DFIG primary frequency regulation strategy with optimal dynamic droop control under variable wind speeds

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Abstract. Speed of doubly fed induction generator (DFIG) is decoupled with system frequency and system inertia is greatly reduced with increasing penetration of DFIG. It brings new challenges to system frequency security. To improve power system frequency stability, a DFIG primary frequency regulation strategy is proposed to tune droop coefficient. Taking rotational kinetic energy (RKE) into account, the droop coefficient is optimized to release both available RKE and power reserves as much as possible. The droop coefficient is optimized under different wind speeds. Comparison is made to examine the performance of the proposed method with IEEE 30 bus system.

1. Introduction
With development of wind power generation technology, large scale wind turbine generators are integrated into power systems. Currently, DFIG is the mostly used wind turbine generator [1]. For traditional DFIG, wind turbine speed is decoupled with power system frequency. To improve economic efficiency, DFIGs are usually operated at maximum power point and therefore have little reserve capacity [2]. System inertia is greatly reduced and system frequency regulation performance is deteriorated. With further integration of more wind power generation, it is necessary to enable the frequency regulation capability of DFIG, and improve power system frequency regulation performance.

There are several methods for DFIG to participate in power system frequency regulation: virtual inertia control, droop control, over-speed control, and variable-pitch control. There are large amounts of RKE stored in DFIG, since it has a wide range of stable operating rotor speed, usually from 0.7 to 1.2 pu. With fast and reliable regulation characteristics of converter, DFIG is possible to release some RKE or absorb excessive power from power grid by virtual inertia control when system frequency changes [3-5]. The virtual inertia control can evidently improve transient frequency. The de-loading operation is achieved by over-speed or variable-pitch control to making DFIGs have some power reserves. DFIGs participate in system PFR continuously and have fast response speed with de-load method, that success in lowing the cost of investment of conventional power reserves [6-8]. Droop control method simulates PFR of conventional units. Therefore DFIGs will increase output of electric power when frequency falls, which makes DFIGs’ output power associated with system frequency. It is benefit to maintain the system stability.

Transient frequency can be supported in a short time by virtual inertia control. However, RKE is finite. That is to say, inertia control is unable to participate in PFR continuously [9]. As for de-load control method, over-speed control is simple and flexible but it is applicable only to the medium wind
speed and below; variable-pitch control is suitable for all wind speed conditions but altering the pitch frequently will be damage to DFIGs’ mechanical structure [10]. PFR capability of DFIGs is closely related to wind speed. On one hand, when wind speed is low, rotor speed can reach lower limit easily with fixed droop coefficient ($K_p$). It will result in action of DFIG’s speed protection and DFIG’s separating from the grid. On the other hand, when wind speed is high, DFIGs cannot make full use of power reserves with fixed $K_p$ [11-13]. There are large amount of RKE stored in DFIG, but few researches combine RKE with droop control.

A DFIG PFR strategy with optimal dynamic droop control is proposed in this paper. The droop coefficient is optimized under different wind speeds in this strategy, which improve practicability and adaptability of this strategy. Taken RKE into account for DFIGs participating in system PFR, it enhances PFR capability of DFIG effectively. Most importantly, optimal dynamic droop control overcomes the inadequacies of fixed $K_p$. $K_p$ is tuned according to power reserves and stored RKE except for the part releasing by virtual inertia method.

The rest of paper is organized as follows. Section 2 introduces optimization model for dynamic droop control. In section 3, droop coefficient tuning method is put forward and its practical application is discussed. The effectiveness of proposed strategy is simulated with IEEE 30 bus system in section 4. Conclusions are given in section 5.

2. Optimization model for dynamic droop control

2.1. Steady state running point

Wind speed ($V_{w}$) is important for DFIG’s mechanical power, which influences active power directly. Thus, DFIG runs at different steady state at different wind speed. In this paper, wind speed is divided into low, medium and high. It is defined that $V_{w1}$ is demarcation point of low and medium wind speed, and $V_{w2}$ is demarcation point of medium and high wind speed.

If wind speed is $V_{w1}$, DFIG can just meet the de-loading demand by over-speed control. That is to say, when wind speed is bigger than $V_{w1}$, DFIG cannot do it only by over-speed method. If wind speed is $V_{w2}$, DFIG’s rotor speed reaches the upper limit (1.2 pu) when it runs at the maximum power point. In this paper, DFIG is operated with the given de-loading rate ($\Delta \%$).

Low wind speed: when wind speed is less than $V_{w1}$, pitch angle is 0 degree. The de-loading order is achieved by adjusting rotor speed (no more than 1.2 pu). Medium wind speed: when wind speed exceeds $V_{w1}$ and pitch angle is 0 degree, rotor speed will exceed upper limit if DFIG meets de-loading demand. Variable-pitch control works on. It makes rotor speed equal to 1.2 pu and increase pitch angle. High wind speed: when wind speed exceeds $V_{w2}$, further rise of pitch angle results in increasing of rotor speed of MPPT ($\omega_{mppt}$). To ensure security operation of DFIG, rotor speed is restricted to 1.2 pu, since DFIG’s steady operating point is located on the left of the $\omega_{mppt}$.

2.2. Primary frequency regulation with different wind speed

To maximize DFIG’s frequency support for the main power system in PFR, advantages and disadvantages of various methods have been considered.

Firstly, by virtual inertia control DFIGs have transient frequency-response characteristic. Through releasing RKE or absorbing excessive power from power grid when faults occur, maximum frequency offset is reduced and impact of frequency change on the system is weaken. Secondly, over-speed control method is used at low wind speed, and variable-pitch control method is used at high wind speed. As for medium wind speed, over-speed control method is used in preference and variable-pitch control method is used when former method cannot meet de-loading requirements. It makes that DFIGs have fast frequency-response characteristic. That is to say, DFIGs can release de-loading active power rapidly, avoid wearing of fan body as much as possible and participate in system PFR for variable wind speed. Thirdly, DFIGs take part in PFR continuously by droop control method. Last but not least, RKE is taking into account for PFR. DFIGs’ control system realizes variable speed operation, and their rotor speed can operate in a wide range. When DFIGs operate in super-synchronous speeds,
ω can reach 1.2 pu. As for sub-synchronous speeds, ω can reach 0.7 pu. That is to say, 65.97 percent of RKE can be provided at most. Conventional units can be operated in 0.95-1 pu, so they can offer 9.75 percent of RKE at most. So when ω is less than 1.2 pu, RKE participates in PFR.

A DFIG PFR strategy with optimal dynamic droop is proposed at different wind speed, as shown in table 1. More specifically, virtual inertia method and droop control method are combined with over-speed control method at low wind speed; virtual inertia method and droop control method are combined with variable-pitch control method at high wind speed; and above mentioned methods are used at medium wind speed. And RKE participates in PFR when wind speed is low and medium.

### Table 1. Primary frequency regulation with different wind speed.

| Wind Speed       | Inertia control | Droop control | Over-speed control | Variable-pitch control | RKE control |
|------------------|-----------------|---------------|--------------------|-------------------------|-------------|
| Low wind speed   | √               | √             | √                  | ×                       | √           |
| Medium wind speed| √               | √             | √                  | √                       | √           |
| High wind speed  | √               | √             | ×                  | √                       | ×           |

a √ and × represents wind speed, method is adopted and method is not adopted.

2.3. Optimization model

The $K_p$ has an important effect on performance of DFIGs’ frequency regulation. Inadequacies of fixed $K_p$ has been noticed. Whether $K_p$ is too small or too large, it cannot suit for all wind speed conditions. Therefore, it is crucial to tune $K_p$ according to DFIGs’ actual operation condition. Dynamic $K_p$ is adopted basing on aforementioned PFR strategy.

Actually virtual inertia coefficient ($K_v$) is another important parameter. If DFIGs release too much RKE to their limitation, system frequency will deteriorate again when rotor speed recovers. Therefore, it is inappropriate to choose a large virtual inertia coefficient ($K_v$). If it is too small, transient frequency response of DFIG will be weakened. Tuning $K_p$ and $K_v$ at the same time is difficult to realize. And it is not very necessary, because the steady state frequency is more attentive for PFR strategy. Thus, this paper adopts fixed $K_v$, and the $K_v$ is conservative. As for stored RKE, except for the part releasing by virtual inertia method, it can be used by tuning $K_p$.

The core of dynamic $K_p$ method proposed by this paper is tuning oriented by releasing power reserves and stored RKE except for the part releasing by virtual inertia method totally in PFR. It means that $K_p$ is tuned as great as possible, and DFIG can operate safely and stably. The optimization model is described as follows.

$$\max_{T_f} K_p \Delta f dt + \int_0^{T_f} K_v \frac{df}{dt} dt \leq \int_0^{T_f} (P_{mec} - P_{mec0}) dt + \Delta E_{ka}, \Delta f < \Delta f_2$$

$$\int_0^{T_f} K_p \Delta f dt + \int_0^{T_f} K_v \frac{df}{dt} dt \leq \int_0^{T_f} (P_{mec} - P_{mec0}) dt, \Delta f \geq \Delta f_2$$

where $\Delta E_{ka}, T_f, \Delta f, f, P_{mec}, P_{mec0}$ are maximum available RKE, PFR time, frequency deviation, frequency and mechanical power and initial mechanical power. In power system, $T_f$ is no more than 30 seconds normally.

3. Droop coefficient tuning method

3.1. Model simplification

It is analyzed from the conservation of energy in equation (1). Due to complexity of integral calculation, some simplifications are done in this optimization model.
There is the first simplification. When system frequency changes get into steady state, the optimization can be analyzed from the power. If $\Delta f$ meets the limit of allowable frequency offset ($\Delta f_{\text{band}}$), maximum available RKE and power reserves are released in $T_f$. Equation (1) is converted to

$$\max K_P$$

s.t. \begin{align*}
P_{\text{mec,max}} [d\% + \frac{1}{T_f} (\Delta E_{k_a} - \int_0^{T_f} K_v \frac{df}{dt} dt)] &\geq K_P \Delta f_{\text{band}}, v_w < v_{w2} \\
\int_0^{T_f} [d\% \geq K_P \Delta f_{\text{band}}, v_w \geq v_{w2}]
\end{align*} \hspace{0.5cm} (2)

It is noteworthy that wind speed changes little in the time scale of PFR. Under a certain working condition, DFIGs’ maximum mechanical power is

$$P_{\text{mec,max}} = 0.5 \rho \pi R^2 C_p (\beta, \lambda_{\text{opt}}) V_w^3$$

$$C_p (\beta, \lambda_{\text{opt}}) = 0.22 (\frac{166}{\lambda_i} - 0.4 \beta - 5) e^{\frac{-12.5}{\lambda_i}}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_{\text{opt}}} + 0.08 \beta - \frac{0.035}{\beta^3 + 1}$$

$$\lambda_{\text{opt}} = \frac{\omega_{\text{mppt}}}{0.08 \omega_{\text{base}} R}$$

$$\omega_{\text{base}} = \frac{2 \pi f_B}{G_p}$$

where $P_{\text{mec,max}}$, $\rho$, $R$, $\beta$, $C_p$, $\lambda_{\text{opt}}$, $\lambda_i$, $\omega_{\text{base}}$, $G$, $f_B$ are maximum mechanical power, air density, radius of wind turbine, wind turbine blade pitch angle, power coefficient, optimal tip speed ratio, intermediate variable, reference speed, transmission coefficient of gear box and rated frequency, respectively. $C_p$ is a function of $\beta$ and $\lambda$.

In initial running state, DFIG runs at the de-loading speed. In this PFR strategy, de-load control is carried out by over-speed or variable-pitch method. $\omega_{\text{del}}$ is de-loading speed and speed of MPPT. If $V_w$, $d\%$ are given, $\omega_{\text{del}}$ and $\omega_{\text{mppt}}$ can be calculated by equation (3). Maximum releasable RKE is

$$\Delta E_{k_m} = \frac{J}{2 p^2} (\omega_{\text{del}}^2 - \omega_{\text{mppt}}^2)$$

To prevent DFIG running at a speed which is less than $\omega_{\text{mppt}}$, RKE don’t release completely and $n\%$ of RKE is reserved as safety margin.

$$\Delta E_{k_a} = (1 - n\%) \Delta E_{k_m}$$

In objective function constraints

$$\int_0^{f_f} K_v \frac{df}{dt} dt = \int_0^{f_f} K_v df = \int_{f_0}^{f_f} K_v df = K_v \Delta f_s$$

where $f_f$, $f_0$, $\Delta f_s$ are frequency of $T_f$, initial frequency and steady frequency deviation. There is the second simplification. Since the PFR strategy is used as advanced off-line control, $\Delta f_s$ takes a value under a serious fault. $\Delta f_s$ is 0.5 Hz normally.

Thus tuning value of $K_P$ is
\[
K_p = \begin{cases} 
\frac{P_{\text{mec,max}} [d\%] + \frac{1}{T_f} (\Delta E_{\text{ss}} - K_v \Delta f_v)}{\Delta f_{\text{band}}}, & v_w < v_{w2} \\
\frac{P_{\text{mec,max}} [d\%]}{\Delta f_{\text{band}}}, & v_w \geq v_{w2}
\end{cases}
\] (7)

Therefore, \(K_p\) can be calculated by equations (2)-(7).

3.2. Practical application
Due to the randomness, volatility and intermittency of wind, wind power has strong uncertainty [14]. The ability of DFIGs participating in PFR is affected directly by uncertain wind power. Therefore, characteristics of wind speed are taken into account in actual optimization of \(K_p\).

If \(K_p\) is tuned in real-time according to wind speed, \(K_p\) may rapidly fluctuates in a small range caused by volatility of wind. On one hand, there is little effect on ability of PFR with aforementioned changes of \(K_p\). On the other hand, wind speed changes almost all the time, in which high quality of internal communication of DFIG is required. Thus, it is unnecessary to tune \(K_p\) in real-time according to wind speed. However, when wind speed varies greatly, it may results in DFIG separating from the grid or unable to make full use of power reserves with fixed \(K_p\). In summary, \(K_p\) needs to be changed according to wind speed with greatly change instead of real-time wind speed. When \(K_p\) tuning method is applied in practice, low, medium and high wind speed can be further divided into several segments respectively, and the same \(K_p\) is used in each segment. And a lookup table can be formulated.

The \(K_p\) tuning method can be applied to the optimal power flow (OPF) under wind energy penetration. Some fruitful researches have been done about OPF under wind energy penetration [15-17]. To achieve OPF, active power of DFIG is given. At this time, it is necessary to tuning \(K_p\) according to DFIG’s actual power reserve. It makes DFIG participating in PFR adequately with OPF.

4. Case studies

4.1. Simulation system

![Figure 1. IEEE 30 node standard system.](image-url)
The PFR strategy is verified in the IEEE 30 bus standard system as shown in figure 1. Total load power of the system is 290.5 MW, and the generator nodes are 1, 2, 5, 8, 11, and 13. The installed capacity is 380 MVA, and the #1 generator is the balance node. The #2 synchronous generator is replaced by 50 DFIGs whose unit capacity is 1.5 MW. Therefore, the proportion of DFIGs is about 20% in the system. The DFIG parameters used in this study case are given in table 2.

**Table 2. DFIG parameters.**

| Parameter                          | Units | Values   |
|------------------------------------|-------|----------|
| turbine inertia (J)                | kgm²  | 7431958  |
| transmission coefficient of gear box (G) |       | 100      |
| number of induction generator poles (p) | pairs | 2        |
| radius of wind turbine (R)         | m     | 35       |

At \( t=5 \) s, the active power of node 17 is disturbed, increasing 30 MW.

4.2. **Simulation of PFR strategy with different wind speed**

DFIGs’ de-loading rate is 10%, and \( K_p=8 \) in inertia control. In the process of tuning \( K_p \), the parameters are set as follows, \( n=4 \), \( \Delta f_{bus}=0.2 \) Hz, \( \Delta f=0.5 \) Hz, \( T_f=30 \) s. The optimal \( K_p 13.95, 32.61, 37.5 \) are when \( V_W \) are 8, 11, 13 m/s respectively. The simulation results of different wind speed are presented in figures 2-4.

![Figure 2. Simulation results with low wind speed (8 m/s). (a) System frequency and (b) Output power of DFIG.](image)

![Figure 3. Simulation results with low wind speed (11 m/s). (a) System frequency and (b) Output power of DFIG.](image)
Effects of tuning $K_p$ are similar under different wind speed, therefore simulation results are analyzed under medium wind speed. In the study case with medium wind speed, droop control adopts four different parameters. Virtual inertia control, over-speed control, and variable-pitch control are carried out.

It can be drawn that all four droop control schemes improve effect of PFR from table 3. $K_p = 32.61$ is calculated based on the improved coordinated strategy. To a certain extent, bigger is better for $K_p$. However, if $K_p$ is too large, rotor speed of DFIG will decline rapidly resulting that DFIG separates from the power system. Therefore, it is necessary to tune $K_p$ according to power reserves and available RKE. It maximizes the PFR output based on the current spare capacity and takes account of the safety and stability of DFIG. Obviously, fixed coefficient is not applicable to different wind speeds.

Table 3. Frequency offset data.

| $K_p$ | Steady PFR output (MW) | steady frequency offset (Hz) |
|------|------------------------|-----------------------------|
| 20   | 49.8286                | 0.2203                      |
| 30   | 53.1083                | 0.1924                      |
| 32.61| 56.2198                | 0.1655                      |
| 40   | 0                      | 0.6475                      |

5. Conclusion

This paper proposes a primary frequency regulation strategy with optimal dynamic droop control under variable wind speed. When the system frequency changes, DFIGs can support the transient frequency effectively, and restrain the frequency deviation adequately and continuously. Through simulation and theoretical analysis, the following conclusions can be drawn. RKE is taken into account in PFR, which improve DFIGs’ frequency support capability during PFR period. For the shortcomings of the droop control method with fixed coefficients, the PFR strategy tunes droop coefficient according to DFIGs’ actual power reserve. It makes that DFIGs participate in PFR for variable wind speed conditions and can releasing power reserves and stored RKE except for the part releasing by virtual inertia method mostly in PFR. How to use $K_p$ tuning method in practice is also introduced.

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