An improved AVC strategy applied in distributed wind power system

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Abstract. Traditional AVC strategy is mainly used in wind farm and only concerns about grid connection point, which is not suitable for distributed wind power system. Therefore, this paper comes up with an improved AVC strategy applied in distributed wind power system. The strategy takes all nodes of distribution network into consideration and chooses the node having the most serious voltage deviation as control point to calculate the reactive power reference. In addition, distribution principles can be divided into two conditions: when wind generators access to network on single node, the reactive power reference is distributed according to reactive power capacity; when wind generators access to network on multi-node, the reference is distributed according to sensitivity. Simulation results show the correctness and reliability of the strategy. Compared with traditional control strategy, the strategy described in this paper can make full use of generators reactive power output ability according to the distribution network voltage condition and improve the distribution network voltage level effectively.

1. Introduction

In the field of new energy power generation, wind power is one of the most competitive and efficient way of generating. At present, the main form developing and utilizing wind power is large-scale wind farm which is located at the end of grid and far away from load centre. Insufficient transmission capacity and limitations of the grid consumptive ability result in a wide range “wind abandoned” phenomenon, seriously reducing the economic benefits of wind power [1]. Compared with large-scale centralized power generation, small-scale distributed wind power generation can access to the distribution network directly and used locally, not requiring long-distance transmission. However, the access of distributed wind power generation will have impact on steady operation and power quality of distribution network with weak structure. Therefore, the study of distributed wind power key technology has a very important significance.

Current study about reactive power optimization control of distributed wind generator accessing to low voltage distribution network are mainly focused on three fields, which are reactive power optimization containing distributed generators, voltage control of reactive power compensation devices and wind farm hierarchical AVC (automatic voltage control) control system. Objective function and constraint conditions are needed in reactive power optimization [2-4]. However, this optimizing strategy can only be used in long time scale global optimization, not for short time rapid
voltage control. As for reactive power compensation device, most of papers pay attention to devices and ignore the reactive power supporting ability, which increase the investment and operation cost [5-8]. The AVC system of wind farm can be divided into reactive power setting layer and distributing layer [9-12]. Reference of reactive power is obtained in setting layer and is distributed into reactive power source in distributing layer. But most research literature about AVC system is for wind farm and only concern about grid connection point, which haven’t take full account of features of distributed wind generator.

In order to solve above problems, this paper puts forward a improved AVC strategy applied in wind power system based on doubly-fed induction generator (DFIG). The strategy takes all nodes of distribution network into consideration and chooses the node having the most serious voltage deviation as control point to calculate the reactive power reference. In addition, distribution principles can be divided into two conditions: when wind generators access to network on single node, the reactive power reference is distributed according to reactive power capacity; when wind generators access to network on multi-node, the reference is distributed according to sensitivity. This strategy considers flexible features of distributed wind power generators, regulating reactive power control and strengthening the resist of distribution network to voltage fluctuation.

2. Characteristics of distribution network voltage considering the integration of wind power

Characteristics of distribution network voltage considering the integration of wind power. There are \( N \) nodes on the electricity line, and the load of each node is \( P_n + jQ_n \) \((n=1,2,\cdots,N)\). The voltage of initial node is \( U_0 \) and the voltage in note \( N \) is \( U_N \). What’s more, the impedance between two nodes is \( R_n + jX_n \).

Define the flow of active power and reactive power in the direction of load is positive, whereas is negative.

![Figure 1. Typical radial distribution network.](image)

Ignoring power loss, the loss of the voltage between nodes \( N \) and \( N-1 \) is [13]:

\[
\Delta U_n = U_n - U_{n-1} = - \sum_{k=1}^{N} P_n R_n + \sum_{m=1}^{N} Q_n X_n
\]

(1)

Due to the load of active power and reactive power are over 0, the loss of voltage between two nodes in equation (1) is negative constantly without considering reactive power compensation devices. According to equation (1), we can get the voltage on node \( N \) is:

\[
U_n = U_0 + \sum_{k=1}^{n} \Delta U_k = U_0 - \sum_{k=1}^{n} P_n R_n + \sum_{k=1}^{n} Q_n X_k
\]

(2)

Considering that wind generators access to distribution network on multi-node, and the active power of generator on nodes \( M \) is \( P_{VM} \), voltage of node \( N \) is shown in equation.

\[
U_n = \begin{cases} 
U_0 - \sum_{k=1}^{n} \left( \sum_{m=1}^{M} P_m - P_n \right) R_k + \sum_{k=1}^{n} Q_n X_k 
& (0 < n \leq p) \\
U_{p-1} 
& (p < n \leq N)
\end{cases}
\]

(3)
Considering that wind generators access to distribution network on multi-node, and the active power of generator on nodes \( M \) is \( P_{\text{Vim}} \), voltage of node \( N \) is shown in equation.

\[
U_{\text{n}} = U_{0} - \sum_{k=1}^{N} \left( \frac{P_{\text{m}} - P_{\text{r}}}{} \right) R_{k} + \sum_{m=1}^{N} Q_{m} X_{k} \tag{4}
\]

If reactive power of generator \( Q_{\text{Vim}} \) is taken into consideration, the node voltage is:

\[
U_{\text{n}} = U_{0} - \sum_{k=1}^{N} \left( \frac{P_{\text{m}} - P_{\text{r}}}{} \right) R_{k} + \sum_{m=1}^{N} (Q_{m} - Q_{\text{r}}) X_{k} \tag{5}
\]

As shown in equation (4), the change of generator active power will result in voltage fluctuation. The reactive power regulation of generator can strengthen the resist of distribution network to voltage fluctuation.

3. Reactive power limits of DFIG

The stator of DFIG is connected to the grid directly and the rotor is connected to the grid through rotor-side converter and grid-side converter which is showed in figure 2. Where \( P_{\text{g}} \) and \( Q_{\text{g}} \) are active power and reactive power of stator, \( P_{\text{r}} \) and \( Q_{\text{r}} \) are active power and reactive power of rotor, \( P_{\text{c}} \) and \( Q_{\text{c}} \) are active power and reactive power of grid-side converter, \( P_{\text{g}} \) and \( Q_{\text{g}} \) are active power and reactive power of generator system.

![Figure 2. Power relationship of DFIG.](image_url)

The stator of DFIG can send out active power and reactive power. The grid-side converter can operate at four quadrants. Thus, DFIG can not only be used as active power source, but also a reactive power source to regulate grid voltage.

3.1. Reactive power limit of stator

Stator power of DFIG is limited by stator winding, rotor winding and current of rotor-side converter, and the most important factor is the limit of rotor-side current from which the range of stator reactive power is obtained [14].

\[
\begin{align*}
Q_{\text{rmax}} &= \frac{U_{1}^{2}}{X_{1}} + \sqrt{\frac{X_{1} U_{1}}{X_{1}} I_{\text{rmax}}^2} - P_{\text{r}}^{2} \\
Q_{\text{smax}} &= \frac{U_{1}^{2}}{X_{1}} - \sqrt{\frac{X_{1} U_{1}}{X_{1}} I_{\text{rmax}}^2} - P_{\text{s}}^{2}
\end{align*}
\tag{6}
\]
Where $Q_{\text{max}}$ and $Q_{\text{min}}$ are reactive power maximum and minimum of stator, $U_1$ is vector amplitude of grid voltage, $X_m$ is the magnetizing reactance, $X_1$ is stator reactance, $I_{\text{r max}}$ is the current maximum of grid-side converter.

### 3.2. Reactive power limit of grid-side converter

The grid-side converter can operate at four quadrants and its capacity generally depends on maximum slip power of DFIG. When the generator is operating at low wind speed, the grid-side converter does not fully play its power handling capability. Consequently, if the network has reactive power requirement, the grid-side converter can output reactive power.

Assuming the rated capacity of grid converter is $S_c$, reactive power limit is showing in equation (7) considering capacity limitation.

$$ -(S_c^2 - P_r^2)^{\frac{1}{2}} \leq Q \leq (S_c^2 - P_r^2)^{\frac{1}{2}} $$

(7)

According to the power relationship between stator and rotor, equation (8) can be obtained.

$$ Q_{\text{max}} = \left[ S_c^2 - (sP)^{\frac{3}{2}} \right]^{\frac{1}{2}} $$

$$ Q_{\text{min}} = -\left[ S_c^2 - (sP)^{\frac{3}{2}} \right]^{\frac{1}{2}} $$

(8)

Where $s$ is the slip ration of generator, $Q_{\text{max}}$ and $Q_{\text{min}}$ are reactive power maximum and minimum of grid-side converter.

In conclusion, the reactive power limit of DFIG is obtained as follows:

$$ \begin{cases} 
Q_{\text{max}} = Q_{\text{r max}} + Q_{\text{max}} \\
Q_{\text{min}} = Q_{\text{r min}} + Q_{\text{min}} 
\end{cases} $$

(9)

### 4. Improved AVC system

The AVC system can be divided into reactive power setting layer and distribution layer [9]. The setting layer detects real time data of DFIG and network to calculate reactive power reference. The distribution layer distributes the reference to each generator according to a certain principle. But traditional AVC system is used for large-scale wind farm and only concerns about grid connection point, which haven’t take features of distributed wind generator into consideration. Therefore, this paper comes up with an improved AVC system, which calculates voltage of each node and choses the node with the most serious voltage deviation as control point. The scheme of improved AVC strategy is shown in figure 3.

Considering actual situation of distribution network, the voltage of all nodes cannot be obtained by measurement due to lack of measuring installation. In view of radiant network, node voltage can be calculated at the basis of measured data and grid data according to formula (5) when the request for control accuracy is not rigid.
4.1. Reactive power setting layer

Reactive power setting layer is to setting reactive reference. The control block diagram is shown in figure 4. The reference voltage and actual voltage of control point are compared to get the adjustment voltage. Then the adjustment voltage goes through dead zone and PI controller. Finally reactive power reference can be obtained while meeting reactive power limit. When calculating adjusting voltage, voltage standard of distribution network is taken into consideration that voltage fluctuation should not exceed the rated voltage to -7% ~ 7%.

\[
Q_{ref} = \left( \frac{Q_{imax}}{Q_{totalmax}} \right) Q_{ref}
\]  

4.2. Reactive power distributing layer

4.2.1. Distributing principle between wind generators.

Reactive power reference is distributed to wind generators in distribution layer. Traditional distribution principles have equal power factor algorithm [11] and reactive power capacity proportion algorithm [12]. It is important to note that equal power factor algorithm may cause overload of wind generator when active power is very large. Therefore, reactive power capacity proportion algorithm is used in this paper when wind generators access to network on single node.

The reactive power reference is distributed according to reactive power capacity when wind generators access to network from on single node.

\[
Q_{ref} = \left( \frac{Q_{imax}}{Q_{totalmax}} \right) Q_{ref}
\]
Where $Q_{\text{ref}}$ is the reactive power reference of each generator, $Q_{\text{max}}$ is the maximum of the reactive power that each generator can generate/absorb, $Q_{\text{totalmax}}$ is the maximum of the reactive power that all generators can generate/absorb, $Q_{\text{ref}}$ is the reactive power reference obtained from setting layer.

When distributed wind generators access to network on multi-node, the scale and direction of power flow will change more frequently and complicatedly. Therefore, voltage regulation will have blindness and power loss of network will increase when reactive power capacity proportion algorithm is adopted. Paper [16] came up with a sensitivity algorithm to calculate reactive power reference of reactive power compensation equipment. This paper applies this method to distribute reactive power between wind generators accessing to network on different nodes.

Assuming that active power of generator is a constant, the relationship between control node voltage and reactive power of DFIG is shown in equation (11).

$$\sum_{i=1}^{N} \frac{\partial U_k}{\partial Q_{V_i}} \Delta Q_{V_i} = \Delta U_k$$

(11)

Where $U_k$ is voltage of control point, $Q_{V_i}$ is the reactive power of wind generator accessing to node $i$.

Define the sensitivity of node voltage $U_j$ to wind generator reactive power output $Q_{V_i}$ accessing to node $i$ as $K_{ij}$.

$$K_{ij} = \frac{\partial U_j}{\partial Q_{V_i}}$$

(12)

The sensitivity is as follows from equation (5) and equation (11).

$$K_{ij} = \begin{cases} \sum_{m=1}^{i} \frac{X_m}{U_{m-1}} & (i > j) \\ \sum_{m=1}^{j} \frac{X_m}{U_{m-1}} & (i < j) \end{cases}$$

(13)

Thus, the reactive power reference of each wind generator accessing to node $i$ is obtained.

$$Q_{\text{ref}} = \frac{k_i}{\sum_{i=1}^{N} k_i} Q_{\text{ref}}$$

(14)

4.2.2. Distributing principle between stator and grid-side converter.

The output of stator reactive power is realized by controlling the rotor side power, and the rotor side only needs to control slip power. Therefore, distributing reactive power should give priority to stator to reduce the power addressed by control system [15], which means when the reactive power reference is within the limit of stator, it will generate only by stator. Otherwise, grid-side converter will be used to generate reactive power.

5. Case study

In order to verify the validity of control strategy, radiant network with 7 nodes has been established in PSCAD. The rated voltage of network is 10 kV, impedance between nodes is 1.12+j1.32Ω and load parameters of distribution network are in table 1. There are wind generators in node3, node4 and node6. The number of generator is shown in figure 5 and parameter is in table 2.
Figure 5. Distribution network topology.

Table 1. Load parameters of distribution network.

| Node  | Active load | Reactive load |
|-------|-------------|---------------|
| node0 | 25MW        | 5Mvar         |
| node1 | 0.45MW      | 0.09Mvar      |
| node2 | 0.45MW      | 0.09Mvar      |
| node3 | 0.45MW      | 0.09Mvar      |
| node4 | 0.45MW      | 0.09Mvar      |
| node5 | 0.45MW      | 0.09Mvar      |
| node6 | 0.45MW      | 0.09Mvar      |

Table 2. Parameters of DFIG.

| Parameters                             | Value       | Parameters                             | Value       |
|----------------------------------------|-------------|----------------------------------------|-------------|
| Rated power/ MW                        | 1.5         | Rotor leakage inductance/H             | 0.0003982   |
| Rated voltage/ V                       | 690         | Line resistance/Ω                       | 0.0003      |
| Mutual inductance/ H                   | 0.00973     | Line inductance/Ω                       | 0.0008      |
| Stator resistance/Ω                    | 0.00579     | Rotor radius/m                         | 38.5        |
| Stator leakage inductance/H            | 0.0002645   | Gearbox ratio                           | 104         |
| Rotor resistance/Ω                     | 0.00621     | DC capacitor/uF                        | 8640        |

Design two cases to analyze and verify the control strategy: power output change of wind generator and load change of network.

Case 1: The operation speed of wind generator3 and wind generator4 is 10 m/s and the operation speed of wind generator1 and wind generator2 is by 9 m/s step to 11 m/s at 5s.

Active power of wind generators in node6 increases with increasing of wind speed, resulting voltage of node6 and node5 beyond the upper limit 1.07, just as figure (a). Figure (b) represents change of node voltage adopting traditional AVC strategy which only considering the voltage of grid connection point. After voltage regulation, voltage of nodes6 is 1.07pu and still greater than upper limit. This is due to that only generators accessing to node6 are involved in voltage control and largest reactive power absorption of generators is 0.38 MVar, when the wind speed is 11 m/s shown in figure 3, which limits the reactive power adjustment ability of wind generator. Figure (d) represents adopting control strategy described in this paper which develops reactive power adjustment ability of other generators to control the voltage within normal range. Figure (e) shows reactive power output of wind generators.

Figure 6. (a) Node voltage when the operation speed of generators is increasing. Figure 6. (b) Node voltage when adopting traditional AVC strategy.
Figure 6. (c) Reactive power output of generators when adopting traditional AVC strategy.

Figure 6. (d) Node voltage when adopting improved AVC strategy.

Figure 6. (e) Reactive power output of generators when adopting improved AVC strategy.

Figure 6. Simulation results for Case 1.

Case 2: The operation speed of 4 wind generators is 8m/s. The load in node5 is by 0.45MW+j0.09Mvar step to 1.65MW+j0.21Mvar at 5s.

Variation of load results voltage of node6, node5 and node4 beyond the lower limit 0.93, just as figure (a). Figure (b) represents change of node voltage adopting traditional AVC strategy. At the moment, generator3 outputs reactive power to compensate the voltage of node4 and generator1 and generator2 outputs reactive power to compensate the voltage of node6. Figure (c) shows reactive power output of wind generators. At last, voltage of nodes5 is 0.9203pu and is still lower than lower limit 0.93. The control point will be node5 which has the most serious voltage exceeding when adopting control strategy described in this paper. At end, the node voltage is within the normal range as shown in figure (d). Figure (e) shows reactive power output of each wind generator.

Figure 7. (a) Node voltage when the load increasing.

Figure 7. (b) Node voltage when adopting traditional AVC strategy.
6. Conclusion

In this paper, the AVC strategy is improved and applied in distributed wind generator. First, the voltage variation mechanism is researched before and after the connection of wind power generator from the viewpoint of voltage drop. The influences of connecting single point and multi points are analyzed. Then the reactive power limit of DFIG is analyzed. At the basis of it, improved AVC strategy is used in reactive power control. The voltage variation of nodes in network is taken into consideration and the node having the most serious voltage deviation is chosen as the control point when setting the reactive power reference. After that, the reference is divided according to the reactive power capacity of generator system for single point and sensitivity for multi points. The improved strategy is suitable for distributed wind generator and gives full play to the reactive power ability of DFIG. In addition, network voltage is been improved effectively when adopting this strategy, also optimizing the power flow distribution and power quality. The research results of this paper look forward to having promoting significance on the rapid development of distributed wind power.

Acknowledgments

I wish to thank my supervisor Professor Liu whose continual guidance and support during my Research process. Thanks for financial support from project support by State Grid Corporation of China (SGSDDK00KJJS1500155).

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