Combined active and reactive power control strategy to improve power system frequency stability with DFIGs

Congwei Tu¹, Jun Cao¹, Lei He², Ye Fang³

¹The State Key Laboratory of Alternate Electric Power Systems with New Energy Resources, North China Electric Power University, Changping District, Beijing, People’s Republic of China  
²Tianjin Electric Power Company, State Grid, Hebei District, Tianjin, People’s Republic of China  
³EHV Transmission Company, China Southern Power Grid, Xingyi, Guizhou, People’s Republic of China

E-mail: tucongwei1993@163.com

Published in The Journal of Engineering; Received on 11th October 2017; Accepted on 3rd November 2017

Abstract: The increasing penetration of wind farms in the electricity grid will have a larger impact of grid operations. This requires wind farms to have the ability to assist in some of the power system control services. Frequency is one of the most important services. Doubly fed induction generator (DFIG), as a widely used machine in modern wind industries; however, its rotor speed is decoupled from the frequency in the power system and thus DFIG cannot response effectively when there’s a frequency fluctuation. This paper proposes a combined active and reactive power control strategy to let DFIGs support primary frequency control. This strategy consists of two parts: One is active power control part based on virtual inertial control, the other is reactive power control part based on the theory that active power of the load is sensitive to the bus voltage magnitude. The effectiveness of the proposed strategy is verified by simulation analysis using MATLAB/SIMULINK and the results prove that it can improve the frequency stability of power systems with wind farms. Meanwhile, compare with the strategy only have one of the two control parts, the proposed strategy can further optimise the capability of DFIGs to participate in frequency regulation.

Nomenclature

\( P' \), \( Q' \) reference active power, reactive power  
\( P_1 \) power delivered to grid  
\( \psi \) stator flux  
\( U_s \) stator voltage  
\( L_s, L_{in} \) stator inductance, rotor inductance  
\( i_{rd}, i_{q} \) rotor current d, q-axis components  
\( \Delta u_{rd}, \Delta u_{dq} \) rotor compensation voltage d, q-axis components  
\( f \) frequency deviation  
\( \Delta P \) output of active power control part  
\( \Delta Q \) output of reactive power control part  
\( K_1 \) control factor of active power control part  
\( K_2 \) control factor of reactive power control part  
\( \Delta P_{ROCOF} \) output of ROCOF loop  
\( \Delta P_{droop} \) output of droop loop  
\( K_a \) proportion coefficient of active power control part  
\( H \) inertia constant  
\( f_0 \) rated frequency  
\( K_{rooof} \) proportion coefficient of droop loop  
\( K_{rococf} \) proportion coefficient of ROCOF loop  
\( n_p, n_q \) exponential parameter of the exponential model  
\( P, Q \) active and reactive components of the load  
\( V \) bus voltage on the load side  
\( P_o, Q_o \) in the initial operating condition  
\( V_o \) in the initial operating condition  
\( \Delta V \) voltage deviation  
\( \Delta P_D \) power load fluctuation  
\( Q_s \) stator reactive power  
\( f_1 \) actual system frequency  
\( K_pK_1 \) proportional parameters of the PI controller in reactive power control part  
\( K_i \) proportion coefficient of reactive power control part  
\( \tau_1, \tau_2 \) parameters of the filter in reactive power control part

1 Introduction

Doubly fed induction generators (DFIGs) cannot participate in the system frequency regulation for the following reasons: First, DFIGs decouple the rotor speed and grid frequency during operation, contributing little to system inertia [1]; secondly, with the integration of the large-scale wind energy, wind turbine generations (WTGs) replace part of the conventional units, the total inertia of the system is further reduced. Thirdly, most DFIGs are designed with maximum power point tracking (MPPT) control, so they have no reserve capacity and cannot participate in the system frequency regulation.

To overcome this issue, one method is to add energy storage system [2–5], it can increase the reserve capacity of DFIGs. Or we can use the pitch angle adjustment [6] to operate DFIGs in the suboptimal wind energy tracking state [7], this method can reduce the active power output of DFIGs to obtain reserve capacity. These strategies require additional equipment or reduce wind power utilisation, so they are not economically-friendly.

In terms of active power control, virtual inertial control (VIC) scheme has been reported on improving economic performance [8–12]. Virtual inertial control includes rate of change of frequency (ROCOF) loop and droop loop. It revises the MPPT curve by detecting the frequency change rate so that DFIGs can adjust the wind power output and release the kinetic energy stored in the rotating masses. Virtual inertia control will not affect the steady-state deviation of the system frequency [13] and it has been applied in the actual wind farms. Improved VIC schemes are proposed in [14–17]. In these schemes, in order to improve the capacity of WTGs to participate in primary frequency control and to mitigate secondary frequency dips, the scale factors of ROCOF and droop loop can coordinate with each other. In reality, the fluctuation of wind speed will affect the output active power of DFIGs. In low
wind speed conditions, the capability of DFIGs to release electrical power is limited. Since DFIGs operate at MPPT state and stores little rotating masses. In high wind speed conditions, though DFIGs store enough rotating masses, its output power is still limited by the capacity of the inverter [18]. Thus, the ability to increase frequency stability by active power control has limits.

In terms of reactive power control, economic performance can be improved by taking advantage of load voltage sensitivity [19]. During an event, except for frequency fluctuations, the system power balance is broken. For lack of reactive power, the voltage on the load side declines in a certain degree. According to load ZIP model, the active power on the load side decreases as the voltage decreases. At present, there is little research on reactive part to improve frequency stability. A voltage control loop based on the frequency regulator of a conventional unit is proposed in [20]. However, this loop can lead to a voltage drop at the terminal of DFIGs and affect their stable operation.

This paper further proposes a combined active and reactive power control strategy for DFIGs to improve the frequency stability of power system with high penetration of wind energy.

This strategy consists of two parts:

(i) active power control part based on VIC.
(ii) reactive power control part based on voltage sensitivity. DFIGs with this strategy can improve the frequency nadir and reduce the active power output demand of the active power control part when the frequency falls. So the proposed strategy can be applied in a larger wind speed range than the strategy only with active power control part. Meanwhile, the proposed strategy will reduce the terminal voltage drop caused by the reactive power control part.

2 Proposed control strategy of a DFIG

In the process of running, the stator windings of DFIGs connected to the power grid directly, and the rotor windings are connected to the grid via a converter. DFIGs can achieve bidirectional energy feed between rotor and grid side and both the stator and the rotor participate in excitation adjustment. So DFIGs combines the characteristics of asynchronous and synchronous generators.

In order to output power to the grid efficiently, traditional DFIGs use controllable rotor AC excitation mechanism. Frequency, amplitude and phase of excitation current on the rotor side are all controllable. DFIGs achieve decoupling control of active and reactive power through vector control system, decomposing the stator current into mutually perpendicular torque component and excitation component. Thus, the output active and reactive power can be controlled separately.

As shown in Fig. 1, this strategy consists of two parts: (i) active power control part and (ii) reactive power control part. \( \Delta P \) from active power control part and \( \Delta Q \) from reactive power control part are added to vector control system and then change the output of a DFIG.

2.1 Active power control part

Active power control part including two loops: (i) ROCOF loop and (ii) droop loop. The output of this part is as follows:

\[
\Delta P = \left( \Delta P_{\text{ROCOF}} + \Delta P_{\text{droop}} \right) \times K_a
\]

The filters are designed to eliminate the interference of frequency measurement noise.

As we all know, in synchronous generators, the relationship between ROCOF and the active power is as follows:

\[
\frac{d\Delta f}{dt} = \frac{\Delta P}{2H}
\]

When frequency changes, electromagnetic power of the conventional generators will fluctuate synchronously. If we add an ROCOF loop shown in Fig. 2, DFIGs can simulate the operation of inertia characteristics of conventional synchronous generators to participate in frequency regulation.

\[
\Delta P_{\text{ROCOF}} = K_{\text{ROCOF}} \times \frac{d\Delta f}{dt}
\]

Meanwhile, the lack of active power in the power system can cause a frequency dip, leading to the decline in the rotor speed of synchronous generator unit. Then the governor in conventional units acts to increase the active power output. This is frequency droop characteristic, shown in Fig. 3. If we add a droop loop shown in Fig. 2, DFIGs can simulate the operation of the governors in conventional synchronous generators to contribute more in frequency regulation.

\[
\Delta P_{\text{droop}} = K_{\text{droop}} \times \Delta f
\]

2.2 Reactive power control part

Traditionally, the voltage dependency of load characteristics has been represented by the exponential model:

\[
P = P_0 \left( \frac{V}{V_0} \right)^n
\]

Fig. 2 Frequency droop characteristic

Fig. 1 Combined active and reactive power control strategy

Fig. 3 Active power control part
\[ Q = Q_0 \left( \frac{V}{V_0} \right)^{n_q} \]  

(6)

Models with different \( n_p, n_q \) can represent constant power, constant current and constant impedance characteristics.

A change in the voltage \( \Delta V \) will result in an active power demand change \( \Delta P_D \) as follows (assuming that \( V \) and \( V_0 \) are both 1 p.u.):

\[ \Delta P_D = ((1 + \Delta V)^{n_p} - 1)P_0 \]  

(7)

From (7), it can be estimated that in a system with \( n_p = 2 \), a 5% decrease in the voltage can reduce the active power demand by around 10.025%. That is to say, a slight voltage drop can result in a comparable active power demand reduction. Thus, reactive power control part can provide a virtual reserve capacity in the system by changing the voltage. Then change the power distribution of the system and reduce the frequency fluctuation. ROCOF can be derived from (2) and (7) as follows:

\[ \Delta V = \left( \frac{dV}{dt} \mu + 1 \right)^{1/n_p} - 1 \]  

(8)

where \( \mu \) is equal to \(-2H/(f_0P_0)\).

The reactive power equation of DFIGs based on stator-flux-oriented vector control is as follows:

\[ Q_s = -U_s I_{ds} \]  

(9)

Hence, the output of the reactive power control part can be expressed as follows:

\[ \Delta Q = -\Delta V \times I_{ds} = -\left[ \left( \frac{dV}{dt} \mu + 1 \right)^{1/n_p} - 1 \right] \times I_{ds}^b \]  

(10)

According to (10), reactive power control part is shown in Fig. 4:

The voltage limiter is designed to prevent the machine terminal voltage from dropping too much to cause the DFIGs to operate improperly.

3 Model system

In this paper, the simulation system uses the four-machine and two-zone model proposed in [20] and replaces the traditional generator set G1 into a large-scale wind farm.

Fig. 5 shows the model system. It consists of two similar areas connected by a weak tie line. The left side of the tie line is area 1, there is a wind farm and a conventional unit; the right side of the tie line is area 2, with two coupled conventional units.

![Fig. 4 Reactive power control part](Image)

![Fig. 5 Model system](Image)

Conventional units are equipped with governors and automatic generation control (AGC).

Fig. 6 shows the load fluctuation situation.

In the proposed strategy, parameters are shown in Table 1. \( K_p \) and \( K_r \) are determined by PRONY analysis, \( \tau_1 \) and \( \tau_2 \) are determined by trial-and-error. Tables 2 and 3 show the results of PRONY analysis.

Table 1 Parameters for the combined control strategy

| Active power control part | Reactive power control part |
|---------------------------|-----------------------------|
| \( K_p \)                 | \( K_r \)                   |
| \( K_{\text{ROCOF}} \)    | \( K_{\text{droop}} \)      |
| \( K_\text{drop} \)       | \( \tau_1 \)                |
| \( \tau_2 \)              |                             |

| \( K_p \) | \( K_r \) |
|----------|----------|
| 1        | 100      |
| 10.8     | 40       |
| -20      | -3       |
| -0.01    | 0.9      |

Table 2 Results of prony analysis (\( K_p \))

| \( K_\text{drop} \) | Damping               |
|---------------------|-----------------------|
| 5                   | \(-1.60 \times 10^2\) |
| 10                  | \(-8.80 \times 10^2\) |
| 20                  | \(-5.30 \times 10^2\) |
| 40                  | \(-5.90 \times 10^2\) |
| 80                  | \(-6.10 \times 10^2\) |
| 150                 | \(-5.50 \times 10^2\) |

Table 3 Results of prony analysis (\( K_r \))

| \( K_r \) | Damping               |
|-----------|-----------------------|
| 0         | \(-5.80 \times 10^2\) |
| -0.5      | \(-6.70 \times 10^2\) |
| -1        | \(-6.30 \times 10^2\) |
| -1.5      | \(-9.10 \times 10^2\) |
| -2        | \(-5.90 \times 10^2\) |
| -2.5      | \(-1.50 \times 10^2\) |
| -3        | \(-1.10 \times 10^2\) |
| -3.5      | \(-1.50 \times 10^2\) |
| -4        | \(-8.00 \times 10^2\) |
| -5        | \(-9.30 \times 10^2\) |
4 Simulation results

This part we discuss the simulation results in two cases with different wind penetration levels. When the system load $L_1$ changes with time, the system appears active power imbalance and the frequency fluctuates.

4.1 Case 1: wind penetration level is 10%

Fig. 7a shows the rotor speed response of DFIGs. Rotor speed decreases under the control of schemes 1 and 3, but it decreases less under the control of scheme 3 than scheme 1. Rotor speed hardly changes under the control of schemes 2 and 4.

Fig. 7b shows the output active power response of DFIGs. The maximum virtual active power output change under the control of scheme 1 is larger than scheme 3. The output active power hardly changes under the control of schemes 2 and 4.

Fig. 7c shows the terminal voltage response of DFIGs. Voltage changes little under the control of schemes 1 and 4. Meanwhile, the voltage change is obvious under the control of schemes 2 and 3. The maximum terminal voltage change under the control of scheme 2 is larger than scheme 3.

Fig. 8 shows the frequency response of the system. In terms of suppressing frequency fluctuation, scheme 3 works the best.

4.2 Case 2: wind penetration level is 30%

Fig. 9a shows that the rotor speed decreases under the control of schemes 1 and 3, but it decreases less under the control of scheme 3 than scheme 1. Rotor speed hardly changes under the control of schemes 2 and 4.

Fig. 9b shows that the maximum virtual active power output change under the control of scheme 1 is larger than scheme 3. The output active power hardly changes under the control of schemes 2 and 4.

Fig. 9c shows that the voltage changes little under the control of schemes 1 and 4. Meanwhile, the voltage change is obvious under the control of schemes 2 and 3. The maximum terminal voltage change under the control of scheme 2 is larger than scheme 3.

Fig. 10 shows the frequency response of the system. In terms of suppressing frequency fluctuation, scheme 3 works the best.
5 Conclusions

This paper proposed a combined active and reactive power control strategy to improve power system frequency stability with DFIGs. The strategy uses two parts: One is active power control part based on VIC, the other is reactive power control part based on the theory that active power of the load is sensitive to the bus voltage magnitude. According to the simulation results, the proposed strategy can reduce the frequency fluctuation in different wind penetration levels.

Compared with the scheme adds active power control part only, the results indicate that the proposed strategy can mitigate the rotor speed decline to some extent. With the decline in rotor speed, the available active power capacity of DFIGs is reduced, and the ability to participate in frequency regulation is weaken. Meanwhile, the proposed strategy can reduce the virtual active power capacity required. If the schemes have to be fully functional, the virtual active power capacity required. If the schemes have to be fully functional, the proposed strategy can be applied in a wider range of wind speed. However, in terms of terminal voltage, the proposed strategy is not conducive to the stable operation of DFIGs.

Compared with the scheme adds reactive power control part only, the proposed strategy does better in maintaining terminal voltage stability. However, it can be applied in a smaller range of wind speed.

Ultimately, the proposed strategy does better in suppressing the frequency fluctuation than the scheme adds active power control part only or the scheme adds reactive power control part only or the scheme with no additional control part. The frequency recovery rate in four schemes are similar. In general, the proposed strategy is more effective.

6 References

[1] Muller S., Deicke M., De Doncker R.W.: ‘Doubly fed induction generator systems for wind turbines’, IEEE Ind. Appl., 2002, 8, pp. 26–33
[2] Abbey C., Joos G.: ‘Supercapacitor energy storage for wind energy applications’, IEEE Trans. Ind. Appl., 2007, 43, pp. 769–776
[3] Qu L., Qiao W.: ‘Constant power control of DFIG wind turbines with supercapacitor energy storage’, IEEE Trans. Ind. Appl., 2011, 47, pp. 359–367
[4] Dreidy M., Mokhlih H., Mekhilef S.: ‘Inertia response and frequency control techniques for renewable energy sources: a review’, Renew. Sustain. Energy Rev., 2017, 69, pp. 144–155
[5] Sarrias-Mena R., Fernández-Ramírez L.M., García-Vázquez C.A.: ‘Fuzzy logic based power management strategy of a multi-MW doubly-fed induction generator wind turbine with battery and ultracapacitor’, Energy, 2014, 70, pp. 561–576
[6] Chen Z., Zou X., Chen Y., et al.: ‘A control strategy for doubly-fed wind power generation system with energy storage’, Autom. Electr. Power Syst., 2014, 38, pp. 1–5
[7] Lin W.M., Hong C.M.: ‘A new Elman neural network-based control algorithm for adjustable-pitch variable-speed wind-energy conversion systems’, IEEE Trans. Power Electron., 2011, 26, pp. 473–481
[8] Fu Y., Zhang X., Hei Y.: ‘Active participation of variable speed wind turbine in inertial and primary frequency regulations’, Electr. Power Syst. Res., 2017, 147, pp. 174–184
[9] Hafa F., Abdelnour A.: ‘Optimal use of kinetic energy for the inertial support from variable speed wind turbines’, Renew. Energy, 2015, 80, pp. 629–643
[10] Moreen J., de Haan W.H., Kling Wil L., et al.: ‘Wind turbines emulating inertia and supporting primary frequency control’, IEEE Power Energy Syst., 2006, 21, pp. 433–434
[11] Liu B., Yang J., Liao K., et al.: ‘Improved frequency control strategy for DFIG-based wind turbines based on rotor kinetic energy control’, Autom. Electr. Power Syst., 2016, 40, pp. 17–224
[12] Díaz G.: ‘Optimal primary reserve in DFIGs for frequency support’, Int. J. Electr. Power Energy Syst., 2012, 43, pp. 1193–1195
[13] Wang G., Shi Q., Cui Z.: ‘A coordinated strategy of virtual inertia control of wind turbine and governor control of conventional generator’, Power Syst. Technol., 2015, 10, pp. 2794–2801
[14] Pan W., Quan R., Wang F.: ‘A variable droop control strategy for doubly-fed induction generators’, Autom. Electr. Power Syst., 2015, 11, pp. 126–131+186
[15] Hwang M., Muljadi E., Park J.-W.: ‘Dynamic droop-based inertial control of a doubly-fed induction generator’, IEEE Trans. Sust. Energy, 2016, 7, pp. 924–933
[16] Gautan D., Goet L.: ‘Control strategy to mitigate the impact of reduced inertia due to doubly fed induction generator on large power system’, IEEE Trans. Power Syst., 2011, 26, pp. 214–224
[17] Liu Z., Ding L., Wang K.: ‘Control strategy to mitigate secondary frequency dips for DFIG with virtual inertial control’, IEEE Conf. Publications, 2016, pp. 1–5
[18] Farrokhhabadi M., Cahilares C.A., Bhattacharya K.: ‘Frequency control in isolated/islanded microgrids through voltage regulation’, IEEE Trans. Smart Grid, 2017, 99, pp. 1–10
[19] Delille G., Yuan J., Capely L.: ‘Taking advantage of load voltage sensitivity to stabilize power system frequency’, IEEE Grenoble Conference, 2013, pp. 1–6
[20] Kundur P.: ‘Power system stability and control’ (McGraw-Hill, New York, NY, USA, 1993)