A coordinated voltage control scheme for power system with wind farm integration based on EID compensation

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Abstract. Rapid increase of wind power installation brings new issues and challenges for grid security operation and one of the most important key issues is reactive power and voltage control capability of wind farms. This paper proposes a coordinated voltage control strategy for power system with wind farm based on equivalent input disturbances (EID) compensation. Firstly, the voltage control model of power system with wind farm based on doubly fed induction generator (DFIG) is established. The power system adopts reactive power compensation device for voltage control, and the wind farm connected to the grid adopts frequency converter of DFIG to adjust reactive power output. They can coordinate each other to realize voltage stability control of the wind farm connected to the grid. Moreover, when the system is subjected to load disturbance or wind speed disturbance, the proposed method based on EID compensation also can keep the voltage stability of power system with wind farm. Finally, the simulation results show the feasibility and effectiveness of the proposed voltage coordinated control method in voltage regulation.

1. Introduction
The voltage stability of wind farm grid connected power system is affected by the active power and reactive power output of wind farm. At present, a variety of voltage coordinated control of wind farms and power systems have been proposed. A terminal voltage control of a doubly-fed induction generator (DFIG) driven by a pitch controlled wind turbine for the supply of autonomous system without any auxiliary source is proposed in [1]. The influence of d axis rotor current on the reactive power output of fixed rotor in DFIG under five different operation modes is investigated in [2], in which an iterative algorithm of rotor current under different operating modes is proposed, which can adjust the reactive power and voltage of the system. The reactive power supply in wind farm includes wind turbine and other reactive power compensation device. When the power system voltage fluctuate or drop, reactive power capacity of wind turbines will first be used in voltage regulation. When it cannot meet the reactive demand of the power grid, the reactive voltage compensation equipment, such as on-load tap changer (OLTC), Static Var Compensator (SVC), will be used to realize voltage control. Voltage fluctuations occur frequently in wind farms as a result of wind power perturbation, while reactive power control of various device is always uncoordinated and often has a time lag when the system operates in the traditional control mode that only uses the current data for decision-making. In
[3], a method for coordinated control of the reactive power of wind turbine generators (WTGs) and static var generators is proposed based on model predictive control (MPC). In [4], it proposes an optimal tracking secondary voltage control scheme applied to double fed induction generator-based wind generators. More, coordinated with the voltage control means of power system, the wind farm can support system voltage quickly by regulating reactive power output, which is benefit to strengthen the voltage control capability and improve the voltage stability of power system [5-8]. By coordinating the internal wind turbine and other reactive power compensation devices, the reactive power regulation capability of the wind farm can be better utilized, but the control strategy is more complex, and the influence factors such as time delay are introduced, and the control effect is affected by the algorithm.

In order to meet the demand of wind farm and the grad for reactive power, a coordinated reactive power and voltage control strategy of doubly fed induction generator (DFIG) based on EID compensation is proposed in this paper. The proposed method with EID compensation does not need accurate model information and has an inherent robustness against various disturbance and internal/external uncertainties. The plant, based on doubly fed induction generator (DFIG) have fast reactive and voltage regulation capability. It is helpful to reduce adverse effects and ensure the stable operation of the wind farm by regulating rationally. The study is mainly related to improve the voltage stability of wind power integrated system. By regulated the wind power generation and allocating the reactive power compensation and the internal wind turbine and other reactive power compensation devices, the reactive power can support system voltage quickly by regulating reactive power output of double-fed induction generator. \(Q_d\) represents the system’s reactive power fluctuation.

2. Voltage control model

Figure 1 is a block diagram of the voltage control transfer function of a power system with wind farm. Where \(\frac{K_1}{\tau_1s+1}\) is the reactive power compensation device of the power system; \(\frac{K_2}{\tau_2s+1}\) is the transmission line transfer function, in which \(\tau_2\) is 0; \(\frac{K_3}{\tau_3s+1}\) is the voltage link, and the gain \(K_3\) is 1 desirable for simulation; \(Q_i\) and \(Q_{qr}\) respectively indicate reactive power compensation and reactive power output of double-fed induction generator. \(u_g\) represents the system’s reactive power fluctuation.

![Figure 1. Transfer function diagram of voltage control system.](image)

The state space expression of the voltage control system is as follows:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + B_gw(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(1)

Where \(x(t) = [K_u u_{gref} - K_u u_g - K_Q Q_g - i_{qr} - K_q i_{qr} - Q_{qr} Q_g - u_g]^{T}\), \(u(t) = u_{gref}\), \(w(t) = Q_d\), \(y(t) = u_g\).

3. Design of controller based on the compensation of EID
This section designs a voltage controller based on the compensation of EID to construct a control system for power system (1).

Based on EID compensation the power system (1) can be written as [9]

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B[u(t) + w_e(t)] \\
y(t) &= Cx(t)
\end{align*}
\]

(2)

3.1. Estimation of EID

It is obvious that the original plant expressed by (1) is controllable, observable and there is no zero on jw-axis. The structure diagram of the EID is shown in Figure 2, where \(K_P\) and \(K_R\) are state feedback gain, and

\[
B^+ := (B^T B)^{-1} B^T
\]

(3)

To obtain an EID compensation with high precision and a high tracking performance, the following IM and GSO observer are used to reproduce the state of the plant:

**IM:**

\[
\dot{x}_d(t) = A_d x_d(t) + B_d \left[ \Delta y_{ref}(t) - y(t) \right]
\]

(4)

**GSO:**

\[
\begin{align*}
\dot{\hat{z}}(t) &= \Phi \hat{z}(t) + \Psi y(t) + \Gamma u_f(t) \\
\hat{x}(t) &= T^{-1} \hat{z}(t)
\end{align*}
\]

(5)

Where \(\Phi, \Psi\) and \(\Gamma\) are the appropriate matrices to be determined; and \(\hat{x}(t)\) is the reconstruction state of the original state \(x(t)\).

![Figure 2. Voltage control structure of wind power system.](image)

3.2. Robust Controller Design

To guarantee the stability of the whole close-loop control power system, first we consider the system without exogenous signals since exogenous signals do not influence the system stability. So letting \(\Delta y_{ref}(t)=0, w(t)=0\), the power system model can be expressed as

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(6)

Thus

\[
\Delta \dot{x}(t) = T^{-1} \Phi T \Delta x(t) + B\tilde{w}(t)
\]

(7)

and

\[
\dot{\tilde{w}}(t) = B^+ (T^{-1} \Phi T - A) \Delta x(t) + \tilde{w}(t)
\]

(8)
Where \( \hat{\omega}(t) \) is an estimation of the actual load variation, \( \hat{\omega}(t) \) is the filtered disturbance estimation and \( \Delta x(t) = \hat{x}(t) - x(t) \).

From (7) and (8), the transfer function from \( \hat{\omega}(t) \) to \( \hat{\omega}(t) \) can be expressed as
\[
G_w(s) = B^T(T^{-1} \Phi T - A)(sI - T^{-1} \Phi T)^{-1} B + 1
\]
\[
= B^T(sI - A)^{-1}(sI - \Phi)^{-1} TB
\]

According to the small gain theory, when the \( H_{in} \) norm of the closed-loop systems satisfies
\[
\| G_w(s)F(s) \| \leq 1
\]

Then, the closed-loop system is stable. Here, \( F(s) \) is a low-pass filter.

To design the controller, we construct an augmented system that contains the power system and IM, that is
\[
\hat{x}(t) = \bar{A}\hat{x}(t) + \bar{B}u(t) + \bar{B}_R\Delta ref(t)
\]

Where \( \bar{x}(t) = \begin{bmatrix} x(t) \\ x_R(t) \end{bmatrix}, \bar{A} = \begin{bmatrix} A & 0 \\ -B_R C & A_R \end{bmatrix}, \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}, \bar{B}_R = \begin{bmatrix} 0 \\ B_R \end{bmatrix} \).

We set \( \Delta y_{ref} = 0 \), by employing the liner-quadratic-regular method [10] to determine the state-feedback gain.
\[
J_K = \int_0^\infty [\hat{x}^T(t)Q_Kx(t) + R_Ku(t)]dt
\]

Where \( Q_K \) and \( R_K \) are weighting matrices.

The optimal state-feedback control gains are determined by minimizing \( J_K \).
\[
[K_P \quad K_R] = -R_K^{-1}\bar{B}_R^TP
\]

Where the matrix \( P \) is a solution of the following Riccati equation:
\[
P\begin{bmatrix} A & 0 \\ -B_R C & A_R \end{bmatrix} + \begin{bmatrix} A & 0 \\ -B_R C & A_R \end{bmatrix}^TP + Q_K - R_K^{-1}\bar{B}_R^{-1}\bar{B}_R^TP = 0
\]

4. Case study

The power system with doubly fed wind farm is selected as the object of study. The parameters of the controlled object are expressed as follows in Table 1:

| \( K_1 \) (pu) | \( K_2 \) (pu) | \( K_3 \) (pu) | \( K_u \) (pu) | \( K_0 \) (pu) | \( T_u \) (s) | \( T_0 \) (s) | \( T_q \) (s) | \( \tau_1 \) (s) | \( \tau_2 \) (s) | \( \tau_3 \) (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 12 | 1.0 | 1.0 | 1.8 | 2.0 | 0.2 | 0.16 | 0.3 | 0.001 | 0 | 0.05 |

Figure 3 shows the dynamic response of a power system with wind farm when the system is subjected to the external reactive disturbance \( q_{ref} \). It can be seen that with the load variation shown in Figure 3(a), the system with traditional controller has serious voltage variations, and the voltage deviation \( \Delta u \) are varied at \([-0.25 0.25]\), as shown in Figure 3(b). However, when using the proposed voltage controller with EID compensation, as shown in Figure 3(b), the voltage deviations are varied at \([-0.15 0.15]\). The proposed voltage control method with EID compensation can better reduce the voltage fluctuation range of the system, and make the voltage fluctuation of the system more smooth. Compared with the traditional PI controller, it has obvious advantages.
Figure 3. Dynamic response of voltage control system of wind farm with load disturbance, (a) Load disturbance; (b) Voltage fluctuation under different control strategies.

Figure 4. Dynamic response of voltage control system under different participation degree of wind farm, (a) Voltage fluctuation; (b) Control inputs for active interference suppression strategies.
In order to verify that the wind farm has a positive effect on the system voltage stability, Figure 4 uses “NO, WF” and “WF” to indicate that the wind farm is not involved in voltage control and wind farm participation in conventional power system voltage control. When the wind farm actively participates in the system voltage control, the reactive power output of the reactive power compensation unit and the DFIG wind turbine is shown in Figure 5(a) and (b). The simulation results show that double-fed induction generator bear most of the reactive power compensation needed for voltage regulation, and reactive power compensation devices serve as supplementary means to further smooth the system voltage fluctuation.

5. Conclusions
In this paper, a controller method with EID compensation is proposed for voltage regulation of DFIG wind farm grid-connected system. The voltage regulation model of wind power system based on DFIG is established. The controller structure and basic design principle are introduced. Since the internal/external disturbances are transformed into EID and one compensator is designed for EID, the proposed method has strong robustness on load variations and wind power variation. Then the paper examines the capability of the proposed control approaches for improvement of voltage regulation under load disturbance or wind speed disturbance. Finally, the implementation of coordinated voltage control strategy for wind power grid-connected system is presented. Simulation result confirm the better dynamic performance of the proposed control method than the traditional one and show the feasibility and effectiveness of the proposed voltage coordinated control method based on EID compensation in voltage regulation.

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