Investigation and Simulation Study on the Cascading Trip-off Fault of a Large Number of Wind Turbines in China on May 14, 2012

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Abstract – The integration of the large-scale wind power brings great challenge to the stability of the power grid. This paper investigates and studies the fault on May 14, 2012 of the large-scale cascading trip-off of wind turbines in North China. According to the characteristics of the voltage variation, the fault process is divided into three stages: the pre-event stage, the critical stage before cascading, and the cascading stage. The scenes in the fault are reproduced, using the full-size actual power system model. Simulation models of double-fed induction generators (DFIGs) and SVCs including protection settings and controller strategies are carefully chosen to find out the reason of voltage instability in each stage. Some voltage dynamic that have never been observed before in the faults of the same kind are analyzed in detail, and an equivalent voltage sensitive dynamic model of DFIG is proposed for the fast computation. The conclusions about the voltage dynamics are validated by the actual PMU observation evidence.

Keywords: Wind power, Fault analysis, Cascading trip-off, Voltage instability, Overvoltage

1. Introduction

As the most promising type of new clean energy, wind power has attracted the worldwide attention. Up to June, 2014, the worldwide wind capacity had reached 336GW [1]. With the increasing of wind power, its effects on system operation have become more and more prominent. In recent years, accidents that incurred trip-off of large-scale wind turbines have been reported in countries [2]. Large-scale wind power bases of GW level have been constructed in China, and the wind power has been transmitted to the HV and EHV systems via long distance lines. These weak transmission systems are often threatened by voltage instability. It was reported that there had been 205 times of faults or failures in China from 2011 to 2012 [3].

Many research has contributes to the voltage stability of the large wind power system, such as the structural bifurcation analysis [4], the stability margin estimation [5-6], and the approaches to improve the voltage stability [7-8]. [9] analyzed the impact of wind power in the Jeju Island Power System. [3] studied the mechanism of the cascading trip-off of wind turbines and analyzes the process of the failure. [10] proposed a methodology based on a Z-bus algorithm to assess the tripping status of wind farms before the fault. Those researches were carried out in the simplified systems, and they could provide useful

information, but only some basic fault scenarios were modeled. The simulated results could hardly figure out the complicated situations of the actual system. Few papers have been found in the instability analysis of the large wind power whose simulation model could be validated by the measured data. [11] provided the comparison between the measured and simulated curves during the voltage dip, but the case was much simpler than what occurred in China.

In the fault analysis, it is essential to find out the inherence of the instability and identify which is the most dangerous risk factor. However, in the actual system, many protection and control strategies would be put into use once the system is suffering from serious disturbances. The dynamic process could be interrupted or changed. It is hardly observed that the measured waveform matched the simulated one. On the other hand, some unusual dynamic processes could be observed and they could not be explained by conventional models, so the new models must be proposed to reveal what really happened.

Based on the actual PMU records, this paper investigates the entire process of one cascading fault in North China on May 14, 2012. The scene of the fault is then elaborately reconstructed to analyze the reason of voltage instability. Some slow dynamic characteristics of the voltage were observed for the first time in the PMU records, and then its mechanism is simulated based on the proposed voltage sensitive model of DFIGs.

Section 2 introduces the grid configuration of the wind power base. Section 3 describes the fault evolution by dividing it into three stages: the pre-event stage, the critical stage and the cascading stage. Section 4 analyzes on the voltage stability of different stages qualitatively. Proper simulation models of multi-time scales are carefully chosen

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to reproduce the fault scene in Section 5, using the topology structure, parameters, protection settings and control strategies of the actual power grid. Conclusions are drawn in Section 6.

2. The Structure Features of the Wind Power Base

On May.14, 2012, a severe fault occurred in North China power grid, resulting in the cascading trip-off of 584 wind turbines in 15 wind farms with the loss of 737.1MW wind power in total. [12].

Fig. 1 shows the power grid before the fault, and the grid was the transmission system composing of the 500kV-level subsystem and the 220kV-level subsystem. 23 wind farms were connected to the A, B, C, and D gathering substations via 220kV or 110kV bus, and then wind power was transmitted to North China Power Grid through two main transformers with the capacity of 750MVA. At that time, the wind power base had 1191 wind turbines with the rated capacity of 2133MW totally. The grid was the pure wind power integration system without any load or synchronous generator, and the total length of all transmission lines of the system was over 700km.

All 23 wind farms were equipped with dynamic

Fig. 1. The grid of the wind power base

Table 1. Reactive power compensation of gathering stations

Gathering Station	Capacitor group		Reactor group	
	Group	Capacity of each bank	Group	Capacity of each group
A	8	10Mvar	4	10Mvar
B	8	12Mvar	4	12Mvar
C	/	/	/	/
D	4	60Mvar	/	/

reactive compensation devices, static var compensators (SVCs), or fixed capacitors and reactors, which were connected with 35kV buses. Table 1 shows the reactive power compensation of all gathering substations.

3. Investigation on the Cascading Trip-off Fault

There were 4 turning points in the process of the fault:

- (1) Since 13:20:00, the output power of all wind farms increased rapidly and then the load flow grew, which led to the reduction of the system voltage. In order to recovery the voltage level, both the gathering substations and the wind farms increased their capacitive compensation. The cut-off operation of reactors and the cut-in operation of capacitors resulted in drastic voltage fluctuation.
- (2) At 13:41:16, a capacitor branch with the capacity of 23.76Mvar in the A-2 wind farm was put into operation, and then the system voltage kept increasing slowly.
- (3) About 5.5 seconds later, at 13:41:21.5, the voltages of some points of common coupling (PCC) exceeded the threshold of the overvoltage protection of wind turbines, and subsequently a large number of wind turbines tripped off in the cascading mode. The loss of a large amount of real power finally incurred frequency decreasing.
- (4) At 13:41:31, the reactive compensation devices gradually quitted due to overvoltage protection, and the system voltage restored to normal.

According to the four turning points, the total process of the fault is divided into four stages. The paper introduces the first three stages in detail.

3.1 The Pre-event stage of the power system

The stage was called the pre-event stage in the time range from 13:20:00 to 13:41:16. The output of wind power increased in general, although it declined for a very short time with the decreasing of the wind speed. Fig. 2 shows the active power flow from A-B and B-D, respectively.

At 13:31:00, the active power output increased more rapidly, resulting in more reactive consumption of transmission lines and the significant reduction of common coupling bus voltages (Fig. 3). The reactive power compensation devices of substations and multiple wind farms were put into operation to recover the voltage. The system voltage fluctuated with the repeating on/off operation of capacitors, as shown in Fig. 4.

3.2 The critical stage before cascading

As the system voltage was low, a capacitor branch of

Fig. 2.The active power flow before cascading

Table 2. The step changes of 220kV buses of substations

Gathering Substation	220kV Bus Voltage	
	Before	After
A	208kV	216kV
B	205kV	209kV
D	214kV	215kV

23.76Mvar in the A-2 wind farm was put into operation at 13:41:16.840, resulting in step changes of the voltages of all 220kV gathering stations bus, as shown in Table 2.

Fig. 5. The active power kept constant when the voltage increased gradually

Fig. 6. The voltage increased slowly

later, respectively. Those actions of SVCs could not incur the system voltage changing in such a mode. The process could be neither caused by the reactive power from wind turbines, since the reactive output of wind turbines also kept zero.

The stage was, in fact, affected by the response of the active power of some DFIGs when the voltage changed. It would be explained in detail in Section 5.

3.3 The stage of cascading

At 13:41:22.220, the terminal voltage of A-3 and A-4 increased to more than 110% of their voltage rating, which was the threshold of overvoltage protection of wind turbines. Wind turbines of A-3 and A-4 tripped off at once. With the loss of the active power from the off-grid turbines, the reactive power became redundant, which caused the system voltage to increase to a higher level.

Like the domino, the cascading fault started. More and more wind turbines were forced to cut off due to overvoltage protection, and the system voltage grew higher and higher. The highest voltage was 263.173kV in the substation A, 251.496kV in B, and 236.069kV in D, as shown in Figure 6. In 2s, 584 wind turbines of 15 wind farms tripped off with the total loss of 737.1MW. Fig. 7 shows the time sequence of the wind turbine tripping (starting at 13:41:22.220).

After 8s later, reactive compensation devices quitted

Fig. 7. The time sequence of wind turbine tripping (starting at 13:41:22.220)

Fig. 8. The frequency fluctuations of the substation A

operation one by one due to their overvoltage protection, and recovered the system voltage to normal.

Due to the loss of a large amount of active power, the system frequency reduced. The lowest frequency in the 220kV-level HV transmission system was 48.992Hz (observed in the substation A), 49.149Hz (in B), and the lowest frequency in the 500kV-level EHV was 49.762Hz (in D). The process of frequency fluctuations of the substation A is shown in Fig. 8. At the end of cascading, the system frequency was gradually restored to normal.

4. Voltage Stability Analysis in Each Stage

Based on the investigation, we can find out that this cascading fault expanded with the voltage changes, then incurred in system frequency fluctuation. The voltage change was the key factor to promote the fault evolution.

Many factors had impacts on the system voltage, including compensative devices, DFIGs and their protection settings and control strategies. They played different roles in each stage, and resulted in multi-time-scale dynamics of the voltage.

According to its time scale, voltage stability can be classified into 3 categories: static voltage stability, transient voltage stability and long-term voltage stability [13]. Therefore, it is essential in the fault analysis to identify of the nature of voltage stability in each stage.

4.1 The Pre-event stage

In this stage, the system ran near the extreme point of static voltage stability. Almost all capacitive compensation, including fixed capacitors and SVCs, had been put into use till the end of this stage. The system voltage fluctuated seriously, but it could still be corrected. The scene of the

voltage profile shown in the PMU records could be reconstructed on the basis of the load flow model, using the P-U and Q-U sensitivity analysis method. See the detailed analysis in Section 5.1.

4.2 The critical stage before cascading

It is a little difficult to identify the category of voltage instability in this stage. At first, the system voltage increased simultaneously once the 23.76MW capacitor group was switched on, and then kept increasing for 5.5 seconds. Such dynamics of the system voltage was unusual, because its mechanism could not be explained by the conventional theory of voltage stability: First, it was almost impossible incurred by static voltage instability, because it has been calculated that the system still had margins to the extreme point of the PV curve (the well-known “nose curve”) before the cascading fault.

Second, it could be hardly classified into transient voltage instability. Recently, dynamic bifurcation theory has been widely used in analyzing transient voltage stability in the power system with DFIGs [4]. Types of bifurcation have been revealed in numerical simulation, including Limit Induced Bifurcation (LIB), Singular Induced Bifurcation (SIB), Period bifurcation (PB). However, bifurcation theory was hardly helpful, because there were some doubts: (1) Time scale and the voltage profile. Once LIB and SIB happens, the voltage almost *collapses instantaneously*, whereas the voltage in this case kept *increasing for seconds* before out of control. (2) The generator portfolio: The power system that is threatened by LIB or SIB always consists of *synchronous generators* or *motors*, whereas the system in this case was composed of nearly pure *wind turbines*.

Finally, the fault was also impossible incurred by the long-term voltage stability, because the typical duration range of long-term voltage stability is for a few minutes, typically for 2-3min or longer. The possibility was also excluded after the investigation, because none of equipment (such as heat load, under-load tap changer) that could response in the same time scale had taken action.

It is deduced that this stage did not fall in any known type of voltage instability. It probably belongs to mid-term voltage dynamics. DFIGs and SVCs should have participated in the system dynamics. See the detailed analysis in Section 5.2.

4.3 The stage of cascading trip-off of wind turbines

Since the voltages had reached the threshold of over-voltage protection of wind turbines, some wind turbines tripped off and the wind power through transmission lines decreases significantly. At the same time, the reactive power compensation devices still kept working because of their longer protection delay and higher protection threshold, which resulted in more wind turbine trip-off due

to the overvoltage protection in the repeated mode. This process is known as the common mode tripping of wind turbines [14].

Previous studies have provided a thorough inventory of the theory analysis and simulation verification of the common mode tripping of turbines. This paper no longer makes a detailed analysis.

5. Simulation Models and Reproduction Studies

According to the actual data, we have reconstructed the scene that day using the MATLAB Power System Analysis Toolbox (PSAT) [15]. Based on the PMU recording data, the pre-event power flow conditions are elaborately adjusted to match the actual situations.

5.1 Reproduction study on voltage fluctuations in the Pre-event stage and the cascading stage

The voltage fluctuation in these two stages can be simulated based on power flow models. Some remarks:

- (1) DFIGs are taken as the negative constant PQ load;
- (2) SVCs that work in the constant voltage mode are taken as the PV nodes with Q limits; SVCs that work in the constant Q mode are taken as the negative constant PQ load; SVCs that have reached their limits are taken as the constant shunt capacity branches.
- (3) The 500kV bus of the substation D is strong enough, so it is taken as the slack bus.

Suppose that there are N nodes in the system, including 1 slack bus, r PV nodes and $n-r$ PQ nodes ($n = N-1$). The linearization of the power flow equation is as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = - \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \theta \\ U^{-1} \Delta U \end{bmatrix} \quad (1)$$

where ΔP and ΔQ denote the increment of active and reactive power, respectively; $\Delta \theta$ is the increment of voltage phase angle; ΔU denotes the increment of voltage amplitude; U is the node voltage; H, N, M, L denote the four sub-block matrixes of the Jacobian matrix.

In a particular operating point, let $\Delta P = 0$:

$$\begin{aligned} 0 &= -H\Delta\theta - NU^{-1}\Delta U \\ \Delta Q &= -M\Delta\theta - LU^{-1}\Delta U \end{aligned} \quad (2)$$

Eliminate $\Delta \theta$ in Eq. (2):

$$U^{-1}\Delta U = (MH^{-1}N - L)^{-1}\Delta Q = S_{uQ}\Delta Q \quad (3)$$

Where S_{uQ} is the Q-U sensitivity matrix whose element denotes the voltage change ΔU with respect to the injection change of the reactive power ΔQ .

The Q-U sensitivity can be used to analyze the voltage fluctuation caused by reactive device operations in Section 3.1. For example, as the reactive power in any wind farm that is connected with the substation A increases or decreases 1Mvar, the simulated voltage changes in the 220kV bus are ranged from 5.3-5.5kV, which matches the PMU recorded data well. The similar verification can be done in other wind farms.

Similarly, assume $\Delta Q = 0$:

$$\begin{aligned} \Delta P &= -H\Delta\theta - NU^{-1}\Delta U \\ 0 &= -M\Delta\theta - LU^{-1}\Delta U \end{aligned} \quad (4)$$

Eliminate $\Delta\theta$ in Eq. (4):

$$U^{-1}\Delta U = (-MH^{-1}N + L)^{-1} \times MH^{-1}\Delta P = S_{up}\Delta P \quad (5)$$

Here, S_{up} is the sensitivity matrix whose element denotes the voltage change ΔU with respect to the injection change of active power ΔP .

The P-U sensitivity can be used to analyze the voltage fluctuation caused by the active power loss from wind turbines in Section 3.3. For example, as the active power output of any wind farm connected to the substation A decreases 1MW, the simulated voltage changes in the 220kV bus are ranged from 4.7kV-5.7kV, which matches the PMU recorded data well. So does other wind farms.

5.2 Reproduction study on Mid-term voltage dynamics in the critical stage

The voltage dynamics in this stage was affected by the slow dynamics of some DFIGs. This subsection will reveal how the conclusion is drawn.

The DFIGs are handled in two ways:

- (1) Some are taken as the negative constant PQ, because the PMU data had shown that those DFIGs kept constant when the voltage changed, identical with the ideal constant PQ model. The DFIGs of this type was up to 53.1%.
- (2) Other must be modeled with dynamic response. The PMU records had shown that the response of their active power was sensitive to the voltage, whereas the reactive power almost kept unchanged. The active power increased simultaneously when there was a step increment in the voltage, and then gradually restored to the original value (as shown in Fig. 9). The DFIGs of this type was up to 46.9%.

First, we use the full order model [16] to simulate the DFIGs of the second type. Based on the stator-flux-oriented vector control method, the DFIG rotor-side

Fig. 9. The response of the active and reactive power of wind turbines to the voltage changes

Fig. 10. The control model of the DFIG rotor-side converter

Fig. 11. The responses to the step voltage increment based on the full order model

converter applies decoupled control to the active and reactive power, which is achieved by regulating the rotor current to control the rotor voltage. The response of the active power is decided by the proportional gain (K_{p2}) and integration gain (K_{i2}) of DFIG rotor-side converter [17]. The control model of the DFIG rotor-side converter is shown as Fig. 10.

Using the full-order model, we can simulate the response of the active and reactive power of a DFIG with respect to the step voltage increment, and their profiles are verified to match the PMU records well, as shown in Fig. 11.

Although the dynamics of DFIGs could be reproduced well using the full-order model, it was almost impossible to reconstruct the scene with it, because there were 1191 wind turbines of 23 wind farms in the system; it was impossible to collect all control strategies and their parameters of

various wind turbines, since they were protected by some commercial secrets. According to the measured response of wind turbines, an equivalent dynamic load model is recommended in this paper [18]. The mathematical model is as follows:

$$\dot{x}_P = -x_P / T_P + P_s - P_t \quad (6)$$

$$P = x_P / T_P + P_t \quad (7)$$

$$P_s = P_0 (V / V_0)^{\alpha_s} \quad (8)$$

$$P_t = P_0 (V / V_0)^{\alpha_t} \quad (9)$$

Where P denotes the active power variable of the DFIG, P_s denotes the static component, and P_t denotes the transient component, and P_0 denotes the steady value; V denotes the voltage of the DFIG stator, and V_0 denotes the steady value, too. The active power of the DFIG is sensitive to the stator voltage, so α_s and α_t denote static exponent and transient exponent; T_P represents the time constant. x_P is defined as a middle variable whose dimension is energy.

Again, using the equivalent model, we simulate the response of the active and reactive power of a single DFIG, shown in Fig. 12. Except the high frequency component that decays quickly, the profile matches in general.

The mathematical model of the SVC is as follows [15]:

$$\dot{b}_{SVC} = (K_r (V_{ref} - V) - b_{SVC}) / T_r \quad (10)$$

where T_r is the time constant, K_r denotes the magnification of the SVC, V_{ref} and V are reference voltage and compensation point voltage, and b_{SVC} is the equivalent susceptance of the SVC.

The reactive power of the SVC is:

$$Q = b_{SVC} V^2 \quad (11)$$

The scene is simulated by two means: *Case A* uses the negative constant PQ loads to model all wind turbines; *Case B* uses the proposed model.

Fig. 12. The response to the step voltage increment based on the proposed model

Fig. 13. The reproduction of the voltage profile of the substation A (Case A: Constant PQ model)

Fig. 14. The reproduction of the voltage profile of the substation A (Case B: the proposed model)

In Case A, Fig. 13 compares records and simulated data (the 220kV bus voltage of the substation A). Obviously, the voltage profile does not match in the following aspects:

- (1) The initial value of the voltage change (t_{0+}). The simulated value is much larger than that in the record.
- (2) The dynamic response of the voltage. Only a step-response-like process can be found in the figure.

We also simulate the same scene using the proposed equivalent dynamic load model. The comparison between the records and simulated curve is shown in Fig. 14. Two curves match much better. We can conclude that the slow response of the active power of some DFIGs had contributed to the slow increasing of the system voltage. In general, it was not the dangerous factor of voltage instability. On the contrary, it was helpful to prevent the system voltage from increasing too quickly.

6. Conclusion

Based on PMU records, this paper has investigated the entire process of the cascading trip-off fault in North China on May 14, 2012, and analyzed the mechanism of the voltage instability through the scene reproduction. The conclusion is summarized as follows:

- (1) The severe fault could be divided into three stages: the pre-event stage, the critical stage before cascading, and the cascading stage. The voltage change was the key to affect the evolution of the fault.
- (2) The voltage fluctuation in the pre-event stage was mainly caused by the operation of reactive compensation devices and wind speed variation; the slow increasing of the voltage in the critical stage was affected by the dynamics of the active power of some DFIGs; the overvoltage was enhanced by the loss of wind turbines, and then conversely higher overvoltage resulted in more tripping of turbines.
- (3) In the reconstruction, most of DFIGs can be taken as the negative constant PQ load, whereas some DFIGs should be handled with nonlinear dynamic characteristics. This paper has proposed the equivalent voltage sensitive dynamic model for fast computation. Simulation has validated the model. In this case, DFIGs were helpful in voltage stability.

The large-scale wind turbine cascading trip-off accident happens sometime, which is closely related to the factors such as the grid structure, wind turbine operation modes, and control strategies of reactive compensation devices. The dynamic process of the fault could be quite complex, and more work must be done in modeling the actual system.

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