Research on Reactive Power Compensation Configuration of Wind Farm Integration

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Abstract. The large-scale wind power integration into power system brings great impact on the grid voltage stability. In order to reduce the influences of grid-connected wind power on the power system and improve the safety of wind power integration, it is necessary to conduct research on reactive power compensation configuration of wind farm integration. Firstly, based on the actual situation of wind power project, the principle of reactive power compensation configuration is studied. Secondly, a theoretical calculation method of reactive power compensation configuration is proposed. On this basis, combined with the practical 300MW wind farm project, the reactive power compensation configuration example is analyzed. Finally, through the modeling and simulation by power system analysis software package (PSASP), the accuracy and effectiveness of the calculation method proposed by this paper are verified. This paper put forward a reactive power compensation configuration method which is applicable to all wind farms connected to the power system. This provides important support for voltage stability in the wind power integration project.

1. Introduction
In order to cope with the global energy and environment problems, vigorously developing clean energy has become an important measure for all countries in the world [1,2]. Wind power generation is currently the most mature and promising renewable energy technology. It has been greatly developed in recent years [3]. However, the wind farm operation requires amount of reactive power support. With the continuous improvement in the scale and capacity of wind farm integration, the system reactive power deficiency and the impact on the system voltage will increase if the reactive power is not compensated in time. The grid’s safe and stable operation will be challenged. Therefore, in order to reduce the influences of grid-connected wind farm on power system and improve the security of wind power access to power system, we conduct the research on reactive power compensation configuration of wind farm integration.

At present, the research on the wind power reactive compensation configuration mainly adopts the estimation method [4], the method of compensation capacity determined by reactive compensation degree, the method of compensation capacity determined by power factor and the method of compensation capacity determined by voltage regulation demand.[5,6] There are few methods about calculating the reactive compensation capacity based on the reactive compensation principle. The current calculation methods are not standardized and the results are not accurate enough. It is difficult to meet the demand of the power grid’s safe and stable operation.

In view of the above problems, we propose the reactive power compensation configuration method of grid-connected wind farm based on the principle of reactive power compensation configuration.
Firstly, the reactive power compensation configuration principle is studied to ensure the reactive power compensation configuration conforms to the relevant principles and regulations of power grid. Secondly, based on the reactive power compensation principle, the reactive power compensation theoretical calculation method is proposed to obtain the best scheme. On this basis, combined with the actual 300MW wind farm project, the reactive power configuration calculation example is analyzed. Finally, the proposed method’s accuracy and validity are verified by PSASP modeling and simulation.

2. Composition of reactive power loss

Typical wind farms are generally equipped with dozens or hundreds of wind turbines. Each wind turbine is provided with one package transformer. The wind turbine and the package transformer are connected by parallel-laid cables. Each package transformer sends the wind power to the low-voltage-side bus of the booster station’s main transformer through the collection line. By being transformed to the high pressure side, the wind power finally will be sent out by the outgoing line. Wind turbine, package transformer, collection line, main transformer and equipment in booster station constitute the main electrical system of wind farm. The wind farm integration diagram is shown in Figure 1.

In the wind farm integration system, the reactive power loss is mainly composed of six parts: wind turbine, the line from wind turbine to package transformer, package transformer, collection line, main booster transformer and outgoing line of the wind farm.

a) Wind turbine

At present, there are three categories of widely used wind turbines: constant frequency constant speed asynchronous generator (squirrel cage asynchronous generator), constant frequency variable speed doubly fed asynchronous generator and direct drive permanent magnet synchronous generator.[7]

The constant frequency constant speed asynchronous generator is in parallel connection with the reactive power compensation device at the end of the generator. The compensation capacity is generally 30% - 50% of the wind turbine capacity. But its compensation capacity can not meet the reactive power requirements when the wind turbine starts and disconnects from the grid. When the wind turbines start or disconnect from the grid at the same time, the wind turbine capacity’s 50% - 70% reactive power needs to be absorbed from the grid again. In view of the small possibility of all wind turbines starting or disconnecting from the grid at the same time, it is recommended to increase the reactive compensation capacity to 30% of the total installed capacity.

The constant frequency variable speed doubly fed asynchronous generator is equipped with a control unit in the rotor winding assembly. In normal operation, the control unit can control the frequency, amplitude and phase of the rotor current to keep the stator frequency, terminal voltage and power factor constant, without the need for the grid to provide reactive power. In the process of wind farm fault or low voltage ride through, the reactive power can be generated by the control unit’s grid
side frequency converter to adjust the terminal voltage. But the generated reactive power can not meet the wind turbine’s needs. It is recommended to increase the reactive compensation capacity to 10% of the total installed capacity.

The direct drive permanent magnet synchronous generator is equipped with full-power converter at the generator terminal. During normal operation and wind farm failure time, the full-power converter can adjust the reactive power, and the permanent magnet synchronous generator does not need to absorb the reactive power from the system. Therefore, for the wind turbine part of the wind farm, it is not necessary to increase the reactive compensation capacity.

b) The line from wind turbine to package transformer

The wind turbine’s outlet voltage is generally 0.69kV, which is connected to the corresponding package transformer by low-voltage cables. Due to the large current flowing, it is generally connected by parallel-laid cables.

c) Package transformer

The package transformer increases the voltage of the wind turbine from 690V to 10kV or 35kV. One wind turbine corresponds to one package transformer.

d) Collection line

After the wind turbine’s power is boosted by the package transformer, it will be sent to the booster station through the collection line. The collection line in the wind farm has three connection methods: overhead line, cable, and hybrid mode of cable with overhead line.

e) Booster transformer

After the power of the wind turbine is boosted by the package transformer, it will be sent to the booster station of the wind farm through the collection line. The collection line in the wind farm has three connection methods: overhead line, cable, and hybrid mode of cable with overhead line.

f) Outgoing line of the wind farm

The outgoing line of the wind farm refers to the transmission line from the wind farm to the public grid. The booster transformer will boost the wind power and connect it to the power system through the outgoing line.

3. Principle of reactive power compensation configuration

According to the "Technical Regulations for Wind Farm Access to the Power Grid (Q/GDW 1392-2015)"[8]:

The reactive power source includes the wind turbine and the reactive power compensation device of the wind farm. The wind turbine should be able to meet the dynamic adjustment of power factor from leading 0.95 to lag 0.95.

The wind farm shall take advantage of the reactive capacity and regulation capacity of the wind turbine. When the reactive capacity can not meet the demand of system voltage regulation, the wind farm shall be equipped with appropriate capacity of reactive compensation device, and if necessary, dynamic reactive compensation device should be equipped.

The reactive capacity shall be configured in accordance with the principle of basic balance of the divided (voltage) layer and divided (power) area, and meet the requirements of maintenance and standby.

For wind farms directly connected to the public grid, the configured capacitive reactive capacity can compensate the sum of the inductive reactive power of the collection system (including the collection line and the wind turbine package transformer), the inductive reactive power of the main transformer and half of the inductive reactive power of the outgoing line of the wind farm when the wind power is fully discharged. The configured inductive reactive capacity can compensate the sum of the capacitive reactive charging power of the wind farm itself and the half of the reactive charging power of the outgoing line of the wind farm.

For the wind farms in the wind farm group that are connected to the public power grid through the 220kV (or 330kV) wind power collection system boosting the voltage to the 500kV (or 750kV) level, the configured capacitive reactive capacity can compensate the sum of the inductive reactive power of
the collection system, the main transformer and the outgoing line of the wind farm when the wind power is fully discharged. The configured inductive reactive capacity can compensate the sum of the capacitive charging reactive power of the wind farm itself and all the reactive charging power of the outgoing line of the wind farm.

4. Theoretical calculation method of reactive power compensation configuration

4.1. Calculation of the line reactive loss and charging power

The line reactive power loss $Q_L$ is calculated using eq. (1):

$$Q_L = 3I^2 \cdot X$$

Where $I$ is the current and $X$ is the line equivalent reactance that are calculated in eq. (2)-(3):

$$I = \frac{P}{\sqrt{3}U \cdot \cos \phi}$$

$$X = x \cdot L$$

Where $P$ is the line active power [kW], $U$ is the line voltage [kV], $\cos \phi$ is the line power factor, $x$ is the reactance per unit length of wire [$\Omega$/km], $L$ is the line length [km].

The line charging power $Q_C$ is calculated using eq. (4):

$$Q_C = U^2 \cdot \omega \cdot C / 1000 = U^2 \cdot 2\pi \cdot f \cdot c \cdot L / 1000$$

Where $f$ is the line frequency [Hz] with the value of 50 Hz, $C$ is the single phase to ground capacitance of conductor [$\mu$F], $c$ is the single phase to ground capacitance of conductor per unit length ($\mu$F/km).

4.2. Calculation of the transformer reactive power loss

The transformer reactive power loss $Q_T$ is calculated using eq. (5):

$$Q_T = n \cdot \left( \frac{U_S \%}{100} \cdot \frac{S^2}{S_n^2} + \frac{I_0 \%}{100} \cdot S_n \right)$$

Where $n$ is the number of transformers, $U_S \%$ is the percentage value of transformer short-circuit voltage, $I_0 \%$ is the percent value of transformer no-load current, $S$ is the operating apparent power of transformer(kVA), $S_n$ is the rated transformer capacity (kVA).

4.3. Calculation of the reactive power compensation device capacity

According to the reactive power compensation configuration principle, the capacitive reactive power compensation capacity is the sum of line loss and transformer loss.

For the wind farm directly connected to the public grid, the calculation formula is shown in formula (6):

$$Q_R = Q_{XT} + Q_{JL} + Q_{ZT} + \frac{1}{2} Q_{SL}$$

Where $Q_R$ is the capacitive reactive power compensation capacity to be configured, $Q_{XT}$ is the reactive power loss of package transformer, $Q_{JL}$ is the reactive power loss of collection line, $Q_{ZT}$ is the reactive power loss of the main transformer, $Q_{SL}$ is the reactive power loss of outgoing line of the wind farm.

For the wind farm connected to the public grid through the wind power collection system, the calculation formula is shown in formula (7):

$$Q_R = Q_{XT} + Q_{JL} + Q_{ZT} + Q_{SL}$$

The inductive reactive power compensation capacity is the sum of the line charging power.
For the wind farm directly connected to the public grid, the calculation formula is shown in formula (8):

\[ Q_G = Q_{jc} + \frac{1}{2} Q_{sc} \]  

(8)

Where \( Q_G \) is the inductive reactive power compensation capacity to be configured, \( Q_{jc} \) is the charging power of collection line, \( Q_{sc} \) is the charging power of the outgoing line of the wind farm.

For the wind farm connected to the public grid through the wind power collection system, the calculation formula is shown in formula (9):

\[ Q_G = Q_{jc} + Q_{sc} \]  

(9)

5. Case study

Taking an actual wind farm as the example, we analyze reactive power compensation configuration of the A wind power project. A wind farm’s capacity is 300MW. Sixteen sets of direct-drive wind turbines with a single unit capacity of 3200kW and seventy-three sets of direct-drive wind turbines with a single unit capacity of 3400kw are installed. The wind turbine and the package transformer are connected in the connection mode of one generator, one transformer unit. The package transformer is located inside the wind turbine, with a capacity of 3600kVA and 3800kVA respectively. After the power is boosted to 35kV through the package transformer, it is sent to the 35kV bus of the 220kV booster transformer by twelve 35kV collection lines. After being boosted to 220 kV, it finally will be sent to the 500 kV transformer substation through by one 220 kV outgoing line.

a) Wind turbine
    The project adopts direct-drive permanent magnet synchronous generator, which does not need to absorb reactive power from the system. So we do not consider increasing the reactive compensation capacity.

b) The line from wind turbine to package transformer
    The package transformer in the project is located inside the wind turbine. The 0.69kv line is very short. The reactive loss and charging power can be ignored, and will not be considered in the project.

c) Package transformer
    The short-circuit voltage percentage and no-load current percentage of the package transformer in the project are 7% and 0.2% respectively. According to the reactive loss formula (5) of transformer, the reactive loss of 3600kVA and 3800kVA package transformer is respectively:

\[ Q_{t1} = 16 \cdot (7% \cdot \frac{3200^2}{3600^2} + 0.2%) \cdot 3600 = 3300.976 \text{kvar} \]  

(10)

\[ Q_{t2} = 73 \cdot (7% \cdot \frac{3400^2}{3800^2} + 0.2%) \cdot 3800 = 16099.931 \text{kvar} \]  

(11)

In accordance with the calculation, the total reactive power loss of eighty-nine booster package transformers is 19400.907kvar.

d) Collection line
    There are 12 circuits of 35 kV collection lines in the wind farm, and the conductor models are LGJ-95/20 and LGJ-240/30. The total length of LGJ-95/20 is 33.5km and the total length of LGJ-240/30 is 90.3km.
    According to the calculation, the reactive loss is 24152.26 kvar and charging power is 428.58 kvar.
e) Booster transformer
    Three 100 MVA booster transformers are installed in the project. The short-circuit voltage percentage and no-load current percentage are 14% and 0.45% respectively. According to the reactive loss formula (5), the reactive loss of three 35 / 220kV booster transformers is as follows:

\[ Q_r = 3 \cdot (14\% \cdot 1 + 0.45\%) \cdot 100000 = 43350k \text{var} \]  

(12)

f) Outgoing line
The outgoing line of this project adopts 2×LGJ-240 conductor. Its length is 22 km. Its capacitance to ground is 0.0115 μ F/km. Its reactance is 0.31 Ω/km.

According to formula (1), (2) of line reactive loss and formula (4) of line charging power, the reactive loss and charging power of 220kV outgoing line are 12682.6 kvar and 3844.83 kvar respectively.

In conclusion, it can be calculated that the reactive power loss and charging power of the 300MW wind power project are 93.244 Mvar and 2.35 Mvar respectively when the wind power is fully generated.

According to relevant regulations [9-11], considering certain margin, we propose to configure a set of ± 32Mvar static dynamic reactive compensation device (SVG) on each 35kV bus of the booster station, with the compensation capacity ranging between 32Mvar (capacitive) to 32Mvar (inductive). The compensation capacity should meet the requirements of dynamic continuous regulation and the response time shall not exceed 30ms. At the same time, the reactive power compensation device of the wind farm shall operate reliably when the wind turbine is connected to the grid and in the process of low voltage ride through and high voltage ride through. A total of 96 Mvar SVG shall be configured under the three main transformers.

Finally, based on PSASP software, the simulation models of A wind farm under the power system small operation mode in winter, small operation mode in summer, large operation mode in winter and large operation mode in summer are built. According to the simulation result, check whether the compensation configuration capacity meets the operation requirements after the wind farm is equipped with ± 96Mvar static dynamic reactive power compensation device (SVG). The simulation results under the power system small operation mode in winter, small operation mode in summer, large operation mode in winter and large operation mode in summer are shown in Figure 2 to Figure 5.

Figure 2. Simulation result under power system small operation mode in winter
Figure 3. Simulation result under power system small operation mode in summer

Figure 4. Simulation result under power system large operation mode in winter
It can be seen after the calculation that the voltage of each node of the system is reasonable in various modes of reactive power check calculation. The capacitive and inductive reactive power compensation capacity configured in the wind farm meet the operation requirements.

6. Conclusion

Based on the principle of wind farm reactive power compensation, this paper puts forward the theoretical calculation method of reactive power compensation. Combined with the actual wind farm project example, the reactive power compensation configuration is analyzed. Finally, the accuracy and effectiveness of the calculation method are verified by PSASP modeling and simulation. The reactive power compensation configuration method studied in this paper is applicable to all wind farms connected to the power system. It provides important support for the voltage stability in the wind power integration project.

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