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# Research on Transient Stability of Large Scale Onshore Wind Power Transmission via LCC HVDC

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***Abstract*—Wind power has a booming development in the world in recent years. In some countries, 'large scale' and 'long distance' are two prominent characteristics of the wind power integration and transmission market, e.g. China and US etc. LCC HVDC hence becomes one of the attractive wind power transmission solutions. A transient stability research was done under different operation conditions for a large scale onshore wind power LCC HVDC transmission system. The results are presented in this paper. It indicates the key features and factors that needs attention during the design of a large scale wind power LCC HVDC transmission system.**

***Keywords-large scale, wind power, LCC HVDC transmission, transient stability***

## I. INTRODUCTION

To reduce the emission level of $CO^2$ and improve the global environment, the utilization of clean energy is greatly encouraged by many countries. Wind power, as one type of clean energy, has had a booming development in the world in recent years. In some countries, 'large scale' and 'long distance' are two prominent characteristics of wind power integration and transmission market, e.g. China and US etc. LCC HVDC hence becomes one of the attractive wind power transmission solutions.

Based on a 8 GW large scale onshore wind power LCC HVDC transmission system, research of transient stability was done under different operation conditions, and time domain simulation results are presented in this paper. This will indicate the key features and factors that needs attention during the design of a large scale onshore wind power LCC HVDC transmission system.

The configuration of the studied system is introduced in section II. Transient stability research under different operation conditions are presented in section III. In section IV, the influence of wind converter parameters on the system transient stability is discussed. The conclusions are presented in section V.

## II. CONFIGURATION OF THE STUDIED SYSTEM

This research is carried out in an 8 GW wind power LCC HVDC transmission system, which is simulated in PSCAD/EMTDC. The configuration of the studied system is showed in Fig 1.

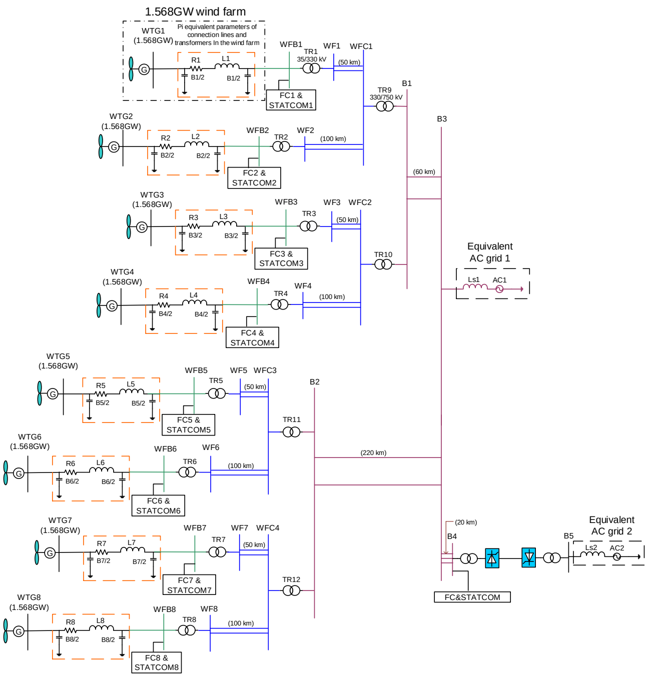


Fig. 1 Overview diagram of the studied system

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 (112 x 2 MW PMSG or DFIG type WTG) wind farms, in which 100% PMSG or 100% DFIG type WTGs are used. 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. 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 $\pi$ line (equivalent to the transformer and 35 kV AC grid in the wind farms) with a length of 1000 m. A detailed description about aggregation methods used for 1.568 GW wind farm sub cluster model is presented in [1]. The terminal voltage of this 1.568 GW wind farm aggregation model is 35 kV.

The supporting AC system connected to rectifier and inverter AC bus of the HVDC system (see AC grid 1 and 2 in Fig.1) are simulated as an ideal voltage source in series with equivalent impedance for corresponding short circuit power level. 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 [2], 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, a fixed capacitor (FC) is also shunt connected at the wind farm sub cluster terminal to work together with the STATCOM for reactive power compensation, as showed in Fig. 1 (bus WFB1 – WFB8). 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. These capacities are designed according to load flow calculation. More detailed parameters of the studied system are presented in [3].

By considering different operation conditions with different WTG types and variable power sources at the sending end of HVDC system, the following four scenarios have been used for the research discussed in later sections:

- Scenario 1: 100% FPC type WTGs, 8 GW wind power

- Scenario 2: 100% FPC type WTGs, 6 GW wind power and 2 GW coal power

- Scenario 3: 75% DFIG type WTGs and 25% FPC type WTGs, 8 GW wind power (WF1 – 6 are DFIG type WTG; WF7 and 8 are FPC type WTG)

- Scenario 4: 75% DFIG WTGs and 25% FPC type WTGs, 6 GW wind power (WF1 – 6 are DFIG type WTG; WF7 and 8 are FPC type WTG) and 2 GW coal power

Except for sub-section C of section III and section IV, a SCR (Short Circuit Ratio) of 3 is used for AC grid 1, and SCR of 5 is used for AC grid 2 (see Fig.1) in this research.

## III. Transient Stability Under Different Operation Conditions

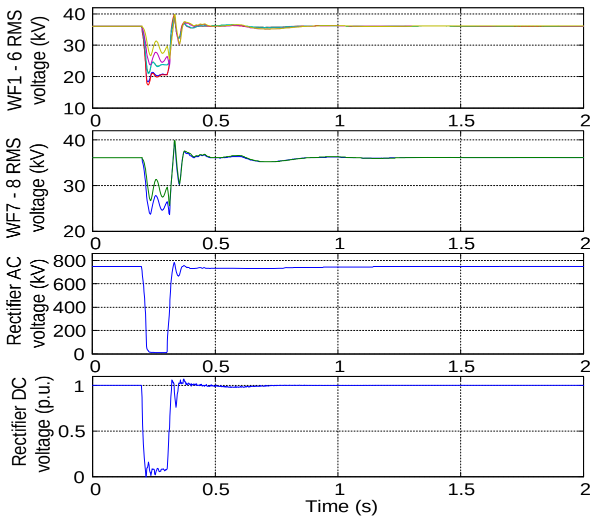
In this section, the typical simulation results of transient stability under different operation conditions are presented and discussed.

### A. *Different fault locations*

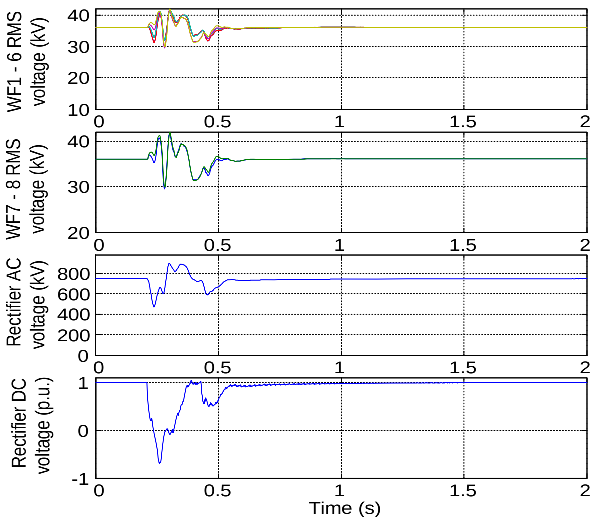
To evaluate the system performance when faults occurs at different locations, a three-phase-to-ground fault was applied at both rectifier and inverter station in Scenario 1. The RMS voltage at the terminal of all wind farms, rectifier AC voltage and DC voltage of the HVDC system are presented in Fig. 2.

Comparing RMS voltage at the terminal of all wind farms, the transient AC overvoltage caused by inverter AC fault is higher than the one caused by rectifier AC fault. This is due to the following reasons:

- For a rectifier AC fault, it shows as voltage dip in rectifier AC system and the voltage at wind farm terminal is decreased during the fault. If the controller response of wind converter adapts to the strength of rectifier AC network (i.e. slow enough), the transient AC overvoltage only occurs at the terminal of wind farms after fault release.
- For inverter AC fault, AC overvoltage will occur quickly after fault occurrence (around 22 ms in our simulations, depending on the controller response speed of wind converter) and occurs after fault release. This is due to the fact that too much excessive reactive power flows from HVDC system to AC system, which is caused by the rectifier of the HVDC system cannot consume the reactive power provided by AC filter and shunt capacitor banks because of no DC power transmission from rectifier to inverter AC network. The AC overvoltage is higher if the supporting rectifier AC network is weaker. Thus, this is the most serious fault in the system.




(a)

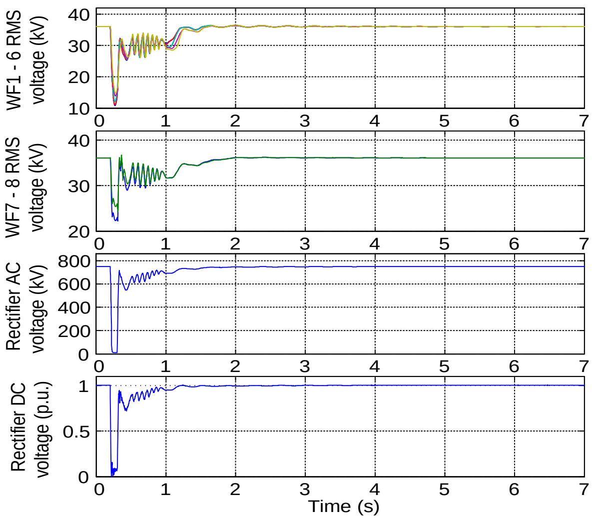



(b)

Fig. 2 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at rectifier (a) and inverter station (b) in Scenario 1

### B. *Different types of wind turbine generator (WTG)*

It is also interesting to check the system transient behavior with different type of WTGs under the same fault condition. A three-phase-to-ground fault was applied at both rectifier and inverter station in the system of Scenario 1 and Scenario 3. The results are presented in Fig. 2 and 3.

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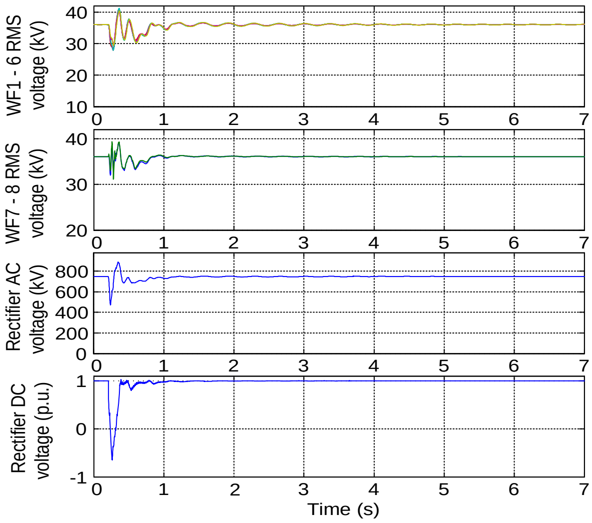



(b)

Fig. 3 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at rectifier (a) and inverter station (b) in Scenario 3

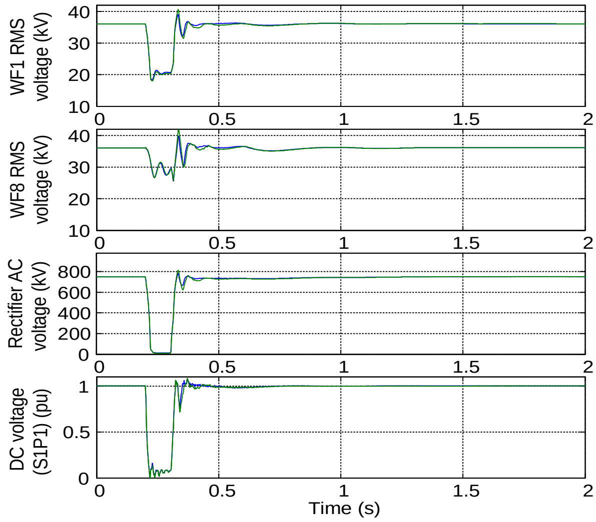
Comparing Fig. 2 with Fig. 3, it is found that the transient AC overvoltage at all wind farm terminals in the system of Scenario 3 is lower than the corresponding ones in the system of Scenario 1. One possible reason is that the DFIG consumes more reactive power than FPC during fault recovery. Thus, overvoltage is avoided. However, it causes a longer recovery time.

### *C. Different strengths of rectifier AC supporting networks*

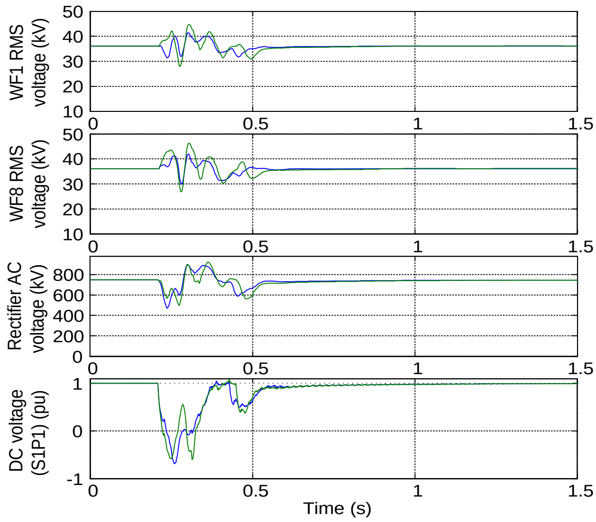
In reality, the system strength might be quite different. Particularly, the rectifier AC supporting network is quite weak in some cases. Thus, it's worth to check the system performance with different strengths of rectifier AC supporting network. The simulations were done for Scenario 1 and 3 by varying the strength of the rectifier AC supporting network.

To guarantee the system get successful fault recovery, the simulation results showed that the minimum requirement on the strength of rectifier AC supporting network in our studied system is:

- For Scenario 1, SCR at rectifier station is 2 (SCR_rec = 2). Typical results are presented in Fig. 4.
- For Scenario 3, SCR at rectifier station is 3 (SCR_rec = 3).




(a)




(b)

Fig. 4 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at rectifier station (a) and inverter station (b) in Scenario 1, blue line: SCR at rectifier station is 3; green line: SCR at rectifier station is 2

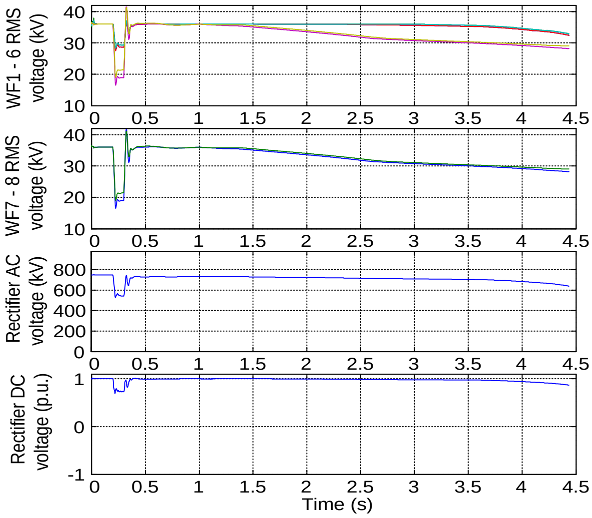
In our studied system, the system cannot get recovery from the fault if a weaker rectifier AC supporting network is connected.

As expected, the results presented in Fig. 4 showed that the transient AC overvoltage is higher (especially for the inverter AC fault) in the system with weaker rectifier AC supporting network (see the green lines in (b) of Fig. 4).

### *D. Different configurations of wind power AC collection grid*

According to 'N-1' security criteria, a system should operate successfully after tripping any single component in the system. As a typical 'N-1' criteria test, a permanent fault applied at bus B2 (see Fig. 1) followed by a trip of one line between bus B2 and B3 (see Fig. 1) after 100 ms was tested.

In the system showed in Fig. 1, two 220 km 750 kV lines are connected in parallel between bus B2 and B3. If a permanent fault occurred at bus B2/B3, one line will be tripped after 100 ms. In the simulations, it was found that the system cannot get recovery from the fault after tripping one line (see (a) of Fig. 5). This is due to the fact that the WTG connection at bus B2 becomes very weak if only one line is connected between bus B2 and B3, even though the transmission capacity of single line is enough (i.e. theoretically, single line could transmit such amount of power). Another case with three 220 km 750 kV lines in parallel connected between bus B2 and B3 was also tested. The system can get successful fault recovery after tripping one line between B2 and B3 (see (b) of Fig. 5)

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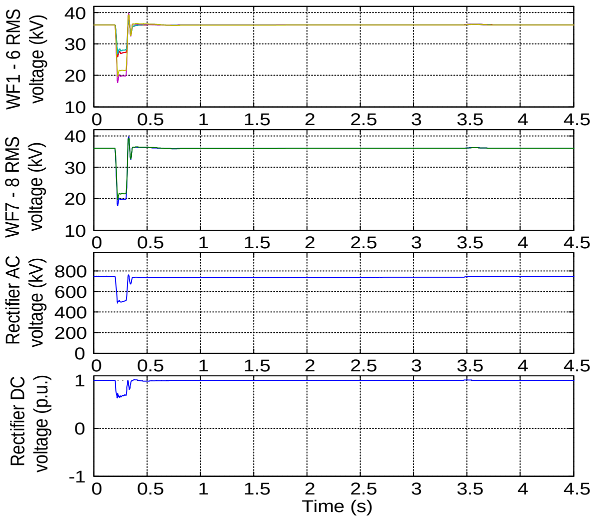



(b)

Fig. 5 A permanent three-phase-to-ground fault (start at 0.2 s and one line between bus B2 and B3 was tripped at 0.3 s) applied at bus B2 in the system of Scenario 1 ((a): two lines connected between B2 and B3 before fault; (b): three lines connected between B2 and B3 before fault)

The phase angle difference, which can indicate the impedance of connected lines, was measured between bus B1 and B3 (Phdiff_B1B3, two 60 km 750 kV lines in parallel connected) and between bus B2 and B3 (Phdiff_B2B3). The results are presented in Fig. 6. The phase angle difference between bus B1 and B3 is around 3.4° before and after fault in both cases. In the system with two lines connected in parallel, the phase angle difference between B2 and B3 jumped from 12.4° before fault, to 27.2° after fault.

If three lines are connected in parallel between B2 and B3, the phase angle difference jumped from 7.9° before fault, to 12.7° after fault (see Fig. 7). Comparing the phase angle difference between B2 and B3 in these two cases (Fig. 6 and 7), it is clearly observed that the B2 to B3 link is too weak to handle the power flow with only one line in combination with the performance of the WTG control even though the transmission capacity of a single line is enough.

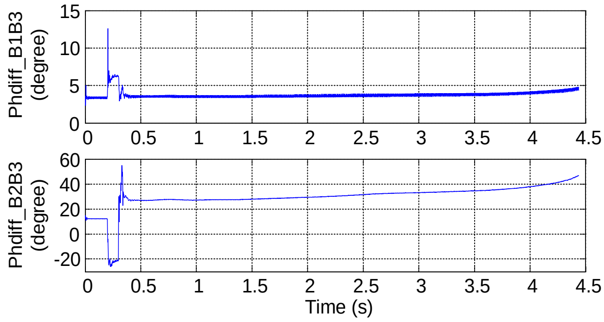



Fig. 6 A permanent three-phase-to-ground fault (start at 0.2 s and one line between bus B2 and B3 was tripped at 0.3 s) applied at bus B2 in the system of Scenario 1 with two lines connected between B2 and B3 before fault

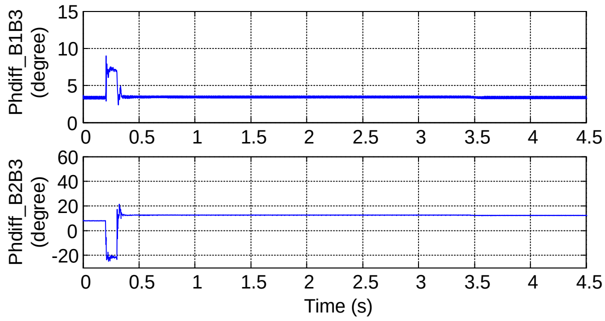



Fig. 7 A permanent three-phase-to-ground fault (start at 0.2 s and one line between bus B2 and B3 was tripped at 0.3 s) applied at bus B2 in the system of Scenario 1 with three lines connected between B2 and B3 before fault

### *E. Impact of a thermal power plant connected to the rectifier AC network*

In this research, a 2 GW thermal power plant is used in Scenario 2 and 4, and is simulated as a synchronous generator. To check the influence of thermal power plant on the system transient performance, a comparison was made between the system with and without thermal power plant for the same type of fault. The simulation results of the system with 100% FPC type WTG and with 75% DFIG type WTG are presented in Fig. 8 and 9 respectively. The following information can be observed from the results showed in the figures:

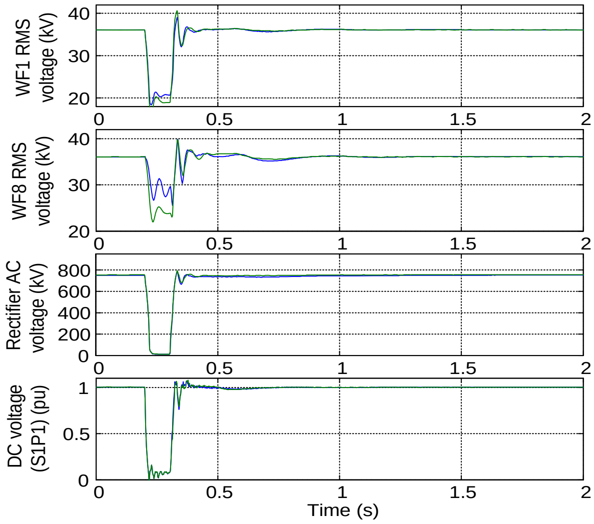
- For the system with 100% FPC type WTG, there is no big difference between the system with and without thermal power plant for a three-phase-to-ground fault occurred at rectifier station. However, the AC voltage at wind farm terminal during the fault is easier to get stable in the system of Scenario 2 (with 2 GW thermal power plant) because of the stronger rectifier AC network (the thermal power plant increased the strength of rectifier AC network). For a three-phase-to-ground inverter ac fault, the AC overvoltage occurred at wind farm terminals (WF5 – WF8) is higher in the system of Scenario 2 (with 2 GW thermal power plant). These results are obtained by using the same controller parameters of wind converters in the system with and without thermal power plant.

- For the system with 75% DFIG type WTG, the transient AC overvoltage at the wind farm terminal is lower and the system stabilizes faster after fault release in the system of Scenario 4 (with 2 GW thermal power plant) (see green line in (b) of Fig. 9). This is due to the strength of rectifier AC network is increased because of adding thermal power plant and reducing the wind power output.

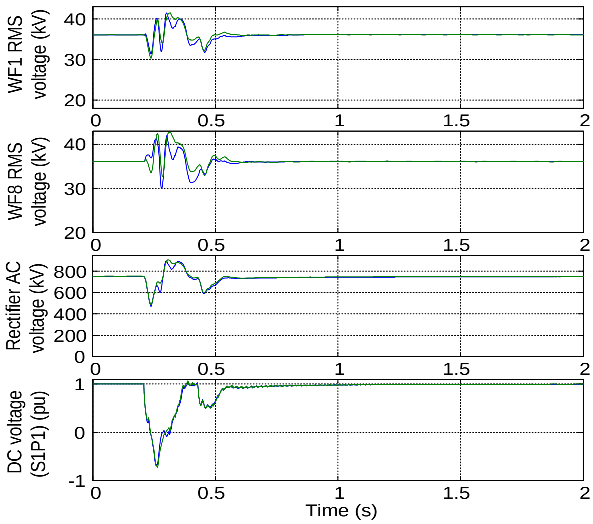
Comparing the results obtained in the system with 75% DFIG type WTG with the results obtained in the system with 100% FPC type WTG, the following observations are made:

- From the transient AC overvoltage level (at wind farm terminals) point of view, the controller response speed of FPC is more sensitive to the strength of rectifier AC network.

- From the fault recovery point of view, the system with FPC type WTG is faster to get fault recovery.




(a)

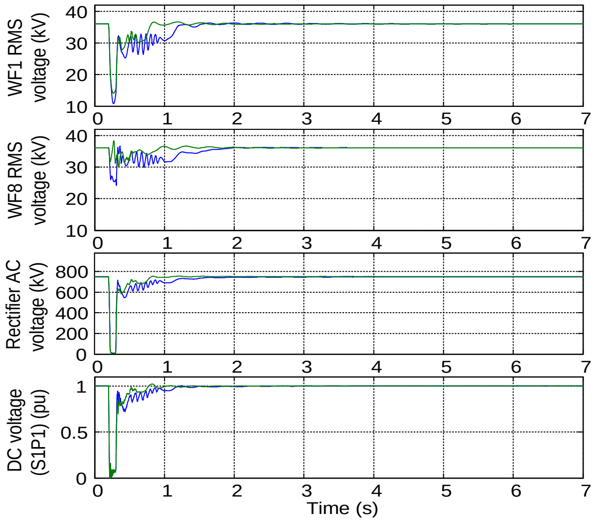



(b)

Fig. 8 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at rectifier (a) and inverter station (b), blue line: Scenario 1; green line: Scenario 2

## IV. Influence of Wind Converter Parameters on Transient Stability

In a large scale onshore wind power transmission system, the AC overvoltage level is one of the sensitive factors for transient stability. This is due to the fact that the wind converters are more sensitive to overvoltage than other conventional equipment, e.g. transformer etc. According to Chinese grid code [2], the wind converter will trip if the AC voltage is higher than 1.2 p.u.

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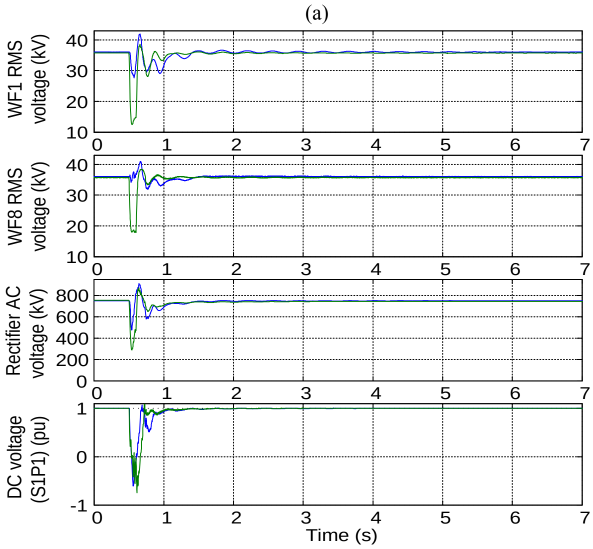


(b)

Fig. 9 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at rectifier (a) and inverter station (b), blue line: Scenario 3; green line: Scenario 4

Looking at the RMS voltage at WF1 and 8 terminal showed in (b) of Fig. 4, the AC overvoltage of green lines (rectifier AC system with SCR of 2) caused by fault is higher than 1.2 p.u. To explore ways to limit the AC overvoltage at wind farm terminal, the following two simulation cases were made and compared in the system of Scenario 1 (SCR of rectifier AC system is 2).

- Case 1: Wind converter with fast controller response
- Case 2: wind converter with slow controller response

The detailed controller parameters used in these two cases are presented in table 1. A three-phase-to-ground fault was applied at the inverter station in these two cases. The simulation results are presented in Fig. 10. Comparing the results obtained from these two cases, it is found that the transient AC overvoltage at wind farm terminal could be limited by slowing down the controller response speed of wind converter.

By testing more cases in our research, it is proved that the AC overvoltage at wind farm terminal could be limited if the controller response speed of wind converter could adapt well enough to rectifier ac system strength. The controller response of wind converter should be slower if the rectifier ac system is weaker, which is similar finding as [4]. More methods to limit the AC overvoltage at wind farm terminal are discussed in [3].

Table 1 The controller parameters used in FPC for the tested two cases

| Controller parameters of wind converter (FPC) | | Case 1 | | Case 2 | |
|---|---|---|---|---|---|
| | | WF1-4 | WF5-8 | WF1-4 | WF5-8 |
| PLL | Kp | 1 | 1 | 0.01 | 0.01 |
| | Ti | 5 | 5 | 100 | 100 |
| Current controller of GSC | Kp | 2 | 2 | 0.5 | 0.1 |
| | Ti | 0.1 | 0.1 | 1 | 5 |
| DC voltage controller of GSC | Kp | 0.3 | 0.3 | 0.1 | 0.001 |
| | Ti | 1000 | 1000 | 1000 | 1000 |
| Reactive power controller of GSC | Kp | 0.3 | 1.5 | 2 | 5 |
| | Ti | 1000 | 0.4 | 1000 | 1000 |

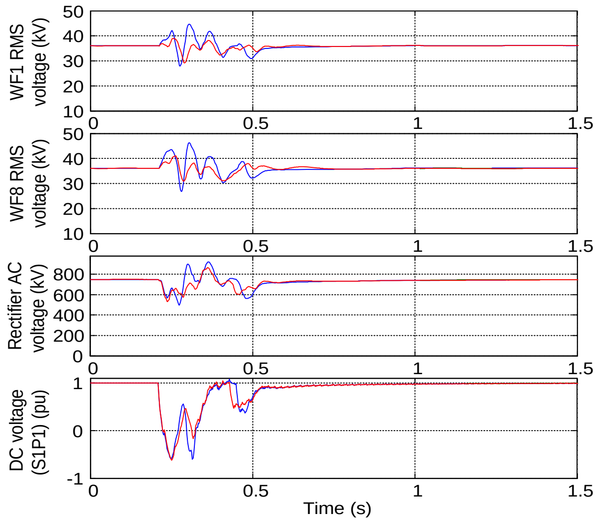


Fig. 10 Three-phase-to-ground fault (start at 0.2 s and release at 0.3 s) applied at inverter station in the system of Scenario 1, blue line: case 1; red line: case 2

## V. Conclusions

An evaluation of the transient stability of a large scale onshore wind power LCC HVDC transmission system was done, and the results are presented in this paper. Based on the time domain simulations, the main conclusions could be drawn as below:

- The rectifier AC system strength, the configuration of wind power collection AC grid and the controller response speed of wind converters are important factors to significantly affect the transient stability of this type of system.
- Comparing with AC fault occurred in rectifier AC system, the AC fault occurred in inverter AC system is a more serious fault due to large amount of excessive reactive power in this system.
- The system cannot get successful fault recovery if the rectifier AC network is too weak (e.g. SCR lower than 2 in our studied system).
- To limit the AC overvoltage caused by fault at wind farm terminal, the controller response speed of wind converters should adapt to the strength of rectifier AC system. The controller response speed of wind converter should be slow if the rectifier AC network is weak.

## References


[1] Xiaobo Yang, Chengyan Yue and Hailian Xie, "An Aggregation Method of Permanent Magnet Synchronous Generators Wind Farm Model for Electromagnetic Transient Simulation Analysis", Power System Technology, Vol. 35, No.2, Feb. 2011

[2] GB/T 19963 – 2011, Technical Rule for Connecting Wind Farm to Power System, Dec. 2011

[3] Rong Cai, Mats Andersson and Hailian Xie, "Methods for Transient AC Overvoltage Reduction at Wind Farm Terminal," Proceeding of 2016 China International Conference on Electricity Distribution (CICED 2016), 10 – 13 Aug. 2016, Xi'an, China

[4] Australian Energy Market Operator, 'Wind Turbine Plant Capabilities Report – 2013 wind integration studies', 2013