Methods for Transient AC Overvoltage Reduction at Wind Farm Terminal

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Abstract — In the booming developing wind power market, wind converters are one of the key equipment for wind power integration in the power system. However, the overvoltage level that wind converters can withstand is relatively low compared with the conventional power generation system. Large amount of WTGs might trip due to overvoltage protection if the transient AC overvoltage in the system is too high. Therefore, it is important to limit the transient AC overvoltage in the system. This paper mainly presents four different methods for transient AC overvoltage reduction at wind farm terminal, which could reduce the trip risk of large amount of wind turbine generators (WTGs) and increase the operation stability of the power system integrated with wind power.

Index Terms— Wind power integration, HVDC system, high voltage ride through (HVRT), transient AC overvoltage

I. I NTRODUCTION

To improve the environmental quality, more and more clean energy, e.g. wind energy, is used as a power source. Wind converters are one of the key equipment for wind power integration in the power system. Compared with other conventional equipment (synchronous generator, transformer etc.) used in power system, wind converters are much more sensitive to voltage disturbances. This might cause serious system stability problems if large amount of WTGs trip. In 2011, several serious WTGs tripping accidents occurred in China due to voltage dips and overvoltage [1] [2], which finally caused serious frequency deviations in the grid. Many countries gives clear requirements on low voltage ride through (LVRT) capability of WTG. The requirements on high voltage ride through (HVRT) capability is only given in a few countries. A lot of research has been done to improve the fault ride through (including both LVRT and HVRT) capability of WTGs by improving the control of the wind converter. However, the research on how to improve the wind converter fault ride through capability by considering other controllable equipment (e.g. STATCOM, HVDC converter etc.) in the power system is rarely found.

The research presented in this paper mainly focuses on the reduction of transient AC overvoltage (caused by different types of faults in the power system) in a large scale onshore wind power LCC HVDC transmission system. The configuration of the studied system is introduced in section II. Considering the controllability of HVDC converter and STATCOM connected to wind farm (called wind farm STATCOM in later text), the modifications are made for the control of HVDC system, wind farm STATCOM and wind converters to reduce the transient AC overvoltage. Besides these, a DC chopper installed at rectifier station of HVDC system is also proposed to reduce the transient AC overvoltage. The verification on the system performance with these modifications/methods are done by time domain simulations in PSCAD/EMTDC. The results are analyzed and compared in section III. Considering the transient behavior of different type of WTGs might be different, the effectiveness of the selected method is further tested by using two typical types of WTG (double-fed induction generator (DFIG) and permanent magnetic synchronous generator (PMSG)). The test results are analyzed in section IV. Section V gives the conclusions.

II. CONFIGURAITON OF STUDIED SYSTEM

This research is carried out in a 12.5 GW wind power LCC HVDC transmission system. It is simulated in PSCAD/EMTDC and its configuration is presented in Figure 1. In the studied system, a 12.5 GW (installation capacity) wind farm cluster is composed of eight 1.568 GW wind farm sub clusters. Each 1.568 GW wind farm sub cluster consists of seven 224 MW wind farms, in which 100% PMSG or 100% DFIG type WTGs are used. Each wind farm consists of 112 x 2 MW PMSG or DFIG type WTGs. They are distributed in 16 rows and 7 wind turbines in each row. Each wind turbine is connected to a 35 kV bus via a 0.69/35 kV transformer and AC cable. Then the wind farm is connected to a 330 kV bus via a 35/330 kV transformer. The distance between each row and between two adjacent wind turbines are 700 m and 500m respectively. Limited by the simulation capability of PSCAD/EMTDC, the 1.568 GW wind farm sub cluster is represented by a single machine based aggregation model and equivalent π line (equivalent to the transformer and 35 kV AC grid in the wind farms) with a length of 1000m. A detailed description about aggregation methods used for 1.568

GW wind farm sub cluster model is presented in [3]. The terminal voltage of this 1.568 GW wind farm aggregation model is 35 kV.

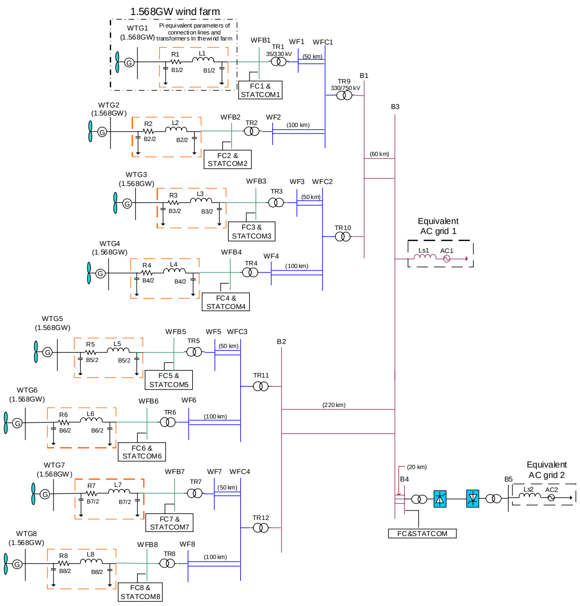

Figure 1 The configuration of the studied system

In order to simulate a more realistic case, the distance between different wind farm sub clusters and the rectifier station of the HVDC system is assumed to be different, as showed in Figure 1 and table A-2.

The supporting AC network (AC grid 1 in Figure 1) connected to rectifier AC bus of the HVDC system and AC network (AC grid 2 in Figure 1) connected to inverter AC bus of the HVDC system are simulated as an ideal voltage source in series with equivalent impedance for corresponding short circuit power level. In this research, short circuit ratio (SCR) of 3 is used for AC grid 1 and SCR of 5 is used for AC grid 2.

A bipolar LCC HVDC transmission system with rated voltage of ± 800 kV and rated power of 8 GW, which includes two 12 pulse converter groups per pole, is used to transmit wind power.

According to Chinese standard [4], a STATCOM is connected at the terminal of each 1.568 GW wind farm sub cluster to provide dynamic reactive power compensation. Similar to realistic situation, certain fixed capacitor (FC) is also shunt connected at wind farm sub cluster terminal to work together with STATCOM for reactive power compensation, as shown in Figure 1 (bus WFB1 – WFB8). The capacity of these reactive power compensation devices are designed according to load flow calculation. For bus WFB1, WFB3, WFB5 and WFB7, the capacity of STATCOM and FC are ± 250 Mvar and 65 Mvar respectively. For bus WFB2, WFB4, WFB6 and WFB8, the capacity of STATCOM and FC are ±150 Mvar and 45 Mvar respectively.

The detailed parameters of transformers used in the studied system are presented in appendix.

III. METHODS FOR TRANSIENT AC OVERVOLTAGE REDUCTION

Table 1 gives the summary about the HVRT requirements in different countries. It can be found that the most relaxed requirement is 1.3 p.u. for 60 ms, which is given in Australia. For this research, the Chinese standard is the main focus. Thus, the HVRT requirement in Chinese standard is used in this research as the target of transient AC overvoltage reduction, i.e. to keep the AC overvoltage (three phase RMS voltage) at wind farm (sub cluster) terminal to a level below 1.2 p.u. within 200 ms.

Table 1 Summary about the HVRT requirements in different countries

Fault Ride Through (HVRT)			
Country	**Requirement for**	**V Profile of fault (p.u. based on Un)**	**Reference**
Australia	A generating system and each of its generating units	1.3 p.u., 60ms; 1.2 p.u., 0.4s; 1.1 p.u. forever	[5][6]
Germany	Generating plant, for fault-related symmetrical voltage dips, as well as for unsymmetrical faults with reference to the positive sequence system.	1.2 p.u., disconnect with a time delay of 0.1s	[7]
Spain	Wind Farm. 3 ph, 2 ph. Overvoltage in one or all phases.	1.2 p.u., 50 ms	[8]
USA	Wind Farm. 3p fault with normal clearing; single line to ground faults with delayed clearing; and subsequent post-fault voltage recovery to prefault voltage.	≥1.2 p.u., Instantaneous trip ≥1.175 p.u., 0.2s ≥1.15 p.u., 0.5s ≥1.10 p.u., 1s	[9]
China	Wind turbine generation system	> 1.2 p.u., instantanous trip > 1.15p.u., 0.2s > 1.1 p.u., 2s	[10]

Transient AC overvoltage in the system typically occurs after fault release. Compared with other fault types in the power system, a three-phase-to-ground fault is the most serious fault and the transient AC overvoltage caused by this type of fault is most critical. Therefore, a low impedance three-phase-to-ground fault at the rectifier station of the HVDC system is selected as the evaluation case. All cases evaluated in this section was made in the system with 100% PMSG type WTGs. Four methods are developed to reduce the transient AC overvoltage caused by three-phase-to-ground fault and presented in this section.

To show the reduction of transient AC overvoltage at the terminal of different wind farms by using developed methods, the following typical signals in the simulation without and with developed method are selected to be showed and compared in this section:

- RMS voltage at the terminal of WF (Wind Farm) 1 (bus WFB1, 35kV level), which is connected to the supporting AC network via a 50 km 330 kV line, and a 60 km 750 kV line (see Figure 1)
- RMS voltage at the terminal of WF8 (bus WFB8, 35 kV level), which is connected to the supporting AC network via a 100 km 330 kV line, and a 220 km 750 kV line (see Figure 1)
- RMS voltage at rectifier AC bus of the HVDC

system
- DC voltage of S1P1 (pole 1 of rectifier)

The transient AC overvoltage at the terminal of WF1 and WF8 represents the best and worst results in the system, because they are connected to the shortest and longest AC transmission line respectively.

A. Method 1 - Modification on the control of HVDC system

In a conventional LCC HVDC transmission system, the inverter normally puts up a very high DC voltage, and the rectifier increases its firing angle during the AC fault. The motivation for this control is that otherwise the rectifier DC voltage can become very high when the AC fault releases. However, to reduce the AC overvoltage in the wind power transmission system, the HVDC system could make a fast DC power recovery after fault release, which can result in a fast active power balance in the AC system. Hence, the following modification is done for the control of the HVDC system:
- Rectifier: Set minimum allowed firing angle (to get high DC current)
- Inverter: Set minimum allowed firing angle (to get low DC voltage)

With these modifications, the inverter sets up a low DC voltage by operating at minimum firing angle, and the rectifier operates at minimum firing angle. Hence as soon as the AC fault releases, the rectifier will draw power from the AC system into the DC system. The developed method might be dependent of a relatively strong inverter ac system (In this research, a SCR of 5 is used for the inverter AC system).

A three-phase-to-ground fault (start at 0.2s and release at 0.3s) was applied at rectifier AC bus of the HVDC system. Figure 3 shows the simulation results of typical signals obtained without and with using this method.

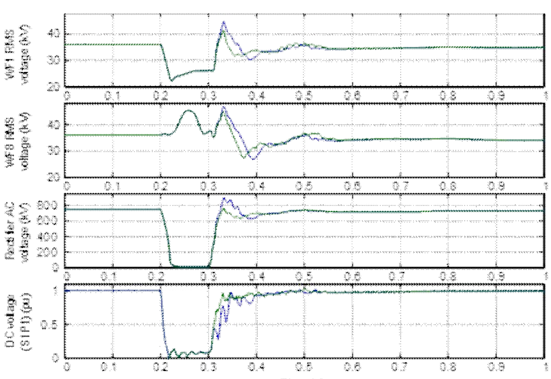

Figure 3 The performance of the system without (blue line) and with (green line) using method 1, graphs from top to bottom: 1) RMS voltage at WF1 terminal (35 kV); 2) RMS voltage at WF8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

The following phenomena could be observed from Figure 3:
- Comparing the RMS voltage at the terminal of different wind farms and rectifier AC bus of the HVDC system, all AC overvoltage are reduced by using method 1 (see green line in all graphs of Figure 3).
- The AC overvoltage at all wind farm terminals after fault release by using method 1 is still higher than 1.2 p.u. (42 kV) of nominal voltage (35 kV). However, it can be observed that the AC overvoltage higher than 1.2 p.u. also occurred at WF8 terminal during the fault. This is caused by a PLL error, and fast response of controllers used in the grid side converter of PMSG type WTG. In the wind converter, the Iq_ref (reference value of reactive power current Iq) used in the current control loop is set to zero. However, the Iq obtained from the measurement is not correct anymore due to the PLL error. Thus, the voltage reference of wind converter obtained from current control loop is not correct anymore and a large amount of reactive power is produced by WF8 during the fault.
- RMS voltage at WF1 and 8 terminals is quite different due to the different lengths of AC transmission line (from wind farm terminal to rectifier station of the HVDC system). A longer AC transmission line is connected to WF8.

B. Method 2 - Modification on the control of wind farm STATCOM

After developing method 1, it was considered that it might be more efficient if a control modification is made for the wind farm STATCOMs that are closer to wind farms, and directly control the voltage at wind farm terminals. The modification made for the control of wind farm STATCOMs is to increase the gain used in the AC voltage controller of STATCOM when an overvoltage at wind farm terminal is detected.

A three-phase-to-ground fault (start at 0.2s and release at 0.3s) was applied at rectifier AC bus of the HVDC system. The simulation results obtained in the system without using developed method and with using method 1 plus 2 are showed in Figure 4. It seems that the voltage profile is not improved much. This is caused by relative slow response speed of STATCOM and limited capacity of STATCOM. The STATCOM response speed is set slow in this large-scale wind power transmission system since it is observed that the whole system cannot get recovery after the fault if the response speed of STATCOM is faster. In this research, the capacity of wind farm STATCOM is designed only based on power flow calculation results (only considering the reactive power requirement under steady state). Not much additional capacity is reserved for STATCOM to control voltage during or after fault. In reality, the capacity of STATCOM also cannot be too large due to cost consideration. Thus, the reduction of transient AC overvoltage at wind farm terminal by STATCOM is limited.

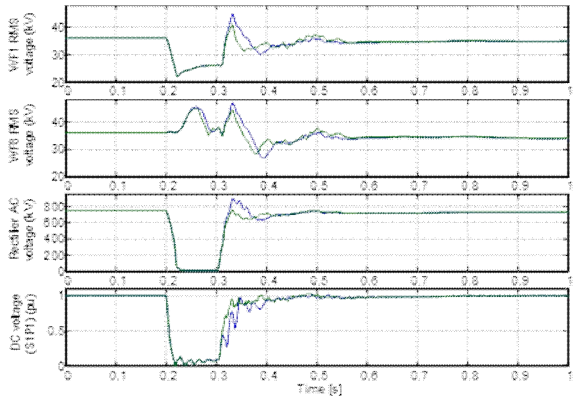

Figure 4 The performance of the system without using developed method (blue line) and with using method 1 plus 2 (green line), graphs from top to bottom: 1) RMS voltage at WF1 terminal (35 kV); 2) RMS voltage at WF8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

C. Method 3 - Modification on the control of wind converter

As mentioned in item A of this section, a large amount of unexpected reactive power was output from the wind converters, which caused an AC overvoltage at the terminal of wind farm (WF5 – WF8) during the fault. To better control the reactive power of the wind converter, a HVRT function (reactive power control) is added into the grid side converter of WTG. The control scheme used in grid side converter of WTG is showed in Figure 5. Both LVRT and HVRT function are implemented in the simulation model of wind converter.

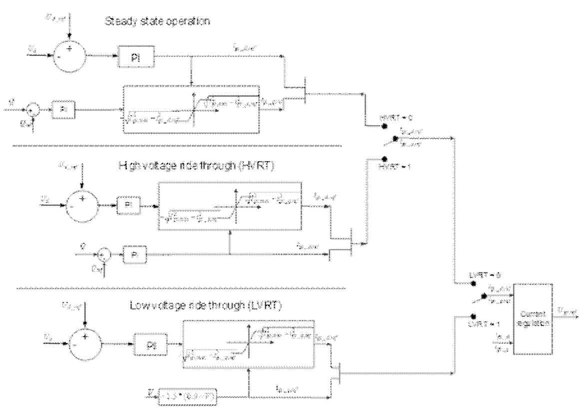

Figure 5 The control scheme used in the grid side converter of PMSG type WTG

For a three-phase-to-ground fault (start at 0.2s and release at 0.3s) applied at the rectifier AC bus of the HVDC system, the tests were done for the system without using developed method and with using method 1 + 2 + 3. The simulation results are showed in Figure 6.

From Figure 6, the following observations are made:

- Transient AC overvoltage at the terminal of all wind farms is lower than 1.2 p.u.
- Comparing with the corresponding results showed in Figure 3 and 4, it is found that the transient AC overvoltage at wind farm terminal is reduced (both during the fault and after fault release) significantly by using method 3.

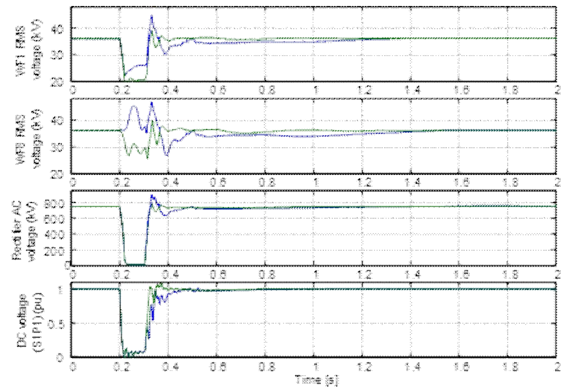

Figure 6 The performance of the system without using developed method (blue line) and with using method 1+2+3 (green line), graphs from top to bottom: 1) RMS voltage at WF1 terminal (35 kV); 2) RMS voltage at WF8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

D. Method 4 – DC chopper installed at rectifier station of the HVDC system

Besides modifications made on the control of converters in the wind power transmission system, a DC chopper installed at the rectifier station of the HVDC system could be also used to reduce the transient AC overvoltage at wind farm terminal. This is different than the existing DC chopper solutions applied in offshore wind VSC HVDC transmission, where the DC Chopper is placed in the inverter station [11]. This is due to the fact that it is necessary to quickly reduce the high voltage of DC OHL (Over Head Line) after a DC fault in any OHL HVDC transmission (LCC or VSC) system. Figure 7 shows a schematic diagram of the DC chopper method.

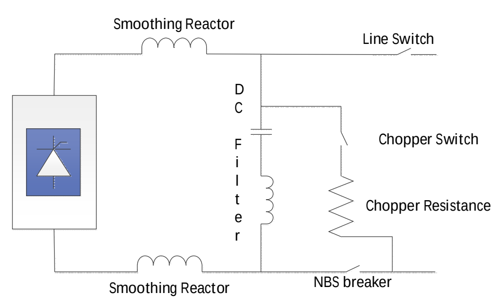

Figure 7 Schematic diagram of the DC chopper method

With a DC chopper installed at rectifier station of the HVDC system, a three-phase-to-ground fault (start at 0.2s and release at 0.3s) is applied at rectifier AC bus of the HVDC system. The simulation results without using the developed method and with developed method 1 + 4 are presented in Figure 8.

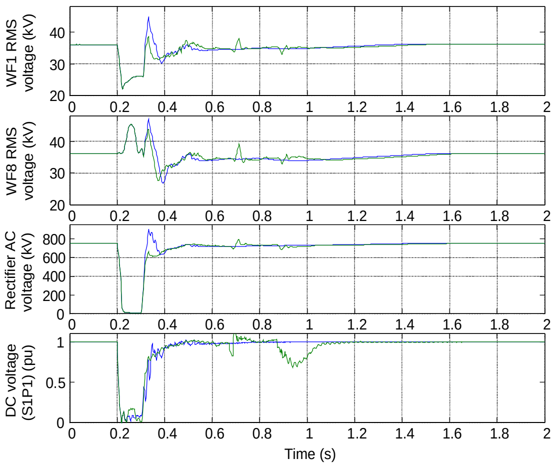

Figure 8 The performance of the system without using developed method (blue line) and with using method 1 + 4 (green line), graphs from top to bottom: 1) RMS voltage at WF1 terminal (35 kV); 2) RMS voltage at WF8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

Comparing with the results obtained in the system without using the developed method, the transient AC overvoltage after fault release is reduced. However, the transient AC overvoltage shortly after fault occurrence cannot be reduced by the DC chopper method, due to the relatively long conventional mechanical breaker switching time (In this research, it is assumed that the DC Chopper is connected 65 ms after receiving connection command, considering conventional mechanical breaker switching time).

E. Overview of transient AC overvoltage reduction results

For a three-phase-to-ground fault at the rectifier AC bus of the HVDC system, an overview of the transient AC overvoltage reduction at different locations, by using different methods, is given in table 2. Comparing these results, it can be found that method 3 (modification on the control of wind converter) is the most effective method.

Table 2 Overview of transient AC overvoltage reduction results

Locations \ Methods		Method 1	Method 1 +2	Method 1 + 2 + 3	Method 1 + 4
WF1 terminal (Best)		1.28 p.u. → 1.18 p.u.	1.28 p.u. → 1.17 p.u.	1.28 p.u. → 1.11 p.u.	1.28 p.u. → 1.1 p.u.
WF8 terminal (worst)	After fault release	1.34 p.u. → 1.28 p.u.	1.34 p.u. → 1.26 p.u.	1.34 p.u. → 1.09 p.u.	1.34 p.u. → 1.25 p.u.
	During fault	1.29 p.u. → 1.29 p.u.	1.29 p.u. → 1.28 p.u.	1.29 p.u. → 0.89 p.u.	1.29 p.u. → 1.29 p.u
Rectifier station of HVDC system		1.2 p.u. → 1.02 p.u.	1.2 p.u. → 1.01 p.u.	1.2 p.u. → 1.04 p.u.	1.2 p.u. → 0.89 p.u.

IV. COMPARISONS BETWEEN DIFFERENT TYPES OF WTG

In current market, both DFIG and PMSG type WTGs are popularly used. It is also interesting to compare the transient AC overvoltage reduction of different type of WTGs by using same developed method. As the results showed in last section, the largest reduction of transient AC overvoltage is obtained by using method 1 plus 2 plus 3. Thus, this method is selected for this comparison research.

In the studied system presented in Figure 1, two scenarios are implemented into the wind farm clusters:

Scenario1: PMSG type WTG is used in all wind farms.

Scenario2: PMSG type WTGs are used in WF1 – WF6 and DFIG type WTGs are used in WF7 and 8. A three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) was applied at rectifier AC bus in the system with both scenarios. The simulation results are presented in Figure 9 and 10.

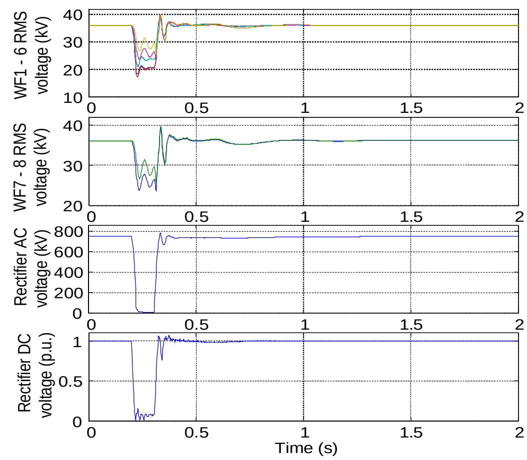

Figure 9 The performance of the system with scenario 1 (100% PMSG type WTGs), graphs from top to bottom: 1) RMS voltage at WF1 - 6 terminal (35 kV); 2) RMS voltage at WF 7 - 8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

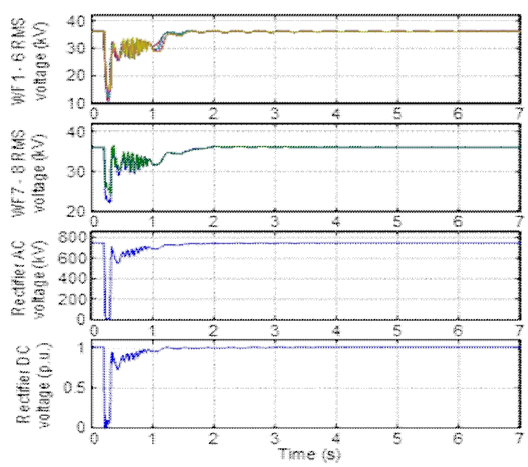

Figure 10 The performance of the system with scenario 2 (DFIG type WTGs installed in WF7 and 8), graphs from top to bottom: 1) RMS voltage at WF1 - 6 terminal (35 kV); 2) RMS voltage at WF 7 - 8 terminal; 3) RMS voltage at rectifier AC bus (750 kV); 4) DC voltage of S1P1 (pole 1 of rectifier)

From Figure 9 and 10, it is observed that the transient AC overvoltage at all wind farm terminals in the system with scenario 2 is lower than the corresponding ones in the system with scenario 1. One possible reason is that the DFIG consumes more reactive power than FPC during fault recovery. Thus, the overvoltage is avoided. However, it causes a longer recovery time.

V. CONCLUSIONS

Based on a large-scale onshore wind power LCC HVDC transmission system, four methods are developed to reduce the transient AC overvoltage at wind farm terminal and verified by time domain simulations. From this research, it can be concluded that the most effective method is to modify the control of wind converter. The modification on the control of HVDC converter and wind farm STATCOM also helps, but limited. When using a mechanical breaker based DC chopper method, the transient AC overvoltage after fault release could be reduced. However, the transient AC overvoltage shortly after fault occurrence cannot be reduced.

APPENDIX

For the studied system (see Figure 1), the voltage levels of different buses, the parameters of transformers, the lengths of different transmission lines (wind power AC collection grid) are listed in table A-1, A-2 and A-3 respectively.

Table A-1 Bus voltages

Bus Name	Base Voltage
WFB1 – WFB8	35kV
WF1 – WF8	330kV
WFC1 – WFC4	330kV
B1 – B4	750kV
HVDC DC side	± 800kV

Table A-2 Parameters of transformers

Transformer name	TR1 – TR8	TR9 – TR12
Apparent power	1750	2700
Winding type	Y/D	Y/Y
Primary side voltage (kV)	35	330
Secondary side voltage (kV)	330	750

Table A-3 AC Transmission lines

Bus1	Bus2	Type	Distance (km)
WF1	WFC1	Double circuit line / 2x300 mm	50
WF2	WFC1	Double circuit line / 2x300 mm	100
WF3	WFC2	Double circuit line / 2x300 mm	50
WF4	WFC2	Double circuit line / 2x300 mm	100
WF5	WFC3	Double circuit line / 2x300 mm	50
WF6	WFC3	Double circuit line / 2x300 mm	100
WF7	WFC4	Double circuit line / 2x300 mm	50
WF8	WFC4	Double circuit line / 2x300 mm	100
B1	B3	Double circuit line / 4x685 mm	60
B2	B3	Double circuit line / 4x685 mm	220
B3	B4	Three circuit line / 4x685 mm	20

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