Resilient DC Voltage Control for Islanded Wind Farms Integration Using Cascaded Hybrid HVDC System

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Abstract- To integrate large-scale islanded onshore wind power with different sizes, this paper proposes an integration system based on the cascaded hybrid HVDC transmission system, which consists of LCC and several MMCs in series connection at the DC side of the rectifier. A large-scale wind farm is connected with one LCC and one MMC while several small-scale wind farms are connected with MMCs directly. Owing to the hierarchical integration arrangement, the operating flexibility can be improved with reduced capacity and the number of step-up interfacing transformers. A resilient DC voltage control is proposed for the integration system to adaptively redistribute power among the converters during wind power fluctuations. Firstly, the topology and operating characteristics of the wind power integration system are introduced. Then, a resilient DC voltage control is proposed to ensure stable operation during wind power curtailments. Finally, a simulation model of the hybrid cascaded HVDC transmission system is built in PSCAD/EMTDC to verify the effectiveness. The research results show that the system provides a new option for long-distance transmission of large-scale islanded wind power.

Index Terms- HVDC transmission; line commutated converter; modular multilevel converter; renewable energy integration; resilient DC voltage control; wind energy.

I. INTRODUCTION

To overcome the challenges of climate change and environmental degradation, integration of large-scale wind farms will still grow significantly, given that many countries launched renewable energy targets, such as the European Green Deal by *European Commission* [1] and 2050 carbon-neutral by the *United Kingdom* [2]. Wind power has become a mainstream source of clean, cost-competitive energy around the world in the last decades. In 2020, more than 93 GW of wind energy capacity had been installed globally, where 93.4% of capacity is onshore wind power [3]-[5].

In many countries, some rich inland wind resources are far away from urban centers where the demand is large, such as

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China, the USA and Pakistan [6]-[10]. To integrate large-scale onshore wind power over long distances, the high-voltage direct-current (HVDC) technology has been considered as a cost-effective and preferred scheme compared to high-voltage alternating-current (HVAC) technology [11]. Among the HVDC applications around the world, the line-commutated converter-based HVDC (LCC-HVDC) system is the most mature solution for large-scale power transmission. For instance, the *Raigarh-Pugalur* project uses LCC-HVDC to transmit large-scale wind power generated in southern India [12]. Since the LCC requires an external AC voltage source for commutation, it conventionally bundles with thermal plants to integrate onshore wind power [13]. Meanwhile, synchronous condensers (SCs) [14] or the static synchronous compensators (STATCOMs) [15] are installed to support the reactive power and the voltage of the local grid. As for the modular multilevel converter-based HVDC (MMC-HVDC) solution, owing to the superior controllability of voltage source converters, it can directly integrate with wind farms without requiring filters and reactive power compensation devices. In 2020, a four-terminal *Zhangbei* MMC based DC grid pilot project was commissioned in China, integrating large-scale islanded onshore wind power in northern China [16]. Due to the low voltage and current ratings of current fully controllable semiconductors, the capacity of MMC-HVDC systems (recently $\pm 525\text{kV}/1400\text{MW}$) is less than that of the LCC-HVDC systems ($\pm 800\text{kV}/8000\text{MW}$).

To combine the advantages of LCC and MMC technologies, several hybrid HVDC schemes as well as hybrid converters have been proposed. Reference [10] proposes a hybrid LCC-MMC converter, where the LCC and MMC are in series connection at the DC side. The MMC is used to maintain the AC voltage of the wind farm and provide commutation voltage for the LCC. Reference [17] uses a capacitor commutated converter (CCC) in series with a two-stage *Vernier* voltage source converter (VSC) on the DC side, where the *Vernier* VSC maintains constant reactive power consumption by the CCC. Reference [18] proposes a flexible LCC-HVDC system by installing additional controllable capacitors at the secondary side of the converter transformer to eliminate the AC filters and reduce the commutation failure probability. To reduce the converter's size and cost, reference [19] proposes a hybrid converter consisting of the diode rectifier and the VSC in series connection. The effectiveness of the above schemes for wind power integration is well validated in [10],[17]-[19]. However, all of them focus on the converter topology without considering the size of wind farms. In these studies, all the wind farms are integrated into the same AC collection network and are simulated by one aggregated model.

Reference [20] proposes a cascaded inverter based on

MMCs in series and parallel connection. Due to the hierarchical infeed and back-to-back interconnection, the multi-infeed short circuit ratio of the receiving grids is optimized. Recently, the State Grid Corporation of China is constructing the *Baihetan-Jiangsu* hybrid HVDC project. In this project, the LCC rectifier is adopted at the sending end to transmit hydropower, while the cascaded LCC-MCC converter is adopted at the receiving end to mitigate the commutation failure problem [21]-[23].

In order to overcome the above problems, this paper proposes a hierarchical integration concept for the islanded onshore wind power based on the cascaded hybrid HVDC system. In the sending end of the hybrid HVDC system, each pole consists of an upper LCC valve and several lower paralleled MMC valves in series connection, where the large-scale wind farm is connected with the LCC and one MMC valve, and the small-scale wind farms are directly connected with the other MMC valves, therefore, providing a cost-effective solution for integrating different scales of wind farms.

The main contributions of this paper are as follows:

- Combined the advantages of different converter topologies, the cascaded hybrid HVDC system provides a solution for islanded onshore wind power integration with different sizes. Compared with the conventional series LCC-MMC approach, the cascaded hybrid HVDC system can integrate different scales of wind farms using its hierarchical structure, which is of high operating flexibility and economic efficiency.
- A resilient DC voltage control is proposed to redistribute the power between the upper LCC valve and the lower MMC valves during wind power curtailments. Different from the conventional droop control, the droop coefficient of the resilient DC voltage control is variable according to different operation conditions, which improves the reliability of the system.
- Considering the hierarchical integration topology, multiple operating modes of the cascaded hybrid HVDC system are investigated, enhancing the operational flexibility of the system.

The remainder of this paper is organized as follows. Firstly, the topology and operating characteristics of the hierarchical onshore wind power integration system are introduced in Section II and Section III. Then, a resilient DC voltage control is proposed in Section IV for the cascaded converter to

facilitate continuous operation during wind power curtailments. Section V studies the operating modes of the hierarchical wind power integration system. And the small-signal stability analysis of the system is developed in Section VI. The simulation validations and conclusions are carried out in Sections VII and VIII.

II. THE HIERARCHICAL WIND POWER INTEGRATION SYSTEM BASED ON HYBRID CASCADED CONVERTER

A. Topology of the Hierarchical Wind Power Integration System

The circuit configuration of the hierarchical wind power integration system is shown in Fig. 1. The rectifier of the HVDC system consists of one LCC and three half-bridge MMCs. The LCC serves as the upper valve and it is paralleled with MMC1 at the AC side while in series connection with three MMCs at the DC side. By means of this cascaded converter scheme, the AC voltage of wind farms at the point of common coupling (PCC) are maintained by the MMCs. Particularly, MMC1 provides both commutation voltage and parts of reactive power compensation for the LCC. To avoid commutation failure problems, the receiving end of the hybrid HVDC system adopts the MMC technology.

The large-scale wind farm 1 connected with LCC and MMC1 is composed of five wind turbine (WT) clusters. Each cluster is made up of 140 fully rated converter (5MW) based WTs. Two small-scale wind farms 2 and 3 are connected with MMC2 and MMC3, respectively. Each of them is composed of 150 fully rated converter (5MW) based WTs.

The AC voltage of each wind turbine is firstly stepped up to 10 kV, and multiple WTs will form a WT string. Several WT strings are then connected to one WT cluster via two-stage step-up transformers of 0.69/10 kV and 10/110 kV [24][25].

For the large-scale wind farm 1, five WT clusters are integrated with the AC collection network through 110/330 kV step-up transformers. For the small-scale wind farms 2 and 3, the WT clusters are directly connected with the interfacing transformers of MMC2 and MMC3. Then, the wind farms at different scales are hierarchically integrated with the hybrid HVDC system and transmitted to the load centers through the long-distance overhead lines.

For simplification, the voltage ratio of high and low voltage valves is designed as 1: 1 in this paper.

Fig. 1. The topology of the hierarchical wind power integration system based on the cascaded HVDC system in the monopole view.

B. Economical Evaluation of Hybrid Cascaded Converter

The existing large-scale onshore wind farms integration schemes mainly include LCC-HVDC with SC or STATCOM paralleled at the rectifier side [14][15] and MMC-HVDC [26][27], as depicted in Fig. 2.

Fig. 2. Layout of the existing onshore wind farms integration schemes.

According to the onshore equipment costs presented in [28], the cost of LCC is about £0.0703 m/MW and the cost of half-bridge MMC is £0.0931 m/MW. To provide commutation voltage for LCC, the capacity of STATCOM and SC has to reach 1/4 and 1/3 of LCC, respectively [10][29]. The cost of STATCOM and SC are £0.1221 m/MVar and £0.0824 m/MVar [28][30].

Comparing with the existing onshore wind farms integration schemes, of which wind farms 2 and 3 have to be integrated with the HVDC system through 110/330 kV step-up transformers and step-down interfacing converter transformers. Supposing the output power of the three wind farms 1, 2 and 3 are P_{w1} , P_{w2} and P_{w3} , respectively. The total transformer capacity required in the power transmission path from the 110 kV WT cluster network to the converters is:

$$P_{\Sigma 1} = 2 \times (P_{w1} + P_{w2} + P_{w3}) \quad (1)$$

While for the proposed hierarchical integration scheme, the corresponding transformer capacity is:

$$P_{\Sigma 2} = 2 \times P_{w1} + P_{w2} + P_{w3} \quad (2)$$

Supposing the power of wind farms 1, 2 and 3 are 3500MW, 750MW and 750MW, respectively. The total transformer capacity of the series LCC-MMC is 10GW. And the total transformer capacity of the hierarchical integration scheme is 8.5GW, which saves 15% of the existing approach. The cost of the saved 1.5GW 110/330 kV step-up transformers is about £17.14 million [28].

Taking the +800kV/5GW monopole HVDC system as an example, the economic comparison of four approaches is given in Table 1. It should be noted that the investment in wind farms is constant. So only the cost of rectifiers (converters and support equipment) and step-up transformers are taken into consideration.

Table 1 Economical evaluation (monopole)

Cost/ £ million	Cost of rectifiers	Cost of 110/330kV transformers [28]	Saved cost (based on LCC-STATCOM)
LCC with SC	488.83	114.28	15.3
LCC with STATCOM	504.13	114.28	/
MMC-HVDC (half-bridge)	465.5	114.28	38.63
Proposed hybrid cascaded converter	408.5	97.14	112.77

Despite this economic advantage, the hierarchical integration scheme will benefit from a more flexible operation and high

efficiency, which will be detailed in the following sections.

III. OPERATING PRINCIPLE AND CONTROL DESIGN OF THE HIERARCHICAL HVDC INTEGRATION SYSTEM

A. Power Flow Analysis of the Hierarchical Integration System

The simplified view of the cascaded rectifier is shown in Fig. 3. The rectifier LCC is composed of two six-pulse thyristor bridges in series with two interfacing transformers to form a 12-pulse converter. The RMS line voltage of LCC is V_L . The DC terminal voltage is V_{dch} . The DC current is I_{dc} . The active power is P_{LCC} , and the reactive power absorbed by the converter is Q_{LCC} . Denoting the commutation reactance of each phase is X_r ; the power factor is $\cos\varphi$; the firing angle is α ; and the commutation overlap angle is μ . Then the mathematical model of LCC is shown as follows:

$$V_{dch} = 2.7V_L \cos\alpha - \frac{6}{\pi} X_r I_{dc} \quad (3)$$

$$\cos\varphi = [\cos\alpha + \cos(\alpha + \mu)] / 2 \quad (4)$$

$$P_{LCC} = V_{dch} I_{dc} \quad (5)$$

$$Q_{LCC} = P_{LCC} \tan\varphi \quad (6)$$

For the three MMCs, the active power, DC terminal voltages and currents are respectively P_{MMCi} , V_{dci} and I_{dci} ($i=1, 2, 3$). Denote V_{dcl} as the DC terminal voltage of the lower valves ($V_{dcl}=V_{dci}$).

Fig. 3. The topology of the cascaded rectifier.

Then, the DC voltages and currents of the four sub-converters satisfy,

$$\begin{cases} V_{dch} + V_{dcl} = V_{dc} \\ I_{dc1} + I_{dc2} + I_{dc3} = I_{dc} \end{cases} \quad (7)$$

The wind power generated by wind farm 1 will be transmitted through LCC and MMC1. And MMC2 and MMC3 transmit the wind power from wind farms 2 and 3, respectively. Thus, the active power of each converter yields:

$$\begin{cases} P_{LCC} = V_{dch} \cdot I_{dc} \\ P_{MMC1} = V_{dcl} \cdot I_{dc1} = P_{w1} - P_{LCC} \\ P_{MMC2} = P_{w2} = V_{dcl} \cdot I_{dc2} \\ P_{MMC3} = P_{w3} = V_{dcl} \cdot I_{dc3} \end{cases} \quad (8)$$

Substituting equation (7) into (8) yields,

$$P_{LCC} = \frac{V_{dch}}{V_{dc}} (P_{w1} + P_{w2} + P_{w3}) \quad (9)$$

$$P_{MMC1} = \frac{V_{dcl}}{V_{dc}} (P_{w1} + P_{w2} + P_{w3}) - P_{w2} - P_{w3} \quad (10)$$

Equations (9) and (10) show that the power distribution between LCC and MMC1 is determined by the valve voltages and output power of the three wind farms.

B. Basic Control Strategy of the HVDC System

The basic control strategy is depicted in Fig. 4. For the fully rated converter-based WTs, the grid-side converter (GSC) controls the DC link voltage of the two VSCs, and the machine-side converter (MSC) controls the active power following the MPPT (maximum power point tracking).

The inverter-side converters control their respective DC terminal voltages to maintain a stable DC voltage for the HVDC system. The MMC1, MMC2 and MMC3 connected with the three wind farms all adopt the constant AC voltage control to provide a solid AC voltage for the wind farms and LCC as well. The LCC controls its DC terminal voltage to retain a stable DC voltage for the three MMCs.

Fig. 4. Basic control strategy of the hierarchical integration HVDC transmission system.

IV. RESILIENT DC VOLTAGE CONTROL UNDER WIND POWER CURTAILMENTS

A. Resilient DC Voltage Control

When the wind speed decreases, the active power captured by the wind turbines will also be decreased. Taking wind farm 1 as an example, under wind power curtailments, the active

power of LCC and MMC1 decreases. Since LCC uses the DC voltage control, according to equations (3)(4), the firing angle α will not change. Thus, the absorbed reactive power of LCC will also be decreased. In order to prevent surplus reactive power in the AC collection network which causes the rise of AC voltage, LCC needs to increase the firing angle to absorb more reactive power, which will result in the decrease in DC voltage of LCC according to equation (3).

While for wind farm 2 or 3, when the captured wind power decreases, the transmitted active power of LCC also decreases. According to equation (8), it results in the increase of active power of MMC1, which poses an overcurrent risk to the IGBTs. Recalling equation (10), the DC current of the MMC1 can be expressed as:

$$I_{dcl} = \frac{P_{MMC1}}{V_{dcl}} = \frac{P_{w1} + P_{w2} + P_{w3}}{V_{dc}} - \frac{P_{w2} + P_{w3}}{V_{dcl}} \quad (11)$$

It can be seen from (10) and (11) that the active power and DC current of the MMC1 is positively related to the DC voltage V_{dcl} when the DC voltage of the HVDC system and the active power of each wind farm are unchanged. Therefore, the power adjustment between the LCC and the MMC1 can be realized by changing the DC voltage distribution of the upper and lower valves.

When the transmitted power decreases, i.e., the captured wind power drops, the DC voltage of LCC will be increased. Since the HVDC voltage is controlled by the inverters, the DC voltage of lower valves will be decreased. According to (11), the DC current of MMC1 will be decreased to prevent MMC1 from overcurrent. When the wind power drop is significant, such as the wind power curtailment of the large-capacity wind farm 1, the DC voltage will be decreased (increase firing angle) to absorb more reactive power. Therefore, a resilient DC voltage control is proposed and its control principle is depicted in Fig. 5.

In Fig. 5, P_{dcn}^{LCC} and V_{dcn}^{LCC} are respectively the rated power and DC voltage of LCC. P_{high}^* , P_c^* and P_{low}^* are the power thresholds of resilient DC voltage under different stages.

In the normal operation stage ($P_{high}^* < P_{LCC} < P_{dcn}^{LCC}$), the power reduction is acceptable, which will neither cause overcurrent of MMC1 nor surplus reactive power. The LCC operates at constant DC voltage control as normal.

In stage I ($P_c^* < P_{LCC} < P_{high}^*$), the power reduction is moderate. To prevent MMC1 from overcurrent, the DC voltage of LCC will be increased. However, due to the constraints of the minimum firing angle of LCC and minimum operating DC voltage of MMC1, the DC voltage has a maximum value, denoted as V_{dcnmax}^{LCC} . The corresponding power is denoted as P_c^* .

In stage II ($P_c^* < P_{LCC} < P_{high}^*$), the DC voltage is slightly decreased to avoid the maximum voltage of V_{dcnmax}^{LCC} .

In stage III ($P_{dcnmin}^{LCC} < P_{LCC} < P_{low}^*$), the power reduction is large (mainly caused by the reduction of wind farm 1). To absorb the surplus reactive power, the DC voltage should be decreased to increase the firing angle.

To realize the above function, the droop coefficient k of the resilient DC voltage control needs to be variable, which is different from the conventional droop control (as shown using

blue dotted line in Fig. 5). More specifically, k is designed as:

$$k = \begin{cases} 0 & , P_{high}^* < P_{LCC} \leq P_{dcn}^{LCC} \\ k_1 = \frac{V_{dcmax}^{LCC} - V_{dcn}^{LCC}}{P_c^* - P_{high}^*} & , P_c^* < P_{LCC} \leq P_{high}^* \\ k_2 = \frac{V_{dcmax}^{LCC} - V_{dcn}^{LCC}}{P_c^* - P_{low}^*} & , P_{low}^* < P_{LCC} \leq P_c^* \\ k_3 = \frac{V_{dcn}^{LCC} - V_{dcmin}^{LCC}}{P_{low}^* - P_{dcn}^{LCC}} & , P_{dcn}^{LCC} \leq P_{LCC} \leq P_{low}^* \end{cases} \quad (12)$$

Fig. 5. Principle of the proposed resilient DC voltage control.

Combining Fig. 5 and equation (12), the control diagram of the resilient DC voltage control can be obtained, as shown in Fig. 6, where the upper, intermediate and lower control loops represent the three control stages. ΔV_{dc} is the output of the resilient DC voltage control. k_i ($i=1, 2, 3$) is the P - V coefficient based on equation (12). V_{dc}^{ref} is the DC voltage reference of the upper valve; V_{dc}^{chref} is the rated DC voltage command.

Fig. 6. The control scheme of the resilient DC voltage control.

In normal operation, the active power P_{LCC} is between P_{high}^* and P_{dcn}^{LCC} . The output of the resilient DC voltage control is zero. When the wind power is slightly decreased and P_{LCC} is between P_{high}^* and P_c^* , the output of the comparator is 1. The upper control loop will superimpose a positive value on V_{dc}^{chref} , while the other two loops output zero. Thus, the DC voltage reference V_{dc}^{ref} is increased. When the transmitted power of LCC is less than P_c^* , the output of the comparator becomes 0. The intermediate control loop will output a positive value on V_{dc}^{chref} . When the transmitted power drops significantly and the active power of the LCC is lower than P_{low}^* , the lower control loop outputs a negative value on V_{dc}^{chref} to decrease the DC voltage of the upper valve.

B. Parameter Design of the Resilient DC Voltage Control

In actual applications, the modulation ratio of MMC ranges from 0.85 to 0.95. For the hierarchical integration system, the

modulation ratio of MMC during normal operation is set as 0.9. When the DC voltage of LCC is increased, to prevent overmodulation of MMC and leave a certain margin, V_{dcmax}^{LCC} is set as 1.08. To avoid a large firing angle affecting the operation performance of the HVDC transmission system and prevent MMC sub-modules from overvoltage, V_{dcmin}^{LCC} is set as 0.9. Hence, the upper and lower limits of the three control loop can be obtained, as depicted in Fig. 6.

The selection of power thresholds should consider the capacity of MMCs. Taking the converter parameters listed in Table 3 as an example, MMC1 adopts the ABB's IGBT 5SMA3000L450300 as the switching device [31]. The maximum transmitted power for the long-time operation of MMC1 is 1080MW when IGBT reaches its maximum tolerable current. Thus, the power margin of MMC1 is 80MW.

To ensure that MMC1 does not exceed its maximum rated power when LCC reaches its maximum voltage regulation limit, P_{high}^* , P_c^* and P_{low}^* are set as 2450MW (0.98 p.u.), 2420MW (0.968p.u.) and 2400MW (0.96 p.u.), respectively. With these parameters, the DC resilient control can withstand 500MW (67%) power reduction of wind farms 2 and 3. Based on the minimum voltage that LCC can reach, the P_{dcn}^{LCC} is set to 1800MW (0.72p.u.).

V. OPERATING MODES OF THE HIERARCHICAL SYSTEM

Due to the hierarchical integration topology, the hybrid HVDC system has multiple operating modes. Once a sub-converter quits operation or is under maintenance, as well as the shutdown of wind turbines during AC collection network faults, it can switch to other operating modes to guarantee a certain power transmission, which improves the system's flexibility.

A. Hierarchical Integration Mode

In normal operation, the system is in hierarchical integration mode, denoted as mode I. When MMC2 or MMC3 quits operation, the cascaded converter can switch to partial hierarchical integration mode, which is defined as mode II. As shown in Fig. 7 (a), when a single converter or wind farm is out of operation, the remaining converters can continue to transmit power, realizing uninterrupted power transmission.

B. Single-Layer Integration Mode

The system will switch to the single-layer integration mode in the following conditions.

1) Upper valve quits operation

During the maintenance of the upper valve converter, or the power of wind farm 1 drops dramatically, to ensure continuous power transmission, LCC and MMC4 quit operation. The system operates at the single-layer integration mode (mode III), as shown in Fig. 7 (b). Since LCC and MMC4 are bypassed, the HVDC system operates at half DC voltage and transmits partial active power.

2) MMC1 quits operation or wind farm 1 shuts down

When wind farm 1 is shut down or MMC1 quits operation, LCC cannot directly connect to the wind farm, and it also needs to be shut down. The system switches to mode IV, as shown in Fig. 7 (c). The normal power transmission of wind farm 2 and

wind farm 3 is not affected.

Fig. 7. Multiple operating modes of the hierarchical integration system.

Fig. 8. Switching strategy from mode I to mode III.

Fig. 9. Switching strategy from mode III to mode IV.

C. Online Switching Strategies between Operating Modes

To smoothly switch between different operating modes, the switching strategies are designed. Since the switching from mode I to mode IV can be divided into two processes (mode I $\rightarrow$ mode III $\rightarrow$ mode IV), the switching strategies from mode I to mode III and mode III to mode IV are considered.

1) Switching strategy from mode I to mode III

The switching strategy of the system from mode I to mode III is shown in Fig. 8. Firstly, the bypass switches S_1 and S_2 are turned on. Then, the thyristors T_{B1} and T_{B2} are turned on to bypass LCC and MMC4. The currents flowing through the subconverters drop to zero, and thyristors T_{S1} and T_{R1} will be turned off. Afterwards, LCC and MMC4 are blocked. The HVDC system switches to operating mode III.

2) Switching strategy from mode III to mode IV

The switching strategy of the single-layer integration from mode III to mode IV is shown in Fig. 9. Firstly, the power reference of wind farm 1 is set to 0. Meanwhile, on detecting that the current flowing through MMC1 is lower than the holding current of T_{S2} , the thyristor T_{S2} will be turned off. Then, the breaker B_{S1} is turned off to isolate the sub-converter. The cascaded converter will be switched to mode IV.

VI. SMALL-SIGNAL STABILITY ANALYSIS

To verify the effectiveness of the proposed hierarchical integration system and coordinated controller, the small-signal stability analysis is developed in this section.

A. Linearized small-signal model

According to [32], the wind turbine can be modelled as a

GSC connected to a DC voltage source. The equivalent circuits of LCC, VSC and MMC are deduced in [33][34].

Utilizing the interfaced equivalent circuits of converters, the interconnections between converters, AC systems and DC line are realized, as depicted in Fig. 10, where a π -type equivalent circuit is used to represent the DC line. The DC side modelling and AC side modelling are similar to those in [33] and are omitted here.

The nonlinear dynamic model of the hybrid cascaded converter based hierarchical integration system can be expressed in the general form of:

$$\frac{dx}{dt} = f(x, u) \quad (13)$$

where x and u are the state and input vectors, respectively.

By linearizing (13), the linearized small-signal model of the system can be derived in a general form as:

$$\frac{d\Delta x}{dt} = A\Delta x + B\Delta u \quad (14)$$

where A and B are the state and input matrices, respectively.

(a) Equivalent circuit of sending end

(b) Equivalent circuit of receiving end

Fig. 10. Equivalent circuit diagram of the hierarchical integration system.

B. Stability analysis

The electromagnetic transient (EMT) model of the HVDC system shown in Fig. 1 is built in PSCAD/EMTDC, and the linearized small-signal model is established in MATLAB/Simulink. The parameters of the test system are listed in Table 2, Table 3 and Table 4.

Table 2 Parameters of the AC/DC systems.

Categories	Items	Values
Overhead-line	Resistance	10Ω
	Inductance	1.62H
	Capacitance	13μF
Receiving AC grid	Rated AC voltage	515kV
	Equivalent resistance	0.76Ω
	Equivalent inductance	0.024H

Table 3 Electrical parameters of the converters.

Parameters	LCC	MMC1	MMC2/3	MMC4/5
Rated capacity/MVA	2500	1000	750	2500
Rated DC voltage/kV	400	400	400	368.75
AC voltage/kV	330	330	110	525
Transformer ratio	330/169	330/210	110/210	525/210
Transformer inductance	0.18pu	0.1pu	0.1pu	0.1pu
DC inductance /mH	300	200	200	200
Arm resistance/Ω	/	0.2	0.2	0.2
Arm inductance/mH	/	30	37	17
Number of SM	/	200	200	200
SM capacitance/mF	/	15	8	32

Table 4 Control parameters of the converters.

Items	Values
LCC's DC voltage controller	$K_{PI}=5, K_{IL}=100$
Outer-loop controller of MMC1 (same for MMC2, MMC3)	$K_{Pod1}=5, K_{Iod1}=100$ $K_{Poi1}=5, K_{Ioi1}=10$
d/q-axis current controller of MMC1 (same for MMC2, MMC3)	$K_{Pid1}=1, K_{Iid1}=1$ $K_{Piq1}=1, K_{Iiq1}=1$
Outer-loop controller of MMC4 (same for MMC5)	$K_{Pod4}=6, K_{Iod4}=200$ $K_{Poi4}=0.5, K_{Ioi4}=50$
d/q-axis current controller of MMC4 (same for MMC5)	$K_{Pid4}=0.3, K_{Iid4}=50$ $K_{Piq4}=0.3, K_{Iiq4}=50$

Based on the small-signal model, the impact of the control parameters of each converter on the system is evaluated and depicted in Fig. 11. When a certain control parameter changes, the rest of the parameters remain at the given value.

Fig. 11 (a)-(b) indicate the eigenvalues loci of the system when the proportional gain (K_{Pod1}) and the integral gain (K_{Iod1}) of the MMC1's d-axis outer-loop controller change from 0.5 to 20 and from 1 to 1000, respectively. It can be observed that the eigenvalues are all in the left half-plane, and the system is stable. The eigenvalues loci of the system with the proportional

gain (K_{Pod4}) and the integral gain (K_{Iod4}) of MMC4's d-axis outer loop controller varying are shown in Fig. 11 8(c)-(d). It can be seen that the dominant mode of the system moves towards the unstable region with the decrease of K_{Pod4} , resulting in the system instability when $K_{Pod4} \leq 2.5$. Moreover, with the increase of K_{Iod4} , the small-signal stability margin of the system declines, and the system becomes unstable when $K_{Iod4} \geq 580$.

In general, the system is stable when the control parameters change within a relatively large range. Tests for other controllers have also confirmed this conclusion, while the simulation results are omitted for space considerations.

Fig. 11. Rot loci of the system with control parameters varying.

The PSCAD/EMTDC simulation results of the hierarchical integration system under a minor disturbance are shown in Fig. 12. A step change from 1 p.u. to 1.05 p.u. is imposed on the DC voltage reference value of MMC4 at 5s while the system is operating under rated parameters. Fig. 12 (a) shows the DC voltages of rectifiers. The AC voltages of wind farms 1 and 2 are well maintained at the rated value, as shown in Fig. 12 (b)-(c). Fig. 12 demonstrates the effectiveness of the proposed integration system and coordinated controller.

Fig. 12. Simulation results under a small disturbance.

VII. SIMULATION VERIFICATIONS

A. Simulation under DC Fault Circumstances

The cascaded hybrid HVDC system has the ability to clear DC fault current. After the DC fault occurs, the lower valve MMCs are blocked to obstruct the discharge path of the submodule capacitor, while the upper valve LCC shifts phase to the inverter state. The thyristors on the transmission line of

Fig. 14. Simulation results under DC fault.

B. Validation of resilient DC voltage control

1) Wind power reduction of wind farm 1

To test the performance of the proposed resilient DC voltage control, the active power order of wind farm 1 drops from 3500MW to 3000MW at 10s, and decreases to 2500MW at 30s. The simulation results are shown in Fig. 15.

Fig. 15 (a) shows the active power of rectifiers. When the active power of LCC is lower than 2450MW, the resilient DC voltage control operates. Firstly, the DC voltage of LCC is increased because a positive value is superimposed on V_{dchref}^* .

the inverter side are adopted to block the current path during the DC fault, and the energy dissipation devices of wind farms are triggered to dissipate surplus wind power after the fault [35].

The structure of the simulation case for the DC fault test is shown in Fig. 13. At 5s, a pole-to-ground fault is occurred at the over-head line and lasted for 0.3s. The fault resistance is 0.1Ω , and the fault maintenance current is 0.01kA. The simulation results are shown in Fig. 14.

Fig. 13. Structure of simulation case for DC fault tests.

Fig. 14 (a)-(b) show the DC link voltages and currents. Once the fault is detected, LCC will increase the firing angle to 150° to prevent the AC system from feeding current to the fault point. Meanwhile, the dissipation resistors are put in. The fault current can be suppressed to 0 within 65ms. Fig. 14 (c)-(d) show the AC voltages of the wind farms, which fluctuate at the moment of the DC fault. After the fault is cleared, the AC voltages of the wind farms maintain at the rated value.

At 5.3s, the HVDC system restores normal operation, and the dissipation resistors are cut off. Each converter's active power reverts to the rated value at 5.6s, as shown in Fig. 14 (e).

Then, the lower limit loop outputs a negative value and the DC voltage of LCC is decreased to 384kV at 10.5s. At 30.5s, the DC voltage is dropped to 360kV, as shown in Fig. 15(b). Finally, the active power of LCC and MMC1 are 1800MW and 700MW, respectively. With the decrease of DC voltage, the firing angle of LCC increases, as shown in Fig. 15 (c).

Fig. 15 (d) shows the reactive power absorbed by LCC after reactive compensation. As can be seen, without resilient DC voltage control, when the power of wind farm 1 drops 500MW, the surplus reactive power is 130MVar. And the surplus reactive power is up to 400MVar when the power of wind farm

1 drops 1000MW. Since the resilient DC voltage control is used, LCC can absorb surplus reactive power. The AC voltage of wind farm 1 can be maintained with the resilient DC voltage control, as shown in Fig. 15 (e). If the resilient DC voltage control is not applied, the surplus reactive power will cause the out of control of MMC1, leading to unstable AC voltage after 35s, as shown in Fig. 15 (f). Fig. 15 (g)-(h) show the average arm capacitor voltages and arm currents of MMC1. The

dynamics show that the system is well operated with resilient DC voltage control during wind farm 1 power curtailment.

2) Wind power reduction of wind farms 2 and 3

Fig. 16 shows the simulation results of the hierarchical integration system when the active power of wind farm 2 and wind farm 3 is decreased. At 10s, the active power of wind farm 2 is reduced from 750MW to 500MW. While the active power of wind farm 3 drops from 750MW to 550MW at 30s.

Fig. 15. Simulation results under wind farm 1 power reduction.

When the active power of LCC is lower than 2450MW, the resilient DC voltage control starts. The DC voltage of LCC is increased to 411kV at 10.5s, and it rises to 426kV at 30.5s, as shown in Fig. 16 (a). Fig. 16 (b)-(d) show the active power of rectifiers, respectively. As can be seen, without resilient DC voltage control, when the power of wind farm 2 drops 250MW, the active power of LCC and MMC1 are 2375MW and 1125MW. When the power of wind farm 3 drops 200MW, the active power of LCC and MMC1 are 2275 MW and 1225MW. MMC1 will withstand more active power when wind power curtailments happen at wind farm 2 or 3, resulting in the overcapacity of MMC1. However, when the resilient DC voltage control is applied, the active power of MMC1 is maintained at 1060MW at 11s and 1074MW at 31s, which indicates that LCC will transmit more active power to prevent MMC1 from over-capacity.

C. Performance under stochastic wind power

The controller should maintain the AC and DC voltages of the system under continuously changing wind farm power. The simulation results of the response to a series of step changes in the active power of wind farms are shown in Fig. 17. The stochastic active power of wind farms 1 and 2 is analyzed, while the output of wind farm 3 is maintained at the rated value. For wind farm 1, the fluctuation of wind power is: 1pu $\rightarrow$ 0.8pu ($t=3s$) $\rightarrow$ 0.9pu ($t=7s$) $\rightarrow$ 0.7pu ($t=11s$) $\rightarrow$ 1pu ($t=15s$). While for

wind farm 2, the fluctuation of wind power is: 1pu $\rightarrow$ 0.6pu ($t=5s$) $\rightarrow$ 0.8pu ($t=9s$) $\rightarrow$ 0.7pu ($t=13s$) $\rightarrow$ 1pu ($t=17s$).

Fig. 17 (a) depicts the active power of wind farm 1, wind farm 2, LCC and MMC1, respectively. As shown in Fig. 17(b), the DC voltage of the HVDC link is maintained at the rated value with slight oscillations during wind power fluctuations, while the voltages of the upper valve and lower valve change reversely according to the resilient DC voltage control principle. It can be observed in Fig. 17(c)-(d) that the AC voltages of wind farms is well controlled by the controllers of rectifier MMCs.

Fig. 16. Simulation results under wind farms 2 and 3 power reduction.

Fig. 18. Simulations of operating modes switching (mode I to III).

Fig. 17. Simulation results under stochastic wind power.

D. Simulation of online operating mode switching

1) Switching strategy from mode I to mode III

Supposing that the LCC is under maintenance, the system will switch to mode III operation. Fig. 18 shows the switching process.

Fig. 18 (a) shows the DC voltages of the system. At 7s, the bypass switches S_1 and S_2 are closed, and the thyristors T_{B1} and T_{B2} are turned on to bypass LCC and MMC4. At 7.1s, the DC voltage of the upper valve drops to approximately 0. Meanwhile, the power of wind farm 1 is reduced to adapt to the transmission capacity of the hierarchical integration system. When the currents flowing through the sub-converters drop to 0, thyristors T_{S1} and T_{R1} will be turned off, as shown in Fig. 18 (b). Afterwards, LCC and MMC4 are blocked, and the HVDC system switches to the single-layer integration mode. The DC voltage, which is maintained by the MMC5, is reduced to 1/2 of the rated value. After a slight oscillation, the active power of MMCs at the rectifier side recover to their rated values, as shown in Fig. 18 (c).

2) Switching strategy from mode III to mode IV

Fig. 19 shows the switching process from mode III to mode IV. Fig. 19 (a) shows the active power of MMCs at the rectifier side. At 6s, the active power of wind farm 1 is controlled to 0. At the same time, the current flowing through MMC1 is decreased to 0, as shown in Fig. 19 (b). The thyristor T_{S2} is turned off at 6.5s, and MMC1 is blocked. Then, the breaker B_{S1} is turned off to isolate MMC1 from the system. During the switching process, the DC voltage is well controlled by MMC5, as shown in Fig. 19 (c). The active power and currents of MMC2 and MMC3 fluctuate slightly, which does not affect the stable operation of the system.

Fig. 19. Simulations of operating modes switching (mode III to IV).

VIII. CONCLUSION

A hierarchical integration topology for the islanded onshore wind power based on the cascaded hybrid HVDC system is proposed in this paper. The hierarchical integration system provides a solution for integrating different scales of wind farms at low cost and maintaining high operating flexibility. The continuous operation during wind power curtailments is realized by the resilient DC voltage control. It can change the DC voltages of the upper and lower valves to adjust the active and reactive power distribution among LCC and MMC1. The hierarchical integration system enables multiple operating modes, enabling the system to continuously transmit power when the wind farms and sub-converters quit operation or are under maintenance. The simulation results show that the hierarchical integration HVDC system has a potential application prospect in the long-distance transmission of large-scale islanded wind power.

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