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Design and Implementation of a Universal System Control Strategy Applicable to VSC-HVDC Systems

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Abstract

This paper proposes a universal system control strategy for voltage source converter (VSC) based high voltage direct current (HVDC) systems. The framework of the designed control strategy consists of five layer structures considering the topology and control characteristics of the VSC-HVDC system. The control commands sent from the topmost layer can be transmitted to the next layer based on the existing communication system. When the commands are sent to each substation, the following transmission of commands between the four lower layers are realized using the internal communication system while ignoring the communication delay. This hierarchical control strategy can be easily applied to any VSC-HVDC system with any topology. Furthermore, an integrated controller for each converter is designed and implemented considering all of the possible operating states. The modular-designed integrated controller makes it quite easy to extend its operating states if necessary, and it is available for any kind of VSC. A detailed model of a VSC-HVDC system containing a DC hub is built in the PSCAD/EMTDC environment. Simulation results based on three operating conditions (the start-up process, the voltage margin control method and the master-slave control method) demonstrate the flexibility and validity of the proposed control strategy.

Key words: DC hub, Integrated controller, System control strategy, VSC-HVDC

I. INTRODUCTION

The VSC-HVDC is considered to be a very promising power transmission technique due to its numerous advantages. It has been used successfully in the integration of renewable energy sources and the construction of multi-terminal HVDC (MTDC) systems [1]-[4]. The advent of the modular multilevel converter (MMC) greatly accelerated the development of VSC-HVDC technology and made it applicable to engineering applications with higher voltage levels and larger capacities. The MMC topology has been applied in most VSC-HVDC projects, and it shows great performance in practice [5]-[8].

Extensive research has been carried out on VSC-HVDC transmission systems. This research has involved the operation control strategy, the new topology structure, the equivalent model, the modulation strategy, the protection strategy, etc. [9]-[13]. Most studies mainly focus on the design of the system control strategies pertinent to specific cases, which can usually be available under certain conditions. The converter controllers or system control strategies may need to be redesigned or modified if some unplanned conditions or extensions take place. It is inconvenient and prolongs the period of design for any project. A proper universal system control strategy suitable for different operating conditions has become essential for the development of VSC-HVDC projects with any topology [14].

There is still no unified standard for the voltage levels in VSC-HVDC systems. Different voltage levels are used in practical projects. The HVDC lines in VSC-HVDC systems with different voltage levels need to be connected with each other. DC/DC converters are designed to solve these problems [15]-[17]. The authors of [18] present a review of the DC/DC converters for HVDC systems and explain the

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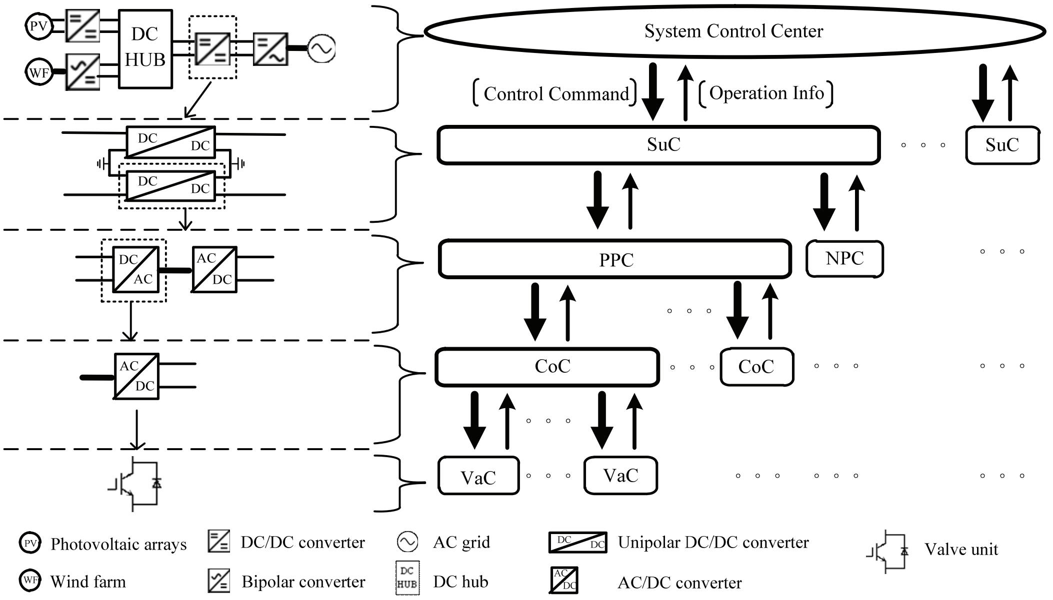

Fig. 1. Frame diagram of the system control strategy.

attributes and limitations of each of the DC/DC converters. Tis study indicates that the MMC-based DC/DC converter offers better a solution for the DC voltage matching in MTDC systems. Some researchers have designed multi-port DC hubs for DC systems with more complicated topologies [19], [20].

AC/DC converters, DC/DC converters and DC hubs can be considered as different kinds of DC substations with specific functions. They bring flexibility and variety to the operation of DC systems. On the other hand, the topology complexity and the design difficulties for these controllers are enhanced at the same time.

Existing practical VSC-HVDC projects such as the point-to-point offshore wind power transmission systems in Europe and the Nan'ao 3-terminal HVDC system in China contain only one kind of DC substation, which is the AC/DC converter. In addition, the corresponding system control strategies are specific and relatively simple. Specifically, they cannot be used directly in a VSC-HVDC system incorporating different DC substations. This paper aims at designing and implementing a universal system control strategy to try to solve this problem. The framework of the strategy can be divided into five layers depending on the control range. The integration of different DC substations is taken into account, and the components in the same layer do not control each other. In this situation, the proposed strategy can be easily applied to VSC-HVDC systems with any topology. The actual executive body for the different kinds of operating conditions is concentrated on the converter control layer. An integrated controller taking most of the operating conditions into account for a single converter is designed to realize the fast switching of a system between different operating conditions. This is done to increase the simulation efficiency and reduce the design period. Simulation results under three different operating conditions are carried out to validate the performance of the proposed control strategy.

II. UNIVERSAL SYSTEM CONTROL STRATEGY

A. Framework of the Control Strategy

When compared with traditional HVDC systems, the VSC-HVDC system contains various substations and bears more flexible operating modes. The hierarchical control framework is widely used in traditional HVDC systems. Although this type of framework cannot be directly applied to a VSC-HVDC system, it can provide a good reference for the design and application of VSC-HVDC systems. The proposed universal system control strategy for VSC-HVDC systems is shown in Fig. 1. The whole framework of the strategy can be categorized as having five layers. These layers are the system control layer, substation control layer, single pole control layer, converter control layer and valve control layer. These layers are introduced in detail below.

1) System Control Layer: The system control layer is the topmost layer of the framework. It mainly implements the operation schedule through the system control center depending on the practical operating conditions of the system. The control commands including the start-up control, power control and voltage control will be transmitted to the next layer. Unlike the strict simultaneity requirements for the current commands of different converters in traditional HVDC systems, the existence of capacitors in a VSC enables the VSC-HVDC system to keep running when the voltage commands or power commands for different substations are non-simultaneous considering relatively short communication delays. The commands can be transmitted based on the existing communication system. Furthermore, this layer also receives the running status information from the next layer to adjust the operating state of the system in real time.

2) Substation Control Layer: The positive and negative sections of each substation in a bipolar system should be controlled independently to make the system more flexible. The substation controllers (SuC) in all of the substations send control commands to each section through the internal communication system. It is relatively fast, and the communication delays can be ignored. It monitors the running status of each section and gives instant feedback to the upper layer.

3) Single Pole Control Layer: The single pole control layer can send out control commands to devices according to the predefined operation sequence in each substation. It includes a positive pole controller (PPC) and a negative pole controller (NPC). The running status of each device will be monitored and fed back to the substation layer.

4) Converter Control Layer: It is known that the converter is the basic unit of the substations in a VSC-HVDC system. The converter controller (CoC) can determine its control mode through the control command from its upper layer. Then, it can send corresponding control commands to the valves inside. The converter can also automatically send blocking commands by measuring the currents and other parameters during faults to immediately protect itself. Moreover, it can be utilized to monitor the running status of each component and feed it back to the upper layer.

5) Valve Control Layer: The valve controller (VaC) produces and sends trigger signals to electronic devices such as IGBTs according to the received control commands. It also monitors their running status.

B. Advantages of the Control Strategy

The advantages of the proposed universal system control strategy can be summarized as follows.

- The actual executive body pertinent to different kinds of operating conditions is concentrated on the converter control layer. This reduces the influences between the actions of each converter and increase the flexibility of the whole system.
- The variety of different devices in a VSC-HVDC system is considered in the proposed strategy. This makes the strategy available for most types of VSC-HVDC projects under study.
- The control commands are transmitted between one layer and the next. The components in the same layer are not supposed to be controlled by each other. Therefore, it is quite convenient for the extension of the system.
- The positive section and the negative section are independent in bipolar systems, which can effectively enhance the reliability of the system.
- Each layer has a clearly defined control range and bears good extensibility. It is easy to design further protection strategy systems based on this type of control strategy.

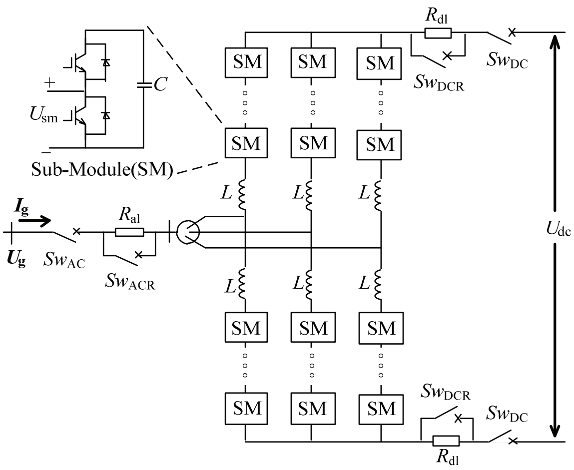

Fig. 2. Topology diagram of a HB MMC.

The aforementioned advantages are demonstrated in the following Sections.

III. INTEGRATED CONTROLLER DESIGN

The converters in different substations should include as many operating states as possible to meet the demands for different situations. This can be realized by designing an integrated controller for each converter.

A MMC based on half bridge sub-modules (HB MMC) is widely used in practical projects. A topology diagram of the HB MMC is shown in Fig. 2. L is the arm inductor. $\boldsymbol{U}_g$ and $\boldsymbol{I}_g$ are the voltage and current at the AC side. U_{dc} is the voltage at the DC side. U_{sm} is the voltage of the sub-module (SM). Auxiliary devices need to be added for the different operation requirement of a MMC. Sw_{AC} and Sw_{ACR} are switches at the AC side. Sw_{DC} and Sw_{DCR} are switches at the DC side. R_{al} and R_{dl} are current limiting resistors.

A. Definition of the Operating State

The operating states of a MMC can be defined by using the following four modes.

1) Operation Mode (Op Mode): A MMC has four operation modes as listed below.

a) Start-up Mode from the AC Side: A MMC can be started by the voltage source at the AC side if it is connected to an AC grid or some other AC voltage source. U_{sm} is charged to some level that is lower than its rated value via the coordination controls from Sw_{ACR}, Sw_{DCR}, the enable signals for the upper arms $fRun_{ku}$(k=a, b, c), the enable signals for the lower arms $fRun_{kd}$(k=a, b, c) and the enable signals for the controller $fRun$.

b) Start-up Mode from the DC Side: A MMC can be started by the voltage source at the DC side if it is connected to a DC grid or some other DC voltage source. U_{sm} is charged to its rated value via the coordination control from Sw_{ACR}, Sw_{DCR}, $fRun_{ku}$, $fRun_{kd}$ and $fRun$.

c) Controllable Mode: A MMC can be turned to the controllable mode after the start-up mode mentioned above. It can select the corresponding control mode and produce trigger signals to electronic devices according to the control commands from the upper layer.

d) Block Mode: A MMC can be blocked quickly via the coordination control from $fRun_{ku}$, $fRun_{kd}$ and $fRun$ if needed.

2) Control Mode (Co Mode): A MMC can work in three control modes during normal operation.

a) Fixed DC Voltage Control.

b) Fixed Active Power Control.

c) Fixed AC Voltage Control.

This can be realized by the double-loop controller in [21]. A MMC may need to work in other specific control modes for some special situations. The control modes can be easily extended based on a double-loop controller. For instance, the voltage margin control is suitable for a radial MTDC system to reduce the dependence on high speed communication systems [22]. Here, only an out-loop control method, as illustrated in Fig. 3, needs to be added to the outer controller to realize the above function. P_{gh} and P_{gl} are power limitations. P_g is the active power of the MMC. i_{gd} is the d component of the AC side current in the dq coordinates. The superscript “*” stands for the reference value.

3) Switch Mode (Sw Mode): A MMC has two switch modes during normal operation. The reference voltages in the outer controller have differences in different modes and need to be defined accordingly.

a) Switch Mode After the Start-up Process: If a MMC is started from the AC side, the reference value of U_{dc} should be set from its measured value to its rated value following some slope when the MMC switches to the controllable mode. The reference value of the voltage at the AC side should be changed from 0 to its rated value following some slope if the MMC is started from the DC side.

b) Switch Mode During Normal Operation: The voltages in both the AC side and the DC side are kept near their rated values. Therefore, the corresponding reference voltages can be set to their rated values if the control mode needs to be switched.

4) Voltage Mode (Vo Mode): The three modes mentioned above are necessary for all kinds of MMCs during normal operation. However, some specific mode may be imperative for some specific MMC. For example, a full bridge based MMC (FB MMC) may be needed for a hybrid MTDC system to realize fast power reversal control. In this case, the corresponding voltage mode should be selected to determine whether it will generate: *a) positive DC voltage* or *b) negative DC voltage.*

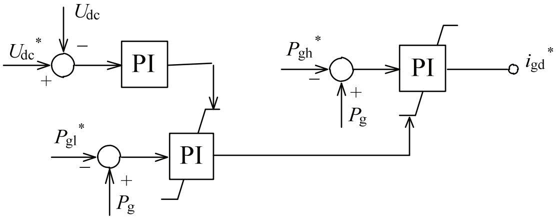

Fig. 3. Outer controller for voltage margin control.

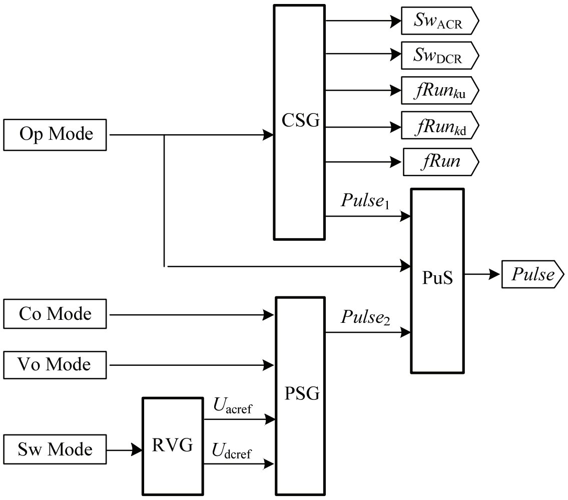

Fig. 4. Structure diagram of an integrated controller.

TABLE I

OPERATING STATE SETTINGS FOR AN INTEGRATED CONTROLLER

time	Op Mode	Co mode	Vo Mode	Sw Mode
t_1	a/b/c/d	a/b/c	a/b	a/b
⋮	⋮	⋮	⋮	⋮
t_n	a/b/c/d	a/b/c	a/b	a/b

For the MMCs of other topologies, specific modes may be necessary such as the voltage mode for a FB MMC. The corresponding modes can be easily added to the integrated controller to meet the requirements of different converters.

B. *Realization of the Integrated Controller*

An integrated controller consists of four modules as shown in Fig. 4. The functions for each of the modules are listed below.

- Control Signal Generator (CSG): This module can generate corresponding control signals according to the Op Mode, including signals for Sw_{ACR}, Sw_{DCR}, $fRun$, $fRun_{ku}$, $fRun_{kd}$ and the trigger signals $Pulse_1$ for SMs.
- Reference Value Generator (RVG): This module can generate corresponding reference values for the voltages according to the Sw Mode.

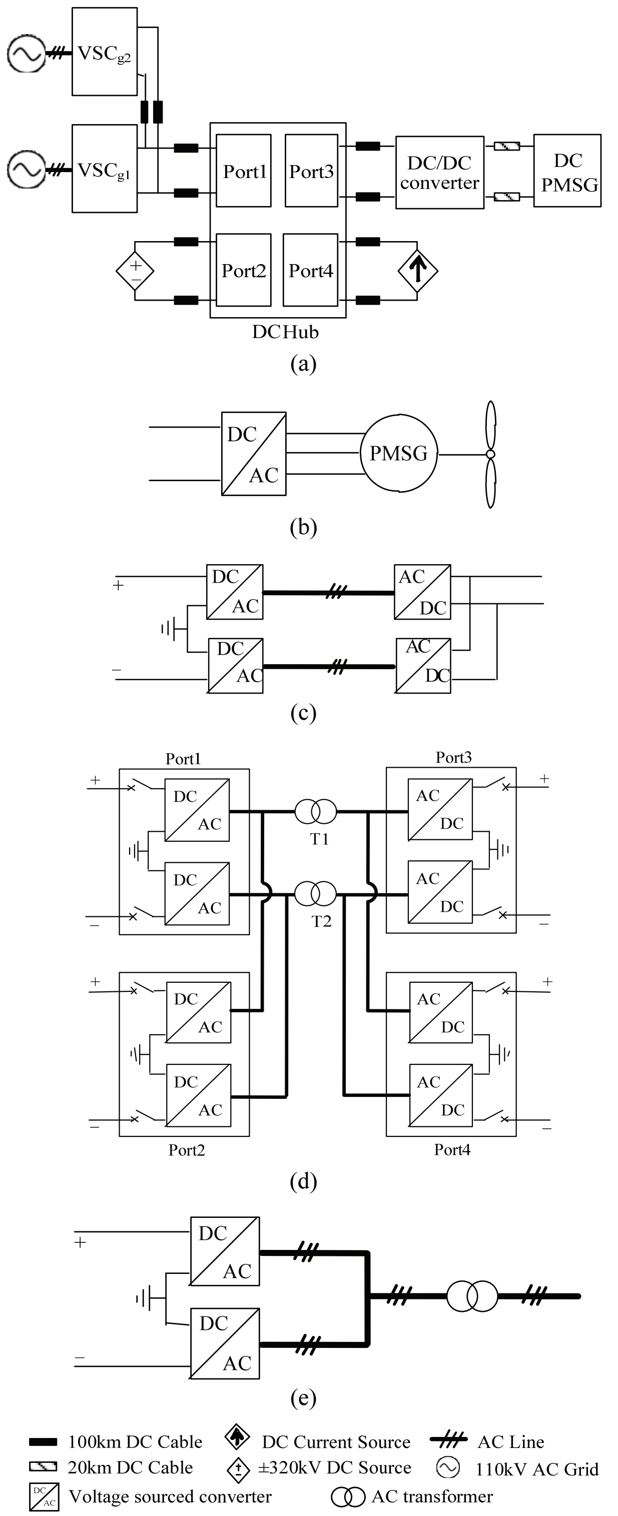

Fig. 5. Topology diagrams of simplified VSC HVDC systems: (a) the test system; (b) DC PMSG; (c) DC/DC converter; (d) DC hub; (e) bipolar converter.

- Pulse Signal Generator (PSG): This module can generate trigger signals $Pulse_2$ for SMs according to the Co Mode and Vo Mode when a MMC is under the controllable mode.
- Pulse Selector (PuS): This module can select trigger signals $Pulse$ for SMs between $Pulse_1$ and $Pulse_2$ according to the Op Mode.

The operating states for each of the MMCs at any time can be defined as shown in Table I. For example, if the DC voltage of the MMC needs to be controlled to some positive value at some time during normal operation, this can be realized by setting the Op Mode, the Co Mode, the Vo Mode, and the Sw Mode to c, a, a, and b respectively.

The meaning of the letter for each mode is defined in Section III. A. If a MMC has multiple states during a period of time, the corresponding states for multiple moments from t_1 to t_n can be set similarly.

The modular design for an integrated controller can be easily extended to meet the different requirements of different converters. This makes the design and testing of a complicated VSC-HVDC system with any topology easy to implement. It can also increase the flexibility and extendibility of the system, shorten the design cycle and improve the design efficiency.

IV. PERFORMANCE EVALUATION

A. Test System

According to relevant researches and some practical projects pertinent to VSC-HVDC systems [6], [8], [14], [16], [19], one of the most promising topology structures pertinent to VSC-HVDC grids in the future is likely to contain DC hubs, DC/DC converters, renewable energies such as offshore wind farms, and local networks using a radial topology. In this paper, a simplified VSC-HVDC test system, as shown in Fig. 5(a), is built to demonstrate the validity of the proposed control strategy. An equivalent DC wind turbine based on the permanent magnet synchronous generator (DC PMSG), as shown in Fig. 5(b), is used to simulate an offshore wind farm. A DC/DC converter is designed to transform the unipolar voltage of the wind farm to bipolar voltage. This converter is composed of two VSCs at the left bipolar side and two VSCs at the right unipolar side as shown in Fig. 5(c). The DC hub provides a good solution for the connection of different power sources and loads with different voltage levels. In this paper, a 4-port DC hub, as shown in Fig. 5(d), is applied in the test system. Port1 is connected to two bipolar AC/DC converters VSC$_{g1}$ and VSC$_{g2}$ to form a local radial system. The topology of the bipolar AC/DC converter is shown in Fig. 5(e). A DC voltage source is used to represent another local system, and it is connected to Port2. Port3 is connected to the wind farm. A DC current source is used to represent another wind farm, and it is connected to Port4. The control modes of the devices in the system during normal operation are listed in Table II. FDVC, FAPC and FAVC represent the fixed DC voltage control, the fixed active power control and the fixed AC voltage control, respectively.

TABLE II

CONTROL MODES OF THE DEVICES DURING NORMAL OPERATION

Devices		Control Modes
VSC_{g1}		FDVC
VSC_{g2}		FAPC
DC Hub	Port1	FAVC
	Port2	FAPC
	Port3	FDVC
	Port4	FDVC
DC/DC converter	Bipolar side	FAVC
	Unipolar side	FDVC/FAPC
DC PMSG		FAPC

TABLE III

PARAMETERS OF THE SYSTEM

Devices		Rated DC voltage/kV	Rated capacity/MVA
VSC_{g1}/VSC_{g2}		±320	640
DC Hub	Port1	±320	640
	Port2	±320	640
	Port3	±160	640
	Port4	±160	640
DC/DC converter		(±160)/160	640
DC PMSG		160	600

TABLE IV

PARAMETERS OF THE MMC

MMC parameters	Values
Cell capacitance	1000μF
Arm inductance	0.3pu
Number of SMs per arm	4

TABLE V

CONTROLLER SETTINGS OF VSC_{g2}

t(s)	Op Mode	Co Mode	Vo Mode	Sw Mode
0	d	-	-	-
1	b	-	-	-
5	c	c	a	a

A detailed model of the test system is built in the PSCAD/EMTDC environment. To speed up the simulation process, the detailed HB MMC topology is only used for the converters in VSC_{g2} and Port2. The other AC/DC converters adopt the topology of a three-phase two-level converter. The parameters of the system and the HB MMC are listed in Table III and Table IV, respectively. The parameters of the DC cables are selected as follows [23]: r=0.01Ω/km, l=1.5mH/km, c=0.27μF/km.

B. Case 1: Start-up Process

As previously mentioned, the system start-up plan is made by the system control layer according to actual situations, and the corresponding control command is transmitted from the upper layer to the lower layer. The detailed start-up plan is given as follows:

- 0.1s~0.5s : VSC_{g1} starts;
- 0.6s~1s : Port1 starts;
- 1s~2s : VSC_{g2} starts;

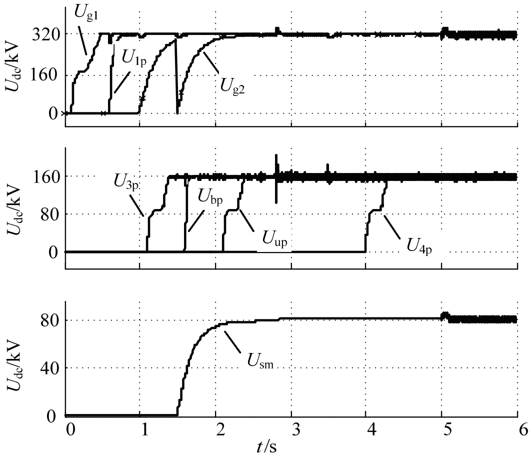

Fig. 6. DC voltages of a system during the start-up process.

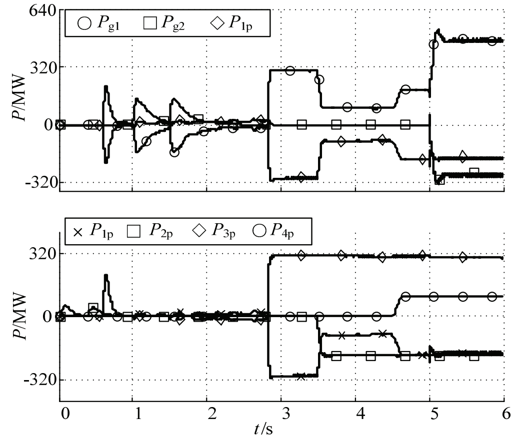

Fig. 7. Active powers of a system during the start-up process.

- 1.1s~1.5s : Port3 starts;
- 1.6s~2.5s : DC/DC converter starts;
- 2.6s~2.8s : DC PMSG is integrated into the system and generates its rated power of 600MW;
- 3.5s : Port2 starts;
- 4s~4.4s : Port4 starts and the DC current source transmits an active power of 400MW to Port4;
- 5s : The active power of VSC_{g2} transmitted to its DC side is set to be 520MW.

Each of the converters in different substations of the system receives the control command, which forms a clear control process through using the integrated controller. Taking

VSC_{g2} as an example, its control process can be determined as shown in Table V. The control processes of other converters can be similarly set.

Fig. 6 shows the positive DC voltages of the system. The bipolar system is structurally symmetrical, and the negative DC voltages are not given here. It can be seen that the DC voltages at different locations can be built smoothly and orderly using the proposed universal control strategy and integrated controller. U_{g1} and U_{g2} are the DC voltages of VSC_{g1} and VSC_{g2}. U_{1p}, U_{3p} and U_{4p} are the DC voltages of three ports in the DC hub. U_{bp} and U_{up} are the DC voltages at the bipolar side and unipolar side of the DC/DC converter.

The active powers transmitted from the dc cables to each of the terminals are illurstrated in Fig. 7. It can be seen that all of the active powers can be kept balanced with each other. For instance, the active powers of the local radial system, P_{g1}, P_{g2} and P_{1p} as well as the active powers of the four ports in the DC hub, P_{1p}, P_{2p}, P_{3p} and P_{4p} are given in Fig. 7.

The simulation results shown in Fig.7 indicate that the proposed universal control strategy and the integrated controller for each of the converters can meet the requirments for normal operations.

C. Case 2: Voltage Margin Control Method

In the local radial system formed by VSC_{g1}, VSC_{g2} and Port1, the voltage margin control method can be employed to reduce the dependence on the remote communication system. For instance, in this paper, VSC_{g1} and VSC_{g2} both work at the voltage margin control mode during normal operation. VSC_{g1} controls the DC voltage of the radial system, and VSC_{g2} controls its active power at the beginning. This method can be easily added to the integrated controller by using the controller given in Fig. 3.

The simulation starts from the steady state. All of the active powers of each converter stay below their rated values as shown in Fig. 8. P_{1p} changes from -380MW to -580MW at 1.5s and causes an increase of P_{gs1} to its limitation of 640MW at 1.52s. The control mode of VSC_{g1} is switched to the fixed power control mode automatically with the voltage margin control method applied. This in turn causes a voltage increase of the system, and it reaches the voltage limitation of VSC_{g2}. VSC_{g2} automatically switches its control mode to the fixed dc voltage control mode to achieve another steady state for the system as shown in Fig. 9.

Simulation results show that it is easy to extend the control modes for each of the converters through using the integrated controller. In addition, the design cycle can be shortened remarkably.

D. Case 3: Master-slave Control Method

All of the ports in the DC hub are located on the same platform. Therefore, it is applicable to the adoption of the master-slave control method to implement the coordination control between each of the ports. In other words, during normal operation, one of the ports in the DC hub should control the voltage of the internal AC bus to guarantee normal operation of the DC hub, and this port is called the mater port. If the master port stops running for some reason, there must be another port to take charge of the stability of the internal AC voltage control, and this port is called the slave port. In this paper, port1 is set to be the master port, and port 2 is set to be the slave port.

It is assumed that the master port, port1, is cut off due to a severe fault at 0.3s. The active powers of the system are shown in Fig. 10. P_{1p} quickly decreases to 0. The slave port, port2, switches its contorl mode at 0.303s to control the internal AC voltage of the DC hub. The system reaches a new steady state and continues running. The internal AC voltage of the DC hub and the voltage of the sub-module of port2 can be kept stable as shown in Fig. 11. This means that the DC hub can maintain continous operation during the whole process.

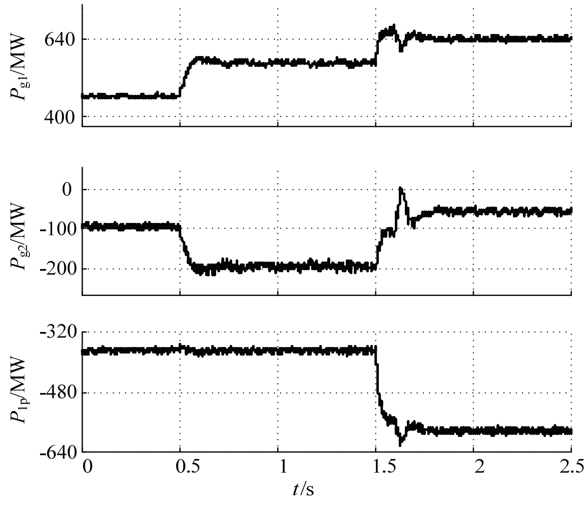

Fig. 8. Active powers of a system under the voltage margin control method.

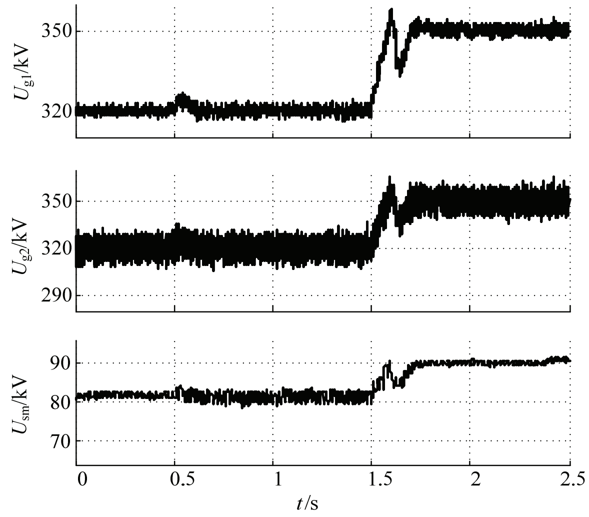

Fig. 9. DC voltages of a system under the voltage margin control method.

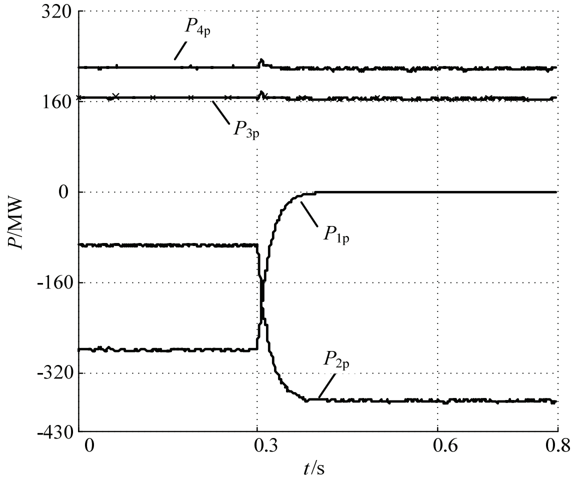

Fig. 10. Active powers of a system under the master-slave control method.

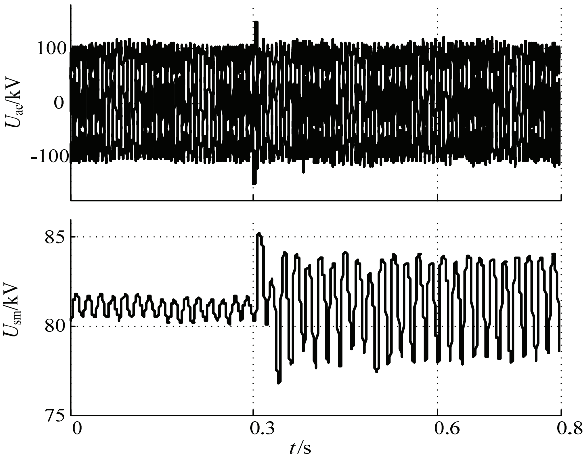

Fig. 11. Internal AC voltage of the DC hub and voltage of the sub-module of port2 under the master-slave control method.

Simulation results show the good performance of the universal control strategy and the integrated controller for systems incorporating a DC hub under specific operating conditions. They are also availiable for similar systems incorportating other DC substations under other specific operating conditions.

V. CONCLUSIONS

This paper proposes a universal system control strategy for VSC-HVDC systems. Its hierarchical structure makes the control strategy more intuitive and can effectively enhance the extensibility of system application. An integrated controller is designed to match the system control strategy. The operating states of the converter are represented by four modes to meet various operating conditions. Simulation results carried out in the PSCAD/EMTDC environment under three case scenarios demonstrate the validity, flexibility and extensibility of the proposed universal control strategy and integrated controller. It should be noted that although this paper only discusses how to implement the proposed control strategy on VSC-HVDC systems under normal operating conditions, it is convenient to add protection functions to the system because the actual executive body for different kinds of operating conditions is concentrated on the converter control layer.

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