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Control Strategy for Operation Mode Identification of Complex DC Distribution Network

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Abstract:

The unpredictable output of renewable energy sources such as wind power and photovoltaics, the charging and discharging behavior of energy storage systems, the random fluctuation of power load, and the complex change in the topology of the DC distribution network all raise the bar for system-level control and the energy management system of the DC distribution network. This chapter will first create the graph theory model of a DC distribution network, and then offer a control approach for determining the operating mode of a complicated DC distribution network based on the Breadth-First Search (BFS) algorithm in order to address the issues raised above.

Keywords*: Energy storage system; Topological structure; DC distribution network; Control strategy.*

I. INTRODUCTION

The advancement of communication technology and computer technology will result in a further reduction in communication latency, an increase in the dependability of communication, and an increase in the speed at which system data is processed, among other benefits. After a change in operation mode of a distribution network system, it is possible that the interval between control mode switching of converter stations will be shorter, and the transient process of system switching will be more stable. As a result, there will continue to be a large number of distribution networks controlled by classic master-slave relationships. The change of the converter station control mode under master-slave control, on the other hand, is dependent on the operation mode table that has been previously specified. It is necessary to re-compile the whole operation mode table whenever a new end of the system or a new line is added or removed, which has a negative impact on the portability and expansibility of the control software. Moreover, at the same time, Some flexible and straight projects have system-level control that employs master-slave control and have been put into operation. If you want to switch to a more flexible system-level control scheme, you will have to invest significant resources in terms of manpower and time to redebug the system, which will take a long time. Aside from that, when the operation mode of an EMS system changes, it is also required to quickly determine which mode of operation is currently active in order to maintain operational continuity. Adjust the energy management algorithm in real time to ensure that the system's power flow is optimized.

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Current research on EMS systems for DC distribution networks is primarily concerned with DC power flow calculation using a voltage source converter, AC/DC hybrid power flow calculation with multiple voltage levels, multi-time scale energy management, and multi-objective function optimization, among other things. According to the literature[1-3], the operating point of the system, the state of charge of energy storage and the operation plan of electric vehicles are optimized in a long time scale; the optimization instruction of controllable power supply is given in a short time scale, and the relationship between the two algorithms can be established by altering the power reserve coefficient, resulting in a system operation co-efficient of 0.9. The system operation co-efficient of 0.9. Using the Newton technique in an augmented rectangular coordinate system, literature[4]calculates AC/DC power flow in a DC distribution network with a DC distribution network, and takes into account converter loss, as well as the control model of VSC and DC transformer.

Literature[5] In this paper, the steady-state model of a DC power network is used to analyze the control modes of a variable speed controller (VSC) and a DC transformer, and the calculation techniques for system power flow and network characteristics under various control modes are developed. Some literatures primarily research EMS systems by developing multi-objective functions, with the key distinction being that various objective functions are employed in different literatures. however These investigations are based on a fixed system topology, and they do not take into account the potential influence of the system on the EMS system in the event of a significant disruption (such as the impact of the change of system operation mode on EMS system). At the moment, the electrical grid is evolving in the direction of automation and artificial intelligence. It is therefore critical to understand how the traditional master-slave control and EMS can automatically and quickly identify the operation mode of the system in situations where the DC distribution line is disconnected, some controllable devices are out of operation, and new ports are added, and how to control the system voltage and optimize the system power flow under the new topology[6-10].

II. GRAPH THEORY MODELING OF DC DISTRIBUTION NETWORK

2.1 Establishment of DC distribution network diagram

It is possible to intuitively depict the connection between vertices by using the equation G=(V,E), which represents the set of vertices V and edges E. As a result, graph is a kind of data structure that is often used in computer science, and many algorithms that are based on graphs are fundamental algorithms in computer science. Computers are capable of solving a wide range of practical issues that may be abstracted into graphs and then solved[11-13].

The subject of this article is a medium voltage flexible DC distribution network with six terminals and seven nodes, which is the subject of this study's investigation. In Figure 1, the circuit breakers on each line are labeled with numbers, and the flexible DC distribution system is shown as a diagram.

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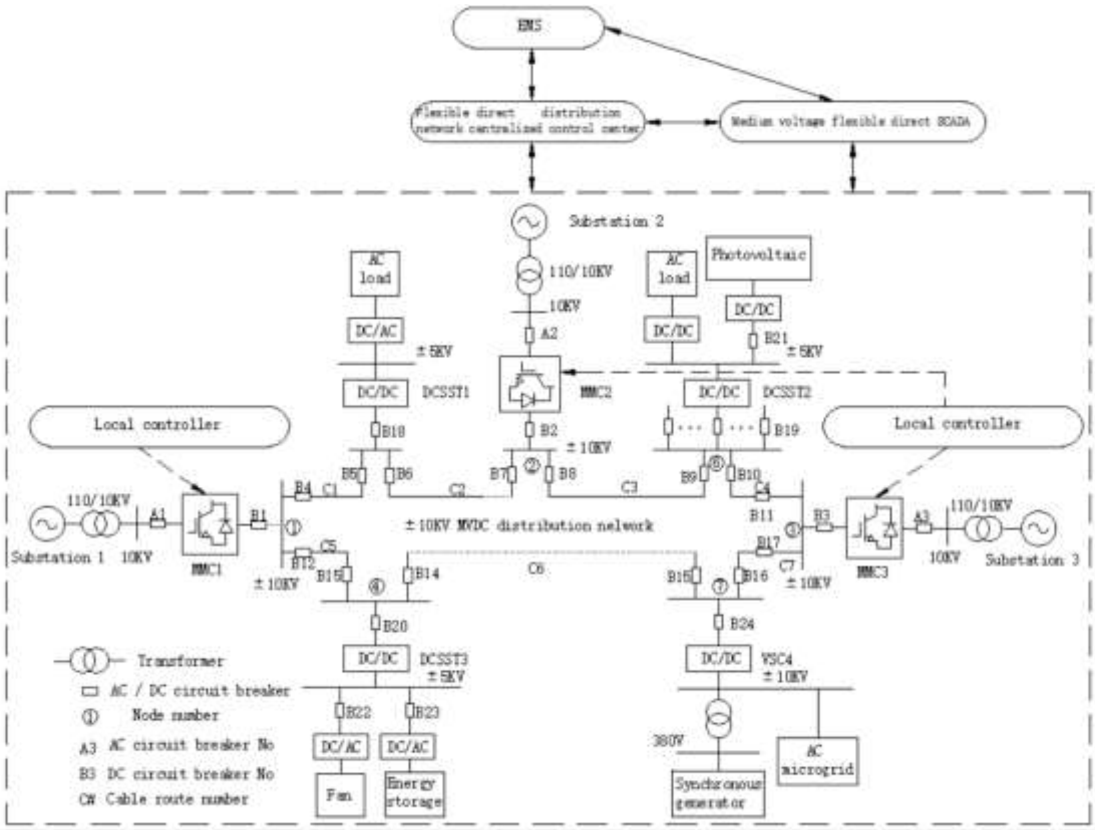

Fig. 1 Low-voltage flexible DC distribution network with six terminals and seven nodes

The undirected graph G=(V,E) corresponding to the topology of flexible and straight distribution network shown in Figure 1 is shown in Figure 2, in which vertices 1-7 indicated by red dots correspond to nodes 1-7 in Figure 1, and the edges of the graph G are composed of DC breakers on the line through logical combination, such as cable lines C1= B4&B5, which means that when both DC breakers B4 and B5 are active, the current on the line will flow in both directions[14-18].

2.2 Storage of DC distribution network diagram

The adjacency table and the adjacency matrix are the two most common ways to store G=(V,E) in a database. Adjacency tables are often used to depict sparse graphs (in which the number of edges |E| in the graph is significantly fewer than the square of the number of vertices |V|2) because they are easy to express. It is common practice to utilize the adjacency matrix representation for dense networks (where |E| is near to |V|2) or when it is important to rapidly assess whether or not there is a relationship between two given vertices, for example. The representation method of node admittance matrix is commonly used in the power system for the representation of network topology; therefore, the representation method of adjacency matrix is more direct for storing the undirected graph of flexible DC distribution network than the representation method of node admittance matrix[19-20]. A sparse adjacency matrix A of order 1717 is generated for the undirected graph seen in Figure 3.

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$A_{17\times17}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	0	0	0	0	A1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	A2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	A3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	A14&A15	A12&A13	0	0	A20	0	0	0	0	0	0
5	0	0	0	0	0	0	0	A4&A5	A6&A7	0	0	0	0	A18	0	0	0
6	0	0	0	0	0	0	0	0	A8&A9	A10&A11	0	0	0	0	A19	0	0
7	0	0	0	A14&A15	0	0	0	0	0	A16&A17	0	0	0	0	0	0	A24
8	A1	0	0	A12&A13	A4&A5	0	0	0	0	0	0	0	0	0	0	0	0
9	0	A2	0	0	A6&A7	A8&A9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	A3	0	0	A10&A11	A16&A17	0	0	0	0	0	0	0	0	0	0
11	0	0	0	A20	0	0	0	0	0	0	0	A23	A22	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	A23	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	A22	0	0	0	0	0	0
14	0	0	0	0	A18	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	A19	0	0	0	0	0	0	0	0	0	A21	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	A21	0	0
17	0	0	0	0	0	0	A24	0	0	0	0	0	0	0	0	0	0

Fig. 2. This matrix is a time-varying matrix, and the components of the matrix change in response to changes in circuit breaker states, allowing the system's topology to be reflected in real time, as seen in Figure 1.

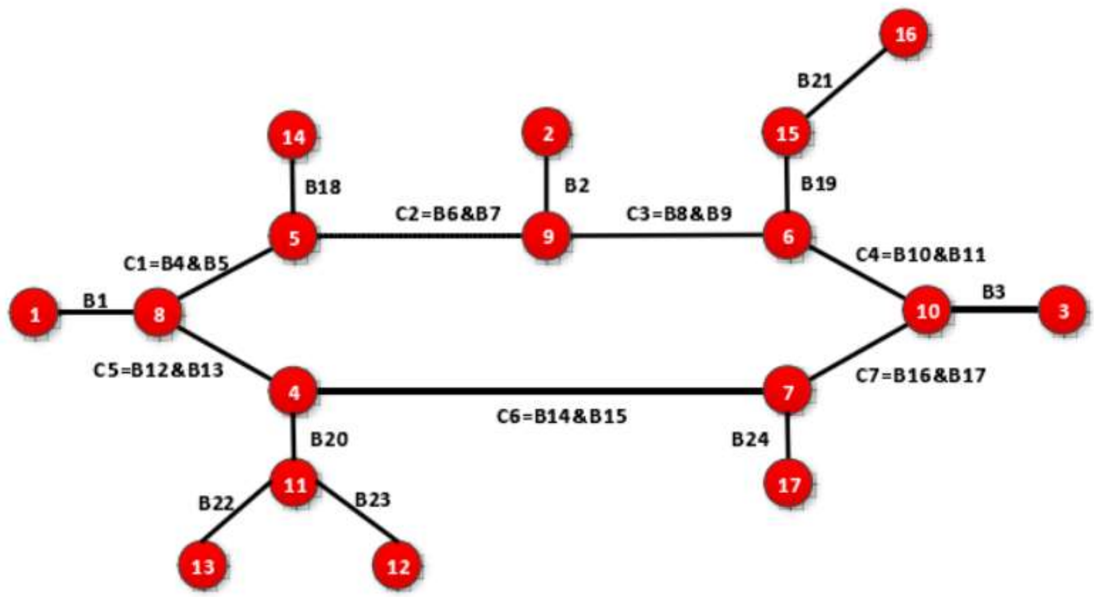

Fig. 3. Undirected diagram of medium voltage flexible DC distribution network with six terminals and seven nodes

III. PRINCIPLE OF BFS ALGORITHM

Assuming that we have a graph G=(V,E) and a single source vertex S, the BFS algorithm will methodically search over the edges of G in order to "find" all of the vertices that may be reached from S[21]. It is a technique of hierarchical search in which the border between known and undiscovered

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vertices is always extended outward in the breadth direction of the search space. The BFS method will first search all vertices with a distance of k from the source vertex S, and then search all vertices with a distance of k from the source vertex S.

In order to record the search track, the BFS algorithm will first color the vertices in three distinct shades of white, gray, and black to differentiate between the various phases of the search process. Each vertex starts off as white, and as the search advances, the color of each vertex will progressively shift from white to gray, and then to black, as the algorithm continues. A vertex is grayed out when it is met for the first time during the search, indicating that the vertex has been discovered. When all of the point's nearby vertices have been identified, the vertex will be colored black to indicate its location. As a result, gray vertices serve as a demarcation line between known and unknown vertex positions. The variables defined in the BFS algorithm code are listed in Table 1.

TABLE 1: Variable definition

variable	meaning
Q	A first-in first-out queue
Enqueue(Q,s)	Add vertex s to queue Q.
Dequeue(Q)	Take out the vertex of the head of queue Q and delete it from the queue.
V[G]	The set of all vertices in a graph
color[u]	For each vertex u∈V, its color storage array color[]
π[u]	U's parents are stored in the array π []
A[u][v]	Adjacent matrix A, if there is an edge between vertices U and V, the value is 1, otherwise it is 0.

Note: When a vertex V is discovered by searching the edge of U, then U is the parent of V, and it is recorded as π [V] = U.

BFS algorithm code:

BFS(G,s)/function name BFS, where g is the graph to be searched and s is the source vertex.

1 for each u∈V[G]

2 color [u] ← white/Every vertex in graph G is white.

3 π[u]←NIL/Let the parents of each vertex be NIL.

4 end for

Color [s] ← gray/white the source vertex S.

6 π[s]←NIL/Set the parents of source vertex S as NIL.

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7 Q←ø/Initialize FIFO queue

Enqueue (q, s)/Insert the source vertex S into the queue.

9 while Q≠ø/As long as the queue is not empty

1do u ← dequeue (q)/Take out the vertex of queue q head to u.

1 for each v ∈ v [g]/take every vertex v in the graph g.

1doif color [v] = white &&a [u] [v] = 1/If there is an edge between vertex V and vertex U and vertex V has not been found.

13 then color[v]=Gray/gray vertex v.

14 π[v] ←u/parents who remember u as vertex v.

1enqueue (q, v)/Insert vertex V into queue Q.

16 end for/every vertex in graph g has been searched.

17 color[u] ←Black/color the vertex u black.

18 end while

Figure 4 depicts a flow chart of the BFS algorithm in action. S is the initial search point, which is generally the location with the highest search priority. S is the starting search point (such as the control master station of the system or other converter station nodes connected with the AC system).

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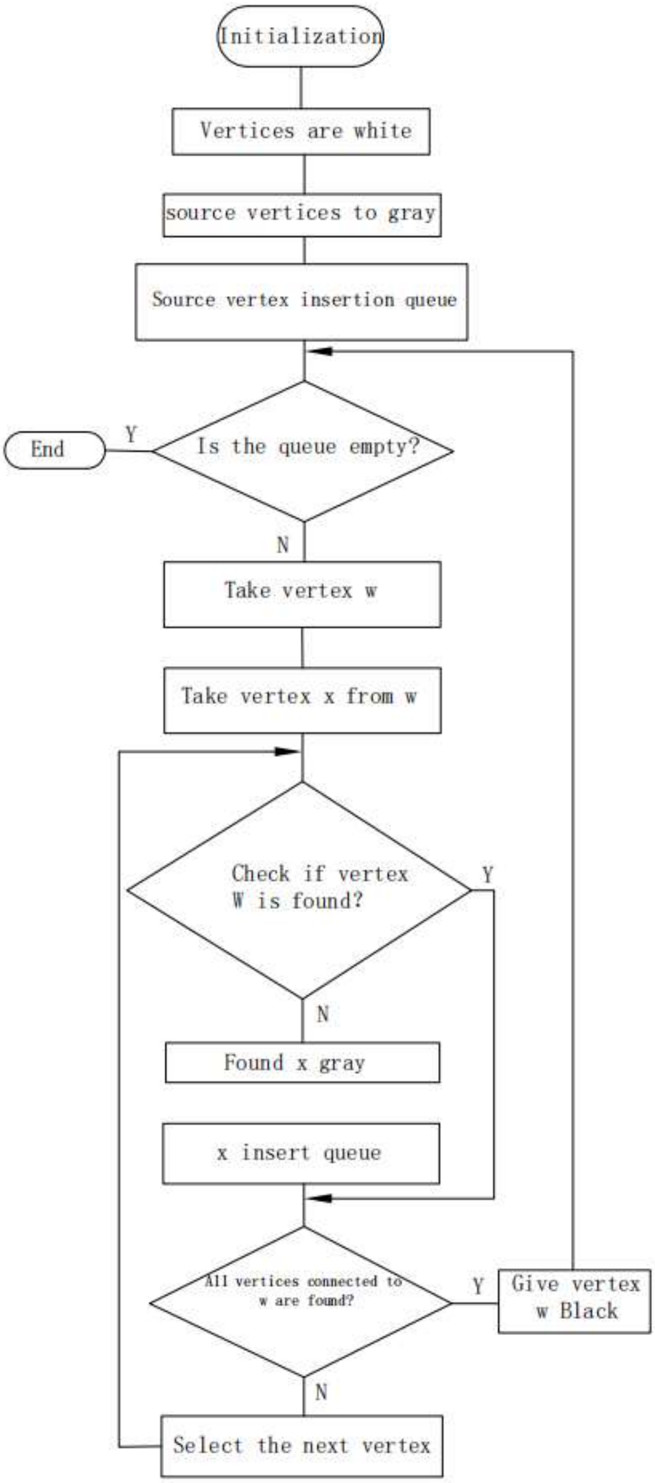

Fig. 4 BFS algorithm flow chart

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IV. CONTROL STRATEGY OF DC DISTRIBUTION NETWORK BASED ON BFS ALGORITHM

This section proposes a control strategy based on the BFS algorithm to solve the operation mode identification problem of the flexible-direct distribution network in order to enable the centralized control center and the EMS system of the flexible-direct distribution network to actively and quickly identify the current operation mode of the flexible-direct distribution network, switch the control mode of converter station and adjust the EMS optimization strategy faster, and better adapt to the development of the flexible-direct distribution network.

The implementation process of this strategy is as follows:

(1) the assignment of a priority to each node in the flexible-direct distribution network system, and the assignment of a higher priority to nodes with controllable output in the system, such as converter stations and energy storage systems connected to the AC system; the assignment of a priority to each node in the flexible-direct distribution network system; Nodes having unpredictable outputs in the system, such as AC/DC loads, are assigned lower priority than other nodes;

(2)The unique DC distribution network is abstracted away and represented as an undirected graph. Because of this, the number of vertices belonging to nodes with greater priority is reduced after abstraction, and the vertices are labeled with the priority of the nodes;

(3) Establishing adjacency matrix or adjacency table for undirected graph;

(4) The BFS method is invoked once to search for nodes based on their priority, and then all of the searched nodes (that is, all of the black vertices acquired in this search) are divided into the same area, and any two points in this region are linked; According to the flexible and straight distribution network, this signifies that the nodes that were searched are all part of the same sub-distribution network that was searched;

(5) Following the exclusion of the previously searched nodes, a BFS search is carried out on the remaining nodes in the order of priority, and the process is repeated until all vertices have been examined and the search is completed;

(6) Transmit the findings of the system's division to the centralized control center of the flexible-straight distribution network, where they are stored. For flexible-straight distribution networks controlled by classic master-slave techniques, the stability of the DC voltage of the system remains the fundamental criterion in a short time span even after the system operating mode has been changed. As a result, if there is a master station in the converter stations in the same area, the control modes of each converter station in this area do not need to be switched; if there is no master station in the converter stations in the same area, it is necessary to re-set a control master station in these converter stations. Among other things, the capacity of the converter stations, the voltage deviation of each converter station, and other criteria might be considered while choosing the master station;

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(7) Converter stations receive mode control instructions from the centralized control center of the flexible-direct distribution network, which is sent to each converter station via the converter station;

(8) EMS systems get the division results from the flexible-straight distribution network system that is controlled by droop control or P-U-I control. The EMS system receives the division results from the centralized control center of the flexible-straight distribution network system. According to the division results of the DC distribution network and the control mode of converter stations in each sub-region, EMS, on a long time scale, optimizes the power flow of the entire flexible-straight distribution network in consideration of system line loss, power supply cost, voltage deviation, and other factors, and the control mode instructions and control parameters of each converter station and energy storage are issued. To sum up, the proposed strategy has the following advantages:

(1) It is not necessary to list the complicated system operation mode table and modify the station control layer for the flexible-straight distribution network system with traditional master-slave control; rather, it is only necessary to add some distribution network topology identification codes in the flexible-straight distribution network centralized control center, which greatly reduces the amount of debugging work. In other words, it is very compatible with the current master-slave control system.

(2) Solved is the issue of how EMS can rapidly identify the system operation mode without depending on the operation mode table and optimize the system operation state under the new topology without the use of the operation mode table.

(3)Whenever the existing flexible and straight distribution network system needs to be expanded and additional converter stations or lines are required, the program can be easily transplanted to the new distribution network by modifying the corresponding adjacency matrix, resulting in a program that is both portable and extensible.

V. DIGITAL SIMULATION EXPERIMENT

For the purpose of evaluating the efficacy and real-time performance of the algorithm, fully linked graphs with tens, hundreds, hundreds of thousands, and thousands of nodes are created and tested on a computer platform running Win7/Core i7/Matlab2012b. The average searching time of the BFS algorithm is displayed in Table 2, which is the second row.

TABLE 2: Time consuming of BFS algorithm

Number of system nodes	10	50	100	500	1000
Average search time (ms)	0.25	0.55	1.17	22	57

The BFS method can search all of the vertices of a completely linked network just once, resulting in a faster search time. However, when the topology of a flexible DC distribution network changes, it is almost

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always difficult for the system to traverse all of the vertices in a single search, and it is almost always necessary to use numerous BFS algorithms to eventually discover the topology of the system.

When the system master station stops operating or the system operation mode changes in a DC distribution network system with master-slave control, the system-level control master station must quickly determine the topology of the network based on the current state of the distribution network and timely issue the mode switching instructions to each converter station in accordance with the control requirements. It is certain that the voltage of the DC distribution network may increase or decrease fast during a transient operation since there is no master station to maintain the system voltage. As a result, in order to fulfill the system's transient voltage requirements, the system is often needed to complete the mode switching process in less than 50 milliseconds. It is thus possible to ensure that the real-time performance of the automated detection method will be achieved when the size of a flexible and straight distribution network system is smaller than 500 nodes.

It is the goal of today's study to test and demonstrate the usefulness and superiority of the automated topology recognition method of flexible DC distribution network based on BFS described in this chapter on the flexible DC distribution network shown in Figure 1.

It has been decided to use the classic master-slave control scheme for the system-level control of the flexible distribution network, and the system is running at a steady 1.5s. Table 3 lists the parameters that were used in the system simulation. At 2s, the cable lines C2 and C6 of the DC distribution network depicted in Figure 1 are disconnected, and the system is partitioned into two isolated subnets (regions). When there are no master stations in a subnet, the converter station with the highest capacity will be re-determined as the master station in that subnet. The master station in the subnet will be re-determined if all converter stations have the same capacity. If all converter stations have the same capacity, the converter station with the biggest DC voltage divergence will be determined as the master station in the subnet. Figure 5 depicts the voltage and current waveforms of each converter station, as well as the control mode switching instruction flowchart for each converter station, as a result of the automated detection technique described above.

TABLE 3: System simulation parameters

parameter	numerical value
Mm/2/3 rated capacity /MVA	10/15/10
Rated DC voltage /k V	±10
Ac load /MW	7
DC load /MW	8
Ac microgrid /MW	5
Scenery /MW	1
Energy storage /MW	2
Synchronous generator /MVA	1

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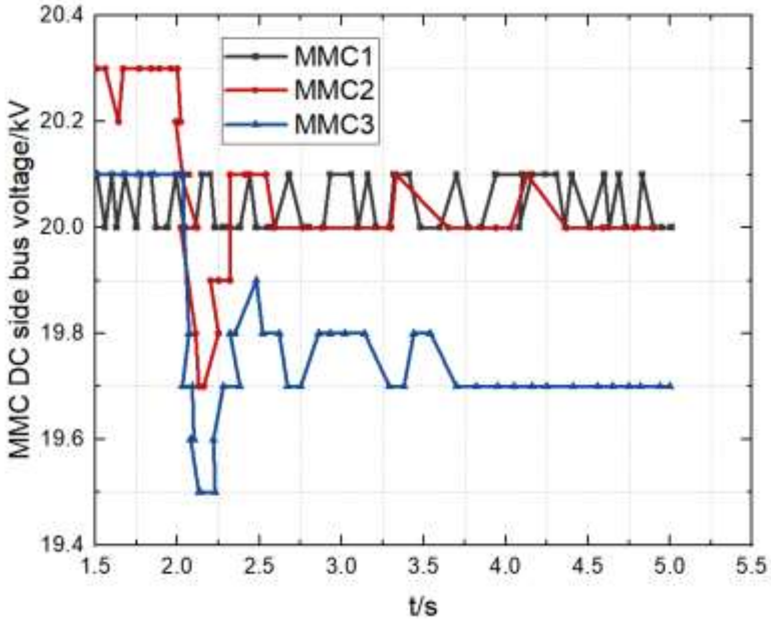
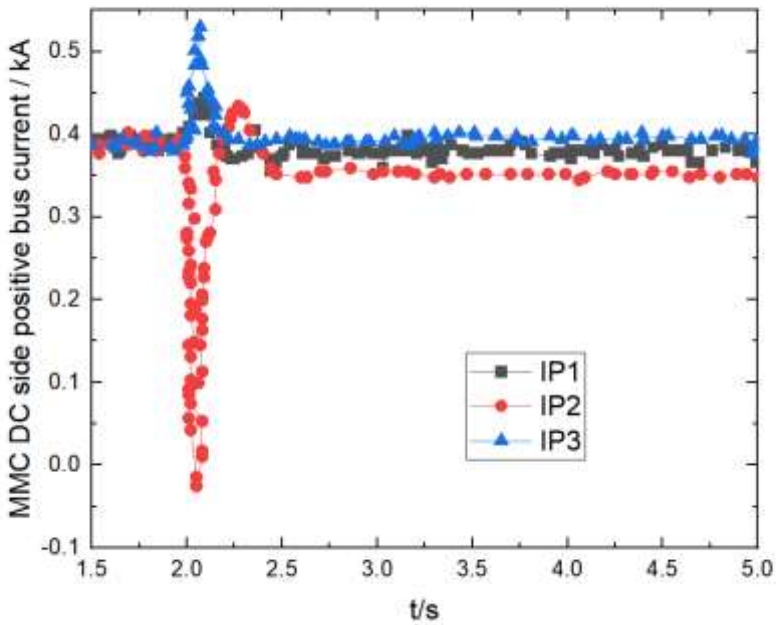


(a) MMC inter-electrode DC voltage



(b) MMC positive DC current

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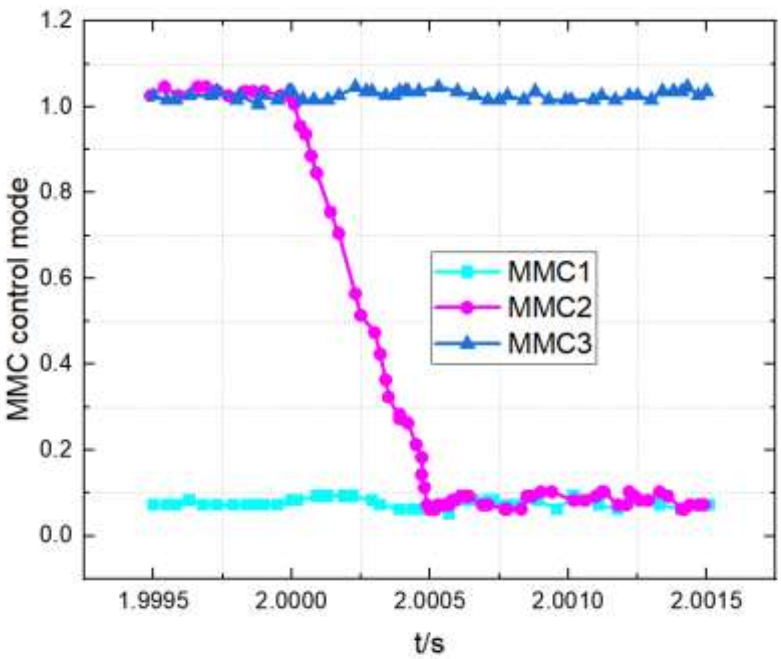

(b) MMC control mode (0: constant voltage, 1: constant power)

(c)

Fig. 5 Dynamic response of DC distribution system under traditional master-slave control

On the contrary, as shown in Figures 4(a) and 4(b), when a transient process occurs, the minimum voltage of each key node of the system (at the outlet bus of the converter station) is 19.34kV and the maximum transient voltage deviation is 3.3 percent, which is significantly less than the 15 percent required by a normal system. As a result of this, there is no excess voltage or current produced by this method, and the final steady-state voltage variation is limited to less than three percentage points (3%%) of the specified voltage. In Fig. 4(c), it can be observed that when the DC distribution network system fails, the system-level master control system can automatically recognize the topology within 0.5ms and provide the relevant inverter mode switching instruction to keep the system operating in a stable manner. According to the results of this study, the automatic detection algorithm of system topology based on BFS algorithm exhibits a good control effect, and the time consumption is essentially consistent with the conclusion in Table 2, and it can be effectively combined with the traditional master-slave control system.

VI. CONCLUSION

The purpose of this study is to investigate how to easily identify the operating mode of a DC distribution network, using the following as the primary work:

(1)The challenges associated with a sophisticated and inflexible operation mode table in a DC distribution network system and an EMS system with classical master-slave control were investigated and documented;

(2) Utilizing the graph theory idea, an abstract modeling of a flexible and straight distribution network

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is completed. Additionally, the graph's storage mode is presented;

(3) A control method for identifying the operation mode of a complex DC distribution network is suggested, which is based on the BFS algorithm and overcomes the issue of a sophisticated and inflexible operation mode table of the system, while also increasing the system's scalability.

(4) The efficacy and logic of the suggested control approach are shown by simulation tests, and the findings further demonstrate the effectiveness and rationality of the proposed technique.

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