Reactive power characteristics analysis on emergency stop of doubly fed induction generator

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Abstract. This paper analyzes the reactive power characteristics of the doubly-fed induction generator (DFIG) during the emergency off-grid process caused by the crowbar protection action. Since the action of the crowbar is much faster than the stator switching, the DFIG would be running with a short-term squirrel cage asynchronous operation. The mathematical model of the DFIG under above situation was proposed in this paper, based on which detailed analysis was given on reactive power demands during squirrel-cage asynchronous state of the DFIG. It is achieved that the amount of reactive power absorption was associated with the initial operating conditions such as the terminal voltage and speed before disconnection, which can be prescribed as the s-Q characteristic of DFIG. Finally, analysis on the measured data of the wind farm disconnected event verified the validity of the model.

1. Introduction

As the most principal means of generating power as non-hydro renewable energy generation presently, wind power is an important way to solve the world wide problems such as the crisis of fossil fuel, environmental deterioration, and so on.

Doubly Fed Induction Generator (DFIG) has been extensively employed in most wind farms for its high wind energy conversion efficiency and flexible active and reactive power control[1-3]. Nowadays, the DFIG in domestic wind farms were operated under unit power factor, which could not supply additional reactive power to the grid. In order to satisfy the generator operating voltage requirement, wind farm usually disposed reactive compensation according to the reactive requirement of the main transformer when the wind farm under rating output. However, which did not take the reactive requirement of the wind farm collect system into consideration, such as booster transformers of wind turbines and cluster lines within the farm.

It is generally considered that a lack of reactive power occurs when the wind farm output is in a high situation, and the reactive compensation disposition mentioned above can not satisfy the reactive power requirement of the main transformer and the collecting system simultaneously. It will cause the PCC voltage obviously declined and further the wind turbine low-voltage protection operating, which result in the generators disconnecting from grid. Therefore, the study aimed at improving the reactive level of wind farm presently, mostly considers excavating the reactive compensation ability of the DFIG, as shown in [4-9].

However, by analyzing the measured data of one certain wind farm disconnecting from the power grid, it was recorded that the PCC voltage was under high level before the disconnecting, which would not trigger the low voltage protection of wind turbine (usually 0.8-0.9pu). It indicates that the above explanation can not explain the generators disconnecting from grid for the lack of reactive compensation.

This paper is to present another possible reason for the disconnecting event by analyzing the difference between the stator and the rotor circuit switching characteristics after the crowbar protection has been triggered.

2. Wind farm disconnecting event overview

The main electrical wiring of the wind farm occurring the disconnecting event is showed in fiigure 1. The wind farm includes two subsets (1#, 2#), the area is about 80 km2, and the total installed capacity is 400MW. Among them, 1# wind farm owns 251 Gamesa G58-850kW wind turbines, 2# wind farm owns 134 SL1500kW-77 wind turbines, all rated voltage 690V; wind farm collect system, including booster transformer and collecting lines, which rating voltage is 35kV.

The 1# wind farm is connected to 1# 220kV bus at the booster substation by four 6.3MVA booster transformers, and the 2# connected to 2# 220kV bus by two 10MVA booster transformers. The parameter of the line between the wind farm and the 1# 220kV substation is LGJ-240*2-100km, while the line between 1# substation and 2# substation is LGJQ-400-34.5km.
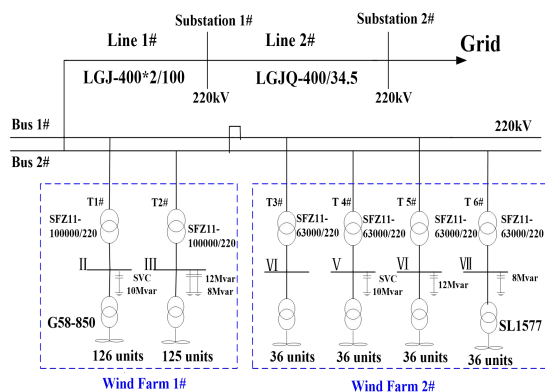

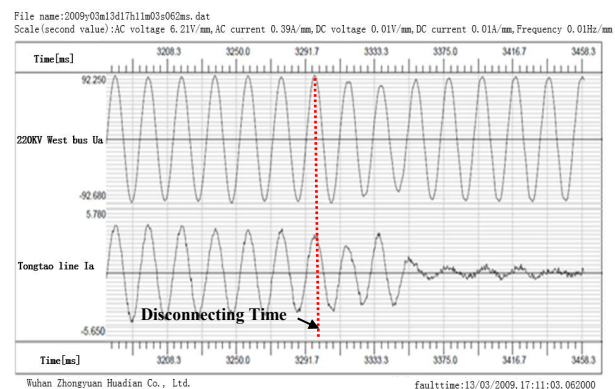**Figure 1.** Main Wiring Diagram of the concerned wind farm.

Figure 2. Record diagram of 220kV substation on current and voltage of phase A.

Under normal operation, every wind turbine is running with unit power factor. To ensure outlet bus voltage level of wind farm, reactive compensation equipment had been disposed at low voltage side (35kV) of each main transformer.

Figure 2 records the wind farm booster substation 220kV bus voltage and the changes of 1# line current, during the wind farm disconnecting from grid. The vertical line in figure 2 shows the disconnecting time. On the basis of the operators taking notes, the disconnecting event caused 1# wind farm, 2# main transformer and 125 units into outages. Short time later, all the turbines were off grid.

Outlet bus voltage of wind farm before the event was high to 1.1pu. The reactive compensation disposed could satisfy farm collect system, and the wind farm did not absorb reactive power from grid, which can be calculated by the data of figure 2. After the disconnecting time, the wind farm booster substation bus voltage appeared obvious fluctuation and three cycles later, all the wind farm turbines disconnected from grid.

The above analysis indicates that the reason reactive compensation lacking resulting in wind turbines disconnecting from grid can not explain the fact generators still disconnected from grid with high voltage (1.1pu). So a further analysis needs to be done to give reasonable explanation.

3. Squirrel-cage asynchronous operating characteristics of doubly fed induction generator

DFIG-based wind turbines mainly include wind turbine, doubly fed induction generator and four-quadrant converter and so on. Figure 3 is the schematic structure.

When the crowbar protection of rotor circuit has been triggered, the DFIG would get into emergency stop as following operating logic.

The three-phase rotor wiring of DFIG are short circuited after the crowbar protection started, meanwhile, the four quadrant converters quit. The execution element of the switch is the power electronic switch (Thyristor or IGBT) with microsecond-class action time.
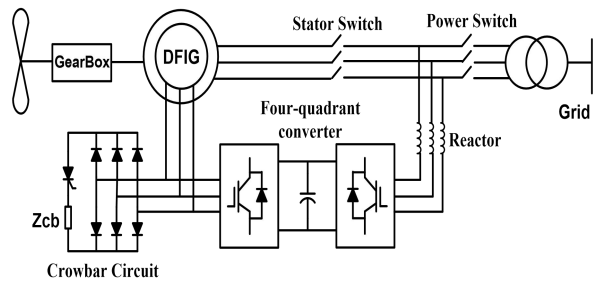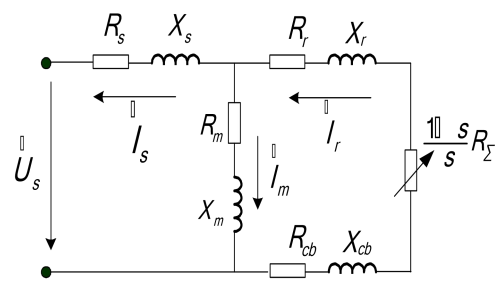

Figure 3. Configuration of DFIG.

Figure 4. Equivalent circuits of a DFIG after crowbar action.

The stator circuit directly starts the stator grid-connected contactor and the execution element is mechanical switch, the action time is several milliseconds.

Therefore, as the crowbar protecting operates in very short time (microsecond-class) while the time for stator contactor to break off is longer (millisecond-class), the stators remain connecting with the grid for 50~70ms, after the crowbar protection started and the rotor converters been short circuited. At the moment, the DFIG was operating on squirrel-cage asynchronous state.

Nowadays, study concerning the mathematical model of DFIG-based wind turbines is various[10-12]. In order to analyze the operating characteristics after the physical construction of DFIG has changed, this paper builds the mathematical model of DFIG on squirrel-cage asynchronous state during disconnecting process, based on previous studies.

The equivalent circuit diagram of DFIG on asynchronous condition after the crowbar protection performed is showed in figure 4, and the corresponding model in dq coordinates, is showed as formulas (1) (2) (3).

$$\begin{cases} U_{sd} = R_s(-i_{sd}) - \omega_l \psi_{sq} \\ U_{sq} = R_s(-i_{sq}) + \omega_l \psi_{sd} \\ U_{rd} = 0 = R_r^{'} i_{rd} + d\psi_{rd}/dt - \omega_s \psi_{rq} \\ U_{rq} = 0 = R_r^{'} i_{rq} + d\psi_{rq}/dt + \omega_s \psi_{rd} \end{cases} \qquad (1)$$

$$\frac{T_j}{N_p} \frac{d\omega_r}{dt} = T_m - T_e \qquad (2)$$

$$\begin{cases} \psi_{sd} = L_s(-i_{sd}) + L_m i_{rd} \\ \psi_{sq} = L_s(-i_{sq}) + L_m i_{rq} \\ \psi_{rd} = L_m(-i_{sd}) + L_r i_{rd} \\ \psi_{rq} = L_m(-i_{sq}) + L_r i_{rq} \end{cases} \qquad (3)$$

The formula $R_r^{'} = R_r + R_{cb} + (R_r + R_{cb})(1-s)/s$; s is the slip ratio; ψ_{sdq}, ψ_{rdq} are respectively the magnetic flux linkage of the stator and the rotor of DFIG.

Owing to the converters that provide the generators with excitation have quitted, the generators must absorb plenty of reactive power for maintaining the present operating condition. According to asynchronous motor operating characteristics, the reactive power the grid needs to supply is as follows.

$$Q = \sqrt{3}\frac{U_s^2}{|Z_\Sigma|}\sin\varphi_S \tag{4}$$

where,

$$Z_\Sigma = Z_s + \frac{(Z_r + Z_{cb})Z_m}{(Z_r + Z_{cb}) + Z_m} \tag{5}$$

Formula (4) is the s-Q characteristics of DFIG on squirrel-cage asynchronous state during disconnecting process, which indicates that the Q is directly related to the grid voltage and rotational speed.
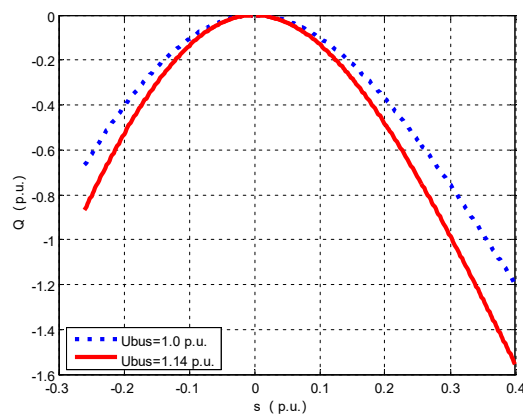

Figure 5. Slip-Reactive power characteristic of DFIG in disconnecting process with different voltage.
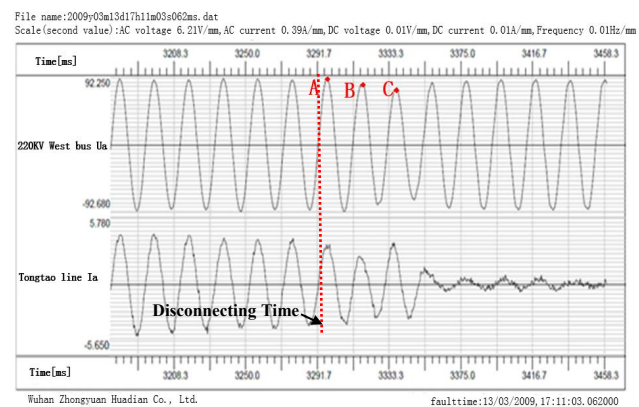

Figure 6. Postmortem analysis diagram of 220kV substation on current and voltage of phase A.

Taking Gamesa G58-850kW wind turbine as an example, since the machine may get into off-grid at different rotational speed or voltage level in practical operating, the reactive power absorbed could be calculated by DFIG at different initial conditions by using formula(4). The two curves in figure 5 respectively shows the s-Q characteristics of G58 generators during disconnecting process with different outlet voltage (1.0pu, 1.14pu) and rotational speed.

Figure 5 indicates the DFIG do not absorb reactive power from the grid only when the rotational speed is synchronous speed before disconnecting time, other rotational speed are opposite. The bigger the slippage is, the more reactive power is absorbed. Under the rated voltage, the slip ratio of Gamesa G58-850kW wind turbines is 0.4(corresponding starting speed 900 rpm) before disconnecting and the maximum reactive power absorbed from the grid reaches 1.2 times as much as generator rated rating.

4. Postmortem of wind farm disconnecting event

This section will make explanation for the process of the wind farm disconnecting event, based on the analysis result of the two sections above.

The obviously fluctuating process of the wind farm booster substation bus bar voltage was showed from A to B in figure 6.

Table 1 gives the recorded data during the adjacent three cycles (from A to C in figure 6) of the disconnecting process, which are the wind farm output active and reactive power, booster substation bus voltage and its phase-angle.

By the analysis of the data recorded by the data acquisition system OPEN3000, the output level of the wind farm was 351MW before the disconnecting event, which has already approached 88 percent of installed capacity (400MW). Taking the wind energy uneven distribution of large wind farm area

into account, most of the wind turbine has been running close to or reach the speed limit at the moment.

Table 1. Wind farm output power and export bus voltage (the datum value: S_B=100MVA; U_B=220kV).

Time	P(pu)	Q(pu)	U(pu)	φ(dec)
A	2.1581	0	1.1411	0
B	1.0592	-0.7616	0.9889	-35
C	1.3967	-1.0148	0.9129	-36

The active power of Gamesa-G58-850kW generator is rated value 850kW at so high wind speed, and the generator rotational speed reaches 1900 rpm. The absorbed reactive power is 595Kvar during the disconnecting process by calculating based on Formula (4). The reason causing the reactive power shortfall during wind farm disconnecting process is analyzed as follows.

1) Form A to B the margin of the wind farm output active power to the power network is ΔP=1.0989pu. Besides PN=0.0085pu, it can be calculated that total 129 generators had disconnected from grid. Because the margin of the reactive power is ΔQ=0.7616pu since QN=0.0059pu, there are 129 units disconnecting from grid, and this moment, the wind farm absorbed reactive power from the grid.

2) Instantaneous large absorption of reactive power by the disconnecting wind generators caused local voltage decreased （ΔU=0.15pu）, and triggered the low-voltage protecting adjacent generators ceased. The development of voltage decline should be an avalanche-like process with an end of all the wind turbines disconnected.

The above analysis shows that the number of the wind turbines disconnecting from grid calculated by the measured data (129 units) is nearly identical to the result recorded by the operators (125 units). Therefore the correctness of the established model and the explanation for the wind turbines disconnecting reason could be verified. The calculation error may come from not taking the loss of the wind farm collect system into consideration.

5. Conclusion

This paper analyses the measured data about one certain wind farm disconnecting from grid under normal voltage level, then reveals one possible reason causing the lack of reactive power during the off-grid process. The conclusions are as follows:

1) After the crowbar protection triggered, there is nearly 50-70ms transient asynchronous time interval due to the different action characteristics between the stator and rotor circuit switches of the DFIG.

2) The asynchronous state of DFIG needs to absorb large reactive power during disconnecting process, and the maximum reactive power absorbed from the grid could reach 1.2 times as much as generator rated capacity.

3) The lack of reactive power caused by wind turbines disconnecting from grid will result in the voltage obviously declined instantly. If the wind farm voltage level is somewhat lower before disconnecting time, part of generators getting into outages will probably causes the adverse consequence with the generators off grid.

4) The analysis of the measured data verifies that the proposed explanation for the disconnecting event is reasonable and correct.

References

[1]   Hao X, Jiang C, Wu L 2015 Based on the Power Factors of DFIG Wind Farm for Power Flow Optimization *Proceedings of the Second International Conference on Mechatronics and Automatic Control* Springer International Publishing 2015 pp 157-65

[2]   Yao-Jia Li, Juan-Juan Wang, Zi-Lin Li and Chuang Fu 2016 VDCOL parameters setting influenced by reactive power characteristics of HVDC system *2016 International Conference on Smart Grid and Clean Energy Technologies* (ICSGCE) Proceedings of. IEEE 2016 pp 364-70

[3]   Li Z, Yang H, Li W 2012 Reactive Power Optimization in Regional Power Grid Considering Voltage and Reactive Power Characteristics of Boundary Buses *Power and Energy Engineering Conference* IEEE 2012 pp 1-4

[4]   Raboni P, Chaudhary S, Chen Z 2016 Design of reactive power regulator of synchronous generators by considering grid impedance angle for characteristic index objectives *Iet Generation Transmission & Distribution* 2016, 10(14) pp 3508-16

[5]   Talavera I, Stepanescu S, Bennewitz F 2015 Vertical Reactive Power Flexibility based on Different Reactive Power Characteristics for Distributed Energy Resources *International ETG Congress 2015;Die Energiewende - Blueprints for the new energy age* Proceedings of. VDE 2015 pp 1-7

[6]   Kumar R, Kumar A 2014 Reactive power cost characteristics for synchronous generator in deregulated electricity markets *Power India International Conference* IEEE 2014 pp 1-6.

[7]   Kraiczy M, Lammert G, Stetz T 2016 Parameterization of Reactive Power Characteristics for Distributed Generators: Field Experience and Recommendations *Int. ETG Congress 2016;Die Energiewende - Blueprints for the new energy age* Proceedings of. VDE 2016 pp1-8

[8]   Yan G, Wang M, Mu G 2008 Modeling of grid-connected doubly-fed induction generator for reactive power static regulation capacity study *Transactions of China Electrotechnical Society* 2008 23(7) pp 98-104

[9]   Fang Y, Liu Q, Hou G 2012 Study of the Reactive Power Characteristics in the Double Fed Variable Speed Constant Frequency Wind Turbine *2012 Asia-Pacific Power and Energy Engineering Conference* IEEE 2012 pp 1-4

[10]   Rezaei-Zare A 2015 Reactive Power Loss Versus GIC Characteristic of Single-Phase Transformers *IEEE Transactions on Power Delivery* 2015 30(3) pp 1639-40

[11]   Fang X, Li F, Wei Y 2015 Reactive power planning under high penetration of wind energy using Benders decomposition *Iet Generation Transmission & Distribution* 2015 9(14) pp 1835-44

[12]   Dai H, Wang Y, Li X 2012 Characteristic Analysis of Reactive Power Compensation Device at HVDC Converter Station *Asia-Pacific Power and Energy Engineering Conference* IEEE 2012 pp 1-5