converters, the positive direction of active power is defined as an injection to the DC grid.

3. Proposed Coordinated Control Strategy of CU-MTDC under Abnormal Conditions *3.1. Basic Concept*

As shown in Figures 1 and 3, if DC unbalanced power exceeds the regulation capacity of the master converter and auxiliary converter, DC voltage will be out of control until the APC converters change into droop control. Therefore, the active power of the APC converter reduces rapidly, and the load ratio of the interconnected critical line increases. As a result, the coordinated power redistribution strategy is required to guarantee power supply security.

In the traditional method, all the normal converters are involved in power distribution. Total regulation capacity is fully utilized, and the security of all the critical AC lines is confirmed. However, the DC power variation impacts the power flow among all areas of the AC system. Meanwhile, the constant active power supply of the APC converter is broken, and some unnecessary costs occur, considering the requirement of the electricity market. As a result, dynamically scheduling the number of the regulation converter according to the value of DC unbalanced power is a feasible solution method when the unbalanced power is less than a certain value. Generally, there exist two basic scenarios of unbalanced power coordinated distribution under abnormal conditions.

Scenario 1: The first scenario is that the DC unbalanced power is absorbed by one or more converters, which is referred to as the priority control mode.

Scenario 2: The second scenario is that the DC unbalanced power will be absorbed by all the normal APC converters, which is referred to as the shared control mode. Under this condition, the active power output value of every regulation converter should be further confirmed by a specific objective. In this paper, the control objective is all the critical AC lines that are interconnected with the APC converters have the same load ratio.

It should be noticed that offshore wind power directly affects DC unbalanced power. Therefore, the influence of offshore wind power on control can be generalized into the effect of the unbalanced power.

As shown in Figure 3c, two active power values of the APC converter are very important for the objective control implementation. The active power reference value P_{refn} and the actual active power output value P_n are calculated according to the proposed method, which is described in Sections 3.2 and 3.3.

3.2. Calculation of Active Power Reference Value

In this section, calculation principles for active power reference value are described as follows:

(1) The reference value should ensure the N-1 security criterion under normal conditions, which is

$$P_{refn} = \max \left\{ P_{refnLi,j} \right\} \tag{1}$$

where P_{refn} is the active power reference value of converter station *n*. $P_{refnLi,j}$ is the active power reference value of the *n* station to ensure the N-1 security after the AC line Li,j outage. Considering the requirement of security operation of the power grid, the security margin of $P_{refnLi,j}$ should be reserved.

$$P_{refnLi,j} = f_p \left\{ (1 - \varepsilon) S_{Li,j} \right\}$$
⁽²⁾

where ε is the security margin of the transmission line. $S_{Li,j}$ is the maximum capacity of the Li,j. According to (1) and (2), the CU-MTDC provides enough power supply security support to the AC system.

(2) Taking offshore wind power into account, the reference value should ensure the wind power is locally absorbed. Assuming N converters are interconnected with the CCUP grid. The maximum offshore wind power absorption can be expressed as

$$\sum_{n=1}^{N} P_{refn} = P_w \tag{3}$$

where P_w is the active power of wind farms. According to (1), (2) and (3), the active power reference value can be confirmed.

3.3. Unbalanced Power Coordinated Distribution Strategy Considering Power Supply Security

When the system DC voltage is out of control, the proposed unbalanced power coordinated distribution strategy will start immediately. The detailed implementation procedure can be divided into three steps, as follows:

Step 1: Calculate the unbalanced power of the DC system

Assuming M converters operate under rectifier mode, and then the DC unbalanced power can be calculated:

$$\Delta P_{dc} = \sum_{m=1}^{M} \Delta P_m \tag{4}$$

where ΔP_{dc} and ΔP_m are the DC unbalanced power and active power variation of rectifier converter *m*, respectively.

Step 2: Calculate the maximum regulation capacity of every APC converter

According to the power flow calculation method, the maximum allowable value of the APC converter active power can be written as:

$$P_{MAXn} = P_{refn\max} \tag{5}$$

where $P_{refnmax}$ is the maximum active power reference value of the APC converter *n* when the active power of interconnected critical line will not exceed the limit value.

The maximum regulation capacity of converter *n* can be expressed as:

$$\Delta P_{dcn\max} = P_{MAXn} - P_{refn} \tag{6}$$

Step 3: Compare ΔP_{dc} with ΔP_{dcnmax} and confirm operation mode

After comparing ΔP_{dc} with ΔP_{dcnmax} , the operation modes of the APC converters are confirmed based on the proposed two scenarios. Because two converters participating in the DC unbalanced power regulation is the most basic and common operation mode in the system, this mode is studied first in this paper. To facilitate analysis, VSC_{i1} and VSC_{i2} of CU-MTDC, which are shown in Figure 1, are set to control DC voltage after the DC unbalanced power exceeds the system regulation capacity of the master converter and auxiliary converter.

(1) Priority control mode: As shown in Figure 1, the control mode can be further divided into VSC_{i1} priority mode and VSC_{i2} priority mode. Because the two modes have a similar calculation procedure, only the VSC_{i1} priority mode is introduced in detail and is shown in Figure 4.



Figure 4. Control characteristics of voltage source converter $(VSC)_{i1}$ priority mode. (**a**). U_{dc-P} characteristics of VSC_{i1}. (**b**). U_{dc-P} characteristics of VSC_{i2}.

Assuming $\Delta P_{dci1max} > \Delta P_{dci2max}$, the judgment process is introduced as follows: Under this condition, VSC_{i1} turns into droop control, and VSC_{i2} keeps the initial operation mode.

If $(\Delta P_{dci2max} < \Delta P_{dc} < \Delta P_{dci1max})$, the DC unbalanced power will be absorbed by VSC_{*i*1}, which is:

$$\begin{cases} P_{i2} = P_{refi2} \\ P_{i1} = 1/k_{i1} * (U_{dc1} - U_{dcLi1}) + P_{refi1} \end{cases}$$
(7)

where k_{i1} is the droop coefficient of VSC_{*i*1}:

$$k_{i1} = \frac{U_{dcLi1} - U_{dcli1}}{P_{refi1} - P_{MAXi1}}$$
(8)

It should be noticed that a backup droop control is applied in VSC_{i2} . The main responsibility of this design is to avoid DC voltage out of control in case of some accidents occur, such as information loss or wind power fluctuation. In addition, the shadow area is represented as the range of droop coefficient and can be confirmed with the requirement of the control effect. Moreover, the control margin, which is reserved for VSC_{i2} , should also be considered.

If $(\Delta P_{dc} < \Delta P_{dci2max})$, VSC_{i2} will operate on a similar mode, and the distribution result can refer to the analysis above.

(2) Shared control mode: As shown in Figure 5, under this condition, VSC_{i1} and VSC_{i2} jointly realize the unbalanced power distribution.



Figure 5. Control characteristics of shared control mode. (a). U_{dc-P} characteristics of VSC_{*i*1}. (b). U_{dc-P} characteristics of VSC_{*i*2}.

If $(\Delta P_{dci1max} < \Delta P_{dc} < \Delta P_{dci1max} + \Delta P_{dci2max})$, the DC unbalanced power will be distributed as follows:

$$P_{i2} = 1/k_{i2} * (U_{dci2} - U_{dcLi2}) + P_{refi2}$$

$$P_{i1} = 1/k_{i1} * (U_{dci1} - U_{dcLi1}) + P_{refi1}$$
(9)

where k_{i2} is the droop coefficient of VSC_{*i*2}:

$$k_{i2} = \frac{U_{dcLi2} - U_{dcli2}}{P_{refi2} - P_{MAXi2}}$$
(10)

To realize the accurate distribution of VSC_{i1} and VSC_{i2} , the load ratio of the critical line is defined as:

$$\beta_{Li,j} = \frac{P_{Li,j}}{(1-\varepsilon)S_{Li,j}} \tag{11}$$

With the proposal of equivalent load ratio of critical lines, that is, $\beta_{Li,j} = \beta_{Lg,k}$, P_{i1} and P_{i2} can be calculated specifically:

$$\begin{cases} P_{i2} = f_p(P_{Lg,k\beta eq})\\ P_{i1} = f_p(P_{Li,j\beta eq}) \end{cases}$$
(12)

$$\sum_{n=1}^{2} P_{refin} - P_{in} = \Delta P_{dc} - \Delta P_{dcloss}$$
(13)

where ΔP_{dcloss} is the variation of DC power loss before and after power distribution.

According to (12) and (13), the DC unbalanced power can be accurately distributed by both VSC_{i1} and VSC_{i2} .

If $(\Delta P_{dc} > \Delta P_{dci1max} + \Delta P_{dci2max})$, a special condition of the shared control mode occurs. Under this condition, the supply security of one critical line should be broken to ensure the stable operation of the DC system. The APC converter, which is interconnected with a strong area, will continue absorbing unbalanced power, and the other one outputs the maximum power allowed by power supply security. At this time, the rated active power capacity of the APC converter connected with the strong area is set to the reserve regulation capacity to maintain the stable DC voltage of the system.

3.4. Unbalanced Power Coordinated Distribution Strategy When the Number of the APC Converter Exceeds Two

When the number of the APC converter, which is set to control DC voltage, exceeds two, the operation mode can be regarded as a combination of the two basic modes and has a similar analysis process.

Taking the number of the APC converter is three as an example, assuming $\Delta P_{dci1max} < \Delta P_{dci2max} < \Delta P_{dci3max}$, the detailed coordinated distribution strategy is described as follows in Table 1.

Table 1. Coordinated distribution strategy when the number of the active power control (APC) converter is three.

Criterion	VSC _{i1}	VSC _{i2}	VSC _{i3}
$\Delta P_{dc} < \Delta P_{dci1max}$	Droop	Constant power	Constant power
$\Delta P_{dci1max} < \Delta P_{dc} < \Delta P_{dci2max}$	Constant power	Droop	Constant power
$\Delta P_{dci2max} < \Delta P_{dc} < \Delta P_{dci3max}$	Constant power	Constant power	Droop
$\Delta P_{dci1max} + \Delta P_{dci2max} < \Delta P_{dc} < \Delta P_{dci3max}$	Constant power	Constant power	Droop
$\Delta P_{dci3max} < \Delta P_{dc} < \Delta P_{dci1max} + \Delta P_{dci3max}$	Droop	Constant power	Droop
$\Delta P_{dci1max} + \Delta P_{dci3max} < \Delta P_{dc} < \Delta P_{dci2max} + \Delta P_{dci3max}$	Constant power	Droop	Droop
$\Delta P_{dci2max} + \Delta P_{dci3max} < \Delta P_{dc}$	Droop	Droop	Droop

As shown in Table 1, it is observed that the coordinated control strategy becomes more complex with the increasing number of the APC converter. It limits the proposed control strategy applied to a very large system. However, in the urban power grid, very many APC converters participating in system regulation is not needed. Thus, the proposed control strategy is appropriate and could be applied to the coastal urban power system with the VSC-MTDC system.

3.5. Calculation of the APC Converter Controller Parameters

Take the CU-MTDC, which is shown in Figure 1 as an example; the detailed calculation procedure of the APC converter controller parameters is described. Meanwhile, the master converter outage is used as an application scenario to guarantee the security operation of the DC system under the most serious abnormal condition. The DC gird equation can be written as:

$$\mathbf{P} = [\mathbf{U}][\mathbf{Y}]\mathbf{U} \tag{14}$$

where $[U]_{n-1 \times n-1} = diag[U_{dc2}, U_{dc3}, U_{dc4}, \dots U_{dcn-1}]$ is a diagonal matrix comprised of DC bus voltage.

As shown in Figures 4 and 5, when the VSC_{i1} and VSC_{i2} are set to control DC voltage, two parameters U_{dcL} and U_{dcl} are very important for control objective implementation. The detailed calculation procedure is described as follows:

(1) The calculation of U_{dcl} . U_{dcL} is the starting voltage of the droop control and should be determined by the minimum DC voltage of the APC converter under normal conditions. In this paper, U_{dcL} should be calculated when the power of the wind farm is zero and APC converters output maximum power. Under shared control mode, the U_{dcL} of VSC_{i1} and VSC_{i2} can be obtained by DC power flow calculation, and a DC voltage security margin should be reserved, which is:

$$U_{dcL} = U_{dcL}^* - U_{dc\varepsilon} \tag{15}$$

where U_{dcL}^{*} is the DC voltage got from the power flow calculation, $U_{dc\varepsilon}$ is the DC voltage security margin.

Under priority control mode, such as VSC_{i1} priority mode, the U_{dcL} of VSC_{i1} can be determined according to (15). The U_{dcL} of VSC_{i2} should be confirmed along with U_{dcl} of VSC_{i1} .

(2) The calculation of U_{dcl}. U_{dcl} is the cut-out DC voltage of the droop control. Under shared control mode, U_{dcl} of the two converters, which are set to control DC voltage, determines the DC unbalanced power distribution directly.

Substitute (10) and (12) into (9), the characteristics of the APC converter can be expressed as:

$$\begin{cases} U_{dci1} = \frac{(U_{dcLi1} - U_{dcli1})}{(P_{refi1} - P_{MAXi1})} (f_p(P_{Li,j\beta eq}) - P_{refi1}) + U_{dcLi1} \\ U_{dci2} = \frac{(U_{dcLi2} - U_{dcli2})}{(P_{refi2} - P_{MAXi2})} (f_p(P_{Lg,k\beta eq}) - P_{refi2}) + U_{dcLi2} \end{cases}$$
(16)

According to (12), (13), (14) and (16), the controller parameters can be calculated.

Based on the above-mentioned, under VSC_{i1} priority mode, the selection of U_{dcli1} should consider the control margin, which is reserved for VSC_{i2}. To ensure control security, the control margin should refer to the practical requirements and not be set too small. In this paper, 3% of the rated DC voltage should be set as the security margin for DC voltage control of VSC_{i2}.

The flowchart of complete operation mode confirmation and controller parameters calculation can be shown in Figure 6.



Figure 6. Flowchart of the complete calculation procedure of the proposed method.

4. Case Study

In this section, the five-terminal CU-MTDC and interconnected CUP grid shown in Figure 7 are studied in PSCAD/EMTDC to verify the feasibility of the proposed coordinated

control strategy under abnormal conditions. An actual CUP grid topology in the eastern coast of China and the data of maximum operation mode in summer [23] are applied in the simulations. Three critical lines L_{5-7} , L_{13-15} , L_{13-14} , are facing transmission stress problems (load ratio exceeds 90%). However, additional AC lines are not allowed because of the shortage of transmission corridors and the limitation of short circuit capacity. The short-circuit current of Bus_{13} and Bus_2 is close to the maximum breaking current of a break. Moreover, offshore wind farm A is interconnected with the CUP grid via the HVAC. The random and intermittent characteristics of the wind power will further increase the transmission stress of the critical lines, even lead to serious security problems. Based on the analysis above, a five-terminal CU-MTDC is finally applied in the CUP grid.



Figure 7. System structure of the five-terminal CU-MTDC. (**a**) Initial coastal urban power grid. (**b**) Final CU-MTDC applied in a coastal urban power grid.

VSC₁ and VSC₃ are directly connected with a high voltage (HV) grid and generally operate on rectifier mode. VSC₂ and VSC₄ interconnect with the CCUP grid and operate on inverter mode. VSC₁ is the master converter station to keep constant DC voltage control under normal conditions. VSC₃ is the auxiliary converter station to assist the DC voltage control. VSC₂ and VSC₄ are APC stations. The APC converter should turn into droop control under abnormal conditions. VSC₅ is an offshore wind farm converter. The active power capacity of converter 1 and 2 are all rated 500 MVA. The rated active power of converter 3, 4 and 5 are 250 MVA, 200 MVA and 400 MWA, respectively. The length of DC cable between terminals are $L_{12} = L_{23} = L_{25} = 40$ km, $L_{34} = 20$ km. The detailed parameters of the DC/AC system are shown in Tables 2–4. The diagram of the whole system is shown in Figure 8.

Table 2. Short-circuit current of the critical bus.

Bus Name	Short-Circuit Current (kA)	Maximum Breaking Current (kA)
B ₁₃	43.6	50
B ₂	56	63

Line Name	Load Ratio (%)	Active Power Capacity (MW)
L _{5–7}	96.47	255
L _{13–15}	73.5	483
L _{13–14}	65.4	483
$L_{13-15} + L_{13-14}$	95.85	700

Table 3. Initial load ratio of critical lines (without multi-terminal DC (MTDC).

 Table 4. Parameters of DC simulation model.

System Component	Major Parameter	Parameter Value	
Converter transformers	Transformation ratio	525 kV/230 kV (1, 3) 220 kV/230 kV (2, 4, 5) 550, 550, 300 250, 450 MVA	
1–5	Rated capacity		
	Leakage reactance	0.1 p.u	
Connection reactor	Inductance	0.15 p.u	
DC capacitor	Capacitance	150 μF	



Figure 8. Simplified diagram of the studied system.

From Table 3, the load ratio of L_{13-15} and L_{13-14} are lower than 90%. However, the power flow of the two transmission lines cannot be control independently. To prevent one of the two transmission lines from exceeding the limit value, a limit security value of the

two lines' power sum is set at 700 MW by the operation department of the power grid. The security margin of the AC lines power limit value ε is set as 5%. Considering the value of ε , the limit value of the critical lines are 243 MW and 665 MW, respectively.

As shown in Figure 7, the CUP grid can be divided into four areas. To reduce the complexity of the description, Figure 8 is shown as a simplified topology. Only some important regions of areas I and II are shown in detail.

The DC voltage reference value of the CU-MTDC is selected at 400 kV. The maximum security of the DC voltage range of all the converters is $\pm 10\%$, and U_{dcc} is set as $\pm 1\%$. According to (1), (2) and (3), the initial active power reference value of VSC₂ and VSC₄ are 500 MW and 200 MW.

In the coastal urban power grid, different load conditions will directly affect the maximum regulation capacity of the APC converter according to the proposed method. In this paper, $load_{18}$ and $load_7$ are selected to simulate different load conditions by changing the active power. The influence of the load variation on the maximum regulation capacity of the converter is shown in Table 5.

Name	ΔLoad ₁₈ (MW)	ΔLoad ₇ (MW)	ΔP _{dc2max} (MW)	ΔP _{dc4max} (MW)	Total Capacity (MW)
Case 1	0	0	460	185	645
Case 2	20	10	442	178	620
Case 3	40	20	424	171	595
Case 4	60	30	406	164	570
Case 5	80	40	388	157	545
Case 6	100	50	370	150	520
Case 7	120	60	352	143	495
Case 8	140	70	334	136	470
Case 9	160	80	316	129	445
Case 10	180	90	298	122	420
Case 11	200	100	280	115	395

Table 5. Load variation on the maximum regulation capacity of the APC converter.

4.1. Simulation under Priority Control Mode

In this case, the load condition is selected No.6 in Table 5. The active power of the *Load*₁₈ and *Load*₇ are increased by 100 MW and 50 MW, respectively. The maximum regulation capacity of the APC converters are $\Delta P_{dc2max} = 370$ MW and $\Delta P_{dc4max} = 150$ MW under this condition. The initial active power of converter 2, 4 and 5 are 500 MW, 200 MW and 220 MW. When t = 0.2 s, a temporary inner fault occurs in master converter 1 and lasts for 0.3 s, which results in the converter 1 blocking. At t = 0.9 s, the active power of the offshore wind farm increases to 400 MW. When t = 1.2 s, converter 1 is out of operation because of a serious converter fault. The simulation results are shown in Figure 9.

As shown in Figure 9a,b, when t = 0.2 s, the master converter is blocked, and active power is decreased to zero immediately. DC unbalance power occurs when the auxiliary converter reaches its maximum capacity. The final unbalanced power is 251 MW, and the operation mode will turn into VSC₂ priority mode. According to equation (15), U_{dcL2} of VSC₂ is 391 kV. Then U_{dcl2} of the VSC₂ is set at 379 kV as the result of a security margin for DC voltage control of VSC₄. The DC unbalanced power is absorbed by VSC₂ independently. Under VSC₂ priority mode, the DC voltage will rapidly reduce until VSC₂ turns into droop control, and then DC voltage is always within the security range.

At t = 0.9 s, the offshore wind farm outputs the maximum active power and the output of VSC₁ and VSC₃ are decreased to 181.7 MW and 130.8 MW, respectively. As a result, DC unbalanced power will be changed to 60 MW if VSC₁ is out of operation.



Figure 9. Simulation under priority control mode. (**a**) Active power of converters. (**b**) DC voltage of converters. (**c**) Active power of critical AC lines.

When t = 1.2 s, VSC₁ will be out of operation for a long time because of a serious fault in the converter. The operation mode will change into VSC₄ priority mode, and the DC unbalanced power is absorbed. The DC voltage is within the normal range during the process.

From Figure 9c, it is observed that the power supply security of critical lines is confirmed during the simulation process. Under VSC₂ priority mode, the sum of active power value of L_{13-15} and L_{13-14} is 616.4 MW, and the active power of L_{5-7} is kept around 199 MW. Under VSC₄ priority mode, the active power of L_{5-7} is 220 MW, and the active power variation of L_{13-15} and L_{13-14} are quite small. The influence on the AC system power flow can be limited in one area.

It can be concluded that, under the priority mode, the APC converter can absorb the DC unbalanced power independently. Meanwhile, power supply security is confirmed, and the influence on power flow can be limited in a small area. In addition, the transmission security of the important power supply area is guaranteed because the important power

supply area usually has greater power supply demand. According to the priority control method proposed in this paper, these converters have lower priority. Therefore, they are the last to participate in power regulation when the DC unbalanced power is small.

4.2. Simulation under Shared Control Mode

The initial simulation set is similar to 4.1. When t = 0.2 s, the output of the offshore wind farm is changed to zero. At t = 0.5 s, converter 1 is blocked due to a temporary fault and unblocked at t = 0.8 s. Simulation results are shown in Figure 10.



Figure 10. Simulation under shared control mode. (**a**) Active power of converters. (**b**) DC voltage of converters. (**c**) Active power of critical AC lines.

As shown in Figure 10a,b, when t = 0.2 s, the maximum DC unbalanced power is changed to 460 MW since the active power of the offshore wind farm is decreased to zero.

At t = 0.5 s, the master converter is blocked because of a temporary fault, and the active power is reduced to zero. The DC unbalanced power occurs, and the DC voltage reduces rapidly. Since the unbalanced power cannot be absorbed by one converter independently, the operation mode turns into a shared control mode. Similar to case 4.1, U_{dcL2} and U_{dcL4} are 391 kV and 390 kV, respectively. U_{dcl2} and U_{dcl4} are 379 kV and 383 kV, according to (12), (13), (14), and (16). Under the shared control mode, the DC unbalanced power is absorbed by both VSC₂ and VSC₄, and the active power is -176.3 MW and -67.1 MW. During the

whole process, the DC voltage of all the converters is within the security range. The fault is cleared after 0.3 s, and converters restore to the initial operation mode immediately.

As shown in Figure 10c, the active power of L_{5-7} , L_{13-15} and L_{13-14} are 237.4 MW, 347 MW and 308.4 MW under the shared control mode. The security of all the critical lines is guaranteed, and the load ratio of L_{5-7} and $L_{13-15} + L_{13-14}$ is 0.9309 and 0.9363.

According to the simulation results above, the DC unbalanced power can be well equilibrated by both the two converters under shared mode. The control objectives of power supply security and equal load ratio of critical lines are also realized.

4.3. Simulation under the Special Conditions of the Shared Control Mode

In this case, the load condition is selected No.10 in Table 5. The active power of the *Load*₁₈ and *Load*₇ is increased by 180 MW and 90 MW, respectively. The maximum regulation capacity of the APC converters is $\Delta P_{dc2max} = 298$ MW and $\Delta P_{dc4max} = 122$ MW. The initial active power of converter 2, 4 and 5 is 500 MW, 200 MW and 220 MW, respectively. When t = 0.2 s, the output of the offshore wind farm is changed to zero. At t = 0.5 s, converter 1 is out of operation because of a serious converter fault. When t = 0.7 s, the AC system is involved in the control and the active power of the *Load*₁₈ is decreased by 40 MW. Simulation results are shown in Figure 11.



Figure 11. Simulation under the special condition of the shared control mode. (**a**) Active power of converters. (**b**) DC voltage of converters. (**c**) Active power of critical AC lines.

As shown in Figure 11a,b, when t = 0.5 s, the master converter is out of operation for a long time because of a serious fault in the converter. Since the DC unbalanced power is 460 MW, shared control mode will be applied in both these two converters. At t = 0.58 s, the two converters reach their maximum regulation capacity limits, but the DC system still has unbalanced power that is not absorbed. At this time, a special condition of the shared control mode occurs. VSC₂ will continue absorbing the remaining unbalanced power, and VSC₄ maintain the maximum active power allowed. At t = 0.65 s, the DC unbalanced power is absorbed by both VSC₂ and VSC₄, and the active power is -168 MW and -78 MW. During the whole process, the DC voltage of all the converters is within the security range.

As shown in Figure 11c, the active power of L_{5-7} , L_{13-15} and L_{13-14} are 242.5 MW, 360.5 MW and 314.5 MW under the special condition of the shared control mode, respectively. The load ratio of L_{5-7} and $L_{13-15} + L_{13-14}$ is 0.95 and 0.9642, respectively. Under this condition, the load ratio of $L_{13-15} + L_{13-14}$ exceeds the allowable security range, and the AC system is involved in control. After the active power of the *Load*₁₈ is decreased by 40 MW at t = 0.7 s, the active power of $L_{13-15} + L_{13-14}$ are 353 MW and 311.5 MW, respectively. The final load ratio of L_{5-7} and $L_{13-15} + L_{13-14}$ is 0.95 and 0.949, respectively.

According to the simulation results above, a special condition of the shared control mode occurs when the total regulation capacity is insufficient. At this time, the VSC interconnected with a strong area will continue absorbing unbalanced power, and the others maintain the maximum power allowed. Since system security cannot be protected by the DC system alone, the AC system should be involved in the regulation. Through the coordination of the AC and DC system, the power supply security of the urban power grid is guaranteed.

5. Conclusions

Considering the influence of power supply security of urban power systems and offshore wind farm integration, a coordinated control strategy of coastal urban multiterminal DC (CU-MTDC) application under abnormal conditions is proposed in this paper. Based on the priority control idea, the calculation and control process are very simple. The proposed control strategy dynamically schedules the number of the regulation converters according to the DC unbalanced power value and the offshore wind power influence, instead of all the converters involved in control. The effectiveness of the proposed control strategy is verified by simulation in PSCAD/EMTDC. The simulation results indicate that the influence range of DC faults on the urban power grid can be limited in a small area, and the transmission security of the important power supply area is guaranteed with the proposed method. In addition, some converters in CU-MTDC could still maintain a fixed power output under the contingencies with the proposed method. Since they can keep the promissory power transmission, the economic benefits could be brought to system operators.

Owing to the fact that the complexity of the control increases with the number of converters involved in the regulation, there are several promising directions for CU-MTDC future research. Future work should focus on how to reduce the control complexity when the number of the regulated converter stations is too large. Moreover, how to introduce the reactive power control function of VSC into the coordinated control strategy to improve the power supply security and voltage security also has been planned.

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Abbreviations

APC	Active power constant
CUP grid	Coastal urban power grid
CU-MTDC	Coastal urban multi-terminal DC
CCUP grid	Center of coastal urban power grid
k	The droop coefficient
P _{MAX}	The maximum active power
P _{MIN}	The minimum active power
P _{ref}	The active power reference value
P _{refnLi,j}	The active power reference value of the n station to ensure N-1 security after line <i>Li,j</i> outage
Prefnmax	The maximum active power reference of the APC converter when the power of the
5	AC line not exceeding the limit value
ΔP_{dcnmax}	The maximum regulation capacity of converter n
ΔP_{dcloss}	The variation of DC power loss before and after power distribution
ΔP_{dc}	The DC unbalanced power
P_w	The active power of wind farm
$S_{Li,j}$	The maximum capacity of the <i>Li</i> , <i>j</i>
U _{dc}	The DC voltage of the converter
U _{dch}	The maximum DC voltage when the converter is under droop control
U _{dc1}	The minimum DC voltage when the converter is under droop control
U_{dcH}, U_{dcL}	The DC voltage when the converter turns into droop control
U _{dcref}	The reference value of DC system
U_H, U_L	The DC limit values of converters
U^*_{dcL}	The DC voltage got from power flow calculation
U _{dce}	The DC voltage security margin
VSC-HVDC	High voltage direct current based on voltage source converter
WFVSC	Wind-farm converter
ε	The security margin of transmission line
$\beta_{Li,j}$	The load ratio of critical line

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