Composite control for disturbed direct-driven surface-mounted permanent magnet synchronous generator with model prediction strategy

Hong-Jun Shi¹ and Xu-Chen Nie²,³

Abstract

In order to obtain the best power in the wind energy conversion system (WECS) of the direct-driven surface-mounted permanent magnet synchronous generator (SPMSG), active disturbance rejection control (ADRC) is introduced to track the motor speed in real time. The control algorithm provides a new design concept and an inherent robust controller component that requires very little system information. Aiming at the problem of system parameter mutation caused by internal factors and external environment changes, an adaptive controller with multi parameter identification is designed, and the disturbance caused by parameter changes is compensated in real time. The model predictive current control (MPC) technology for the sudden change of external environment is designed to accelerate the response speed of the current loop, so as to weaken the estimation of the current disturbance by the active disturbance rejection controller, and make the speed estimation more accurate. Simulation results show that the proposed control strategy is effective and satisfactory.

Keywords

Wind energy conversion system, surface-mounted permanent magnet synchronous generator, active disturbance rejection controller, inertia identification, the maximum power tracking control, model predictive current control

Introduction

With the increasingly prominent problems of environmental pollution and energy crisis, the new energy industry has developed rapidly. In recent years, wind power generation as a new energy development technology has received more and more attention. At present, the research of wind power generation mainly focuses on variable pitch control technology and maximum wind power control scheme. Wind turbine with variable speed is the most widely used power generation equipment in the wind power industry. To get the maximum output power, the speed of variable-speed wind turbine also need to be adjusted in real time with the change of external wind speed. In fact, controlling a variable-speed wind turbine below its rated wind speed can be equivalent to controlling the generator’s speed.¹

This paper mainly discusses the maximum tracking scheme of direct-drive wind power generation system under rated wind speed. According to the best tip speed ratio, the generator speed can be adjusted in real time to keep the wind speed at the optimum blade and ensure that the output power of the generation system is always at its maximum. However, due to the randomness of wind speed and direction, the nonlinearity of generators and wind turbines, the time-varying of the internal parameters of the system, and the influence of sudden changes in the external environment, the

¹Department of Electrical Engineering, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, People’s Republic of China
²Institute for Advanced Interdisciplinary Research, Nanjing University of Aeronautics and Astronautics, Nanjing, People’s Republic of China
³College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing, People’s Republic of China

Corresponding author:
Xu-Chen Nie, Institute for Advanced Interdisciplinary Research, and College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, People’s Republic of China.
Email: xcnie@nuaa.edu.cn

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wind power generation system has actually become a large and complex nonlinear system with disturbance, multi variable and strong coupling. Therefore, it is very challenging to study the control strategy of wind power generation system. Nowadays, with the development of intelligent control technology, more and more researchers have applied it to wind power generation system.\(^2\)

The wind power industry is rapidly developing and increasingly put into use, which puts forward higher requirements for power quality, cost, efficiency, safety and reliability. In recent years, more and more attention has been paid to the study of wind turbine control methods, including classical control methods (typical methods in practice) and advanced control methods. In Du et al.,\(^3\) a controller to adjust the speed of wind power generation system is designed by combining fuzzy neural network with particle swarm optimization algorithm. For uncertain parameters, the system stability is guaranteed and the expected performance level is achieved. A novel side panel control bottom on permenant magnet synchronous motor (PMSM) direct torque control and grid-connected variable speed motor is proposed.\(^4\) Simulation results show that this method can provide an optimal control scheme for wind energy control system based on permanent magnet synchronous generator. In Huang et al.,\(^5\) the nonlinear time-varying evolutionary particle swarm optimization algorithm as the training stage of radial basis function neural network (RBFNN) is adopted to optimize the timing prediction parameters of various electrical models.

Active disturbance rejection control (ADRC) is a new robust control design idea based on the traditional PID control algorithm, which was first proposed in 1995\(^6\) and elaborated in 2009.\(^7\) It has also shown encouraging strength in managing dynamic uncertainties, disturbances and nonlinearities. In this proposal, the external disturbance and internal dynamic uncertainties are regarded as the new states of the system and the dynamic compensation is realized by the feedback controller. In addition, the design of ADRC controller does not require a detailed mathematical model, which is necessary for most classical and modern design methods. In Gao et al.,\(^8\) a linear active disturbance. It inherits the essence of the traditional nonlinear self-disturbance and has more advantages. Nowadays, it has been widely used in various fields of society.\(^9\)\(^\text{–}\)\(^12\)

But LADRC also has some limitations, especially in the case of rapid parameter change or large external random disturbance, it cannot accurately estimate the unknown disturbance. Therefore, the control performance of ADRC may be reduced.\(^13,14\) In this case, LADRC should seek some help.

Such challenges can be mitigated by making full use of the model information in the design of ADRC.\(^15\) The model information obtained via physical laws and system identification, can relieve the load of extended state observer (ESO) and improve the control performance of the whole system. Based on this principle, we design an adaptive controller with multiparameter identification, which can solve the problem of system parameter mutation caused by internal factors and external environment changes, and compensate the disturbance caused by parameter changes in real time.

In the current control scheme, MPC is an optimal control method. It uses the dynamic model of the object to predict the future behavior of the object, and determine the future control behavior according to the optimization of the running cost function at each sampling time. Compared with traditional current PI, model predictive current control has faster dynamic response speed and higher steady-state accuracy.\(^16,17\) Due to the advantages of current predictive control, the control of PMSM based on current predictive control is gradually increasing. The time delay compensation scheme of current predictive control is proposed in literature,\(^18\) which can reduce the oscillation of the current prediction control, improve the current control accuracy and reduce the harmonic content. In Wang et al.,\(^19\) according to the frequency spectrum of load current, the loss function of the algorithm is modified to the discrete transfer function to realize the suppression of current harmonics. We can find out the current predictive control algorithm is not only helpful to improve the response speed of the current, but also to reduce the current harmonics and improve the current control accuracy.\(^20\)\(^\text{–}\)\(^24\) In this paper, the current predictive control is used to replace the traditional PI control, so as to accelerate the response speed of the current and weaken the estimation of the current disturbance by the active disturbance rejection controller, make the speed estimation more accurate. Therefore, this paper designs the current predictive control strategy to meet the situation of sudden change of external environment.

Finally, the simulation experiment is given. The simulation results show that the compound controller designed in this paper improves the system control performance to a certain extent.

Wind energy conversion system modeling

Wind turbine system

The wind impeller absorbs the mechanical energy converted from wind energy which is stated in Betz’s Theory.\(^25\):

$$P_m = \frac{\pi R^3 C_p(\lambda, \beta) \nu^3}{2}$$

where \(C_p(\lambda, \beta)\) is power coefficient of the

$$T_m = \rho C_p(\lambda, \beta) R^3 \nu^2 / 2 \lambda$$

where \(\rho\) is the air density (typically 1.25 kg/m\(^3\)), \(R\) is the blade radius (m), and \(C_p(\lambda, \beta)\) is power coefficient of the

\(\lambda\), \(\beta\), \(\nu\), \(P_m\), \(T_m\), \(R\), \(C_p\), \(\rho\), and \(\beta\).
wind turbine, β is the pitch angle (°), and λ is the tip-speed ratio.

The tip-speed ratio λ is given by:

$$\lambda = \frac{2\pi Rn}{v} = \frac{\omega R}{v}$$  \hspace{1em} (3)

where ω is the angular velocity of the wind turbine (rad/s), v is the wind velocity (m/s), n is the Speed of the wind turbine (r/s), and C_p is a function of β, and λ can be expressed as:

$$C_p(\lambda, \beta) = 0.5 \left( \frac{116}{\lambda^4} - 0.4\beta - 5 \right) e^{-\frac{\beta}{50}} + 0.0068\lambda$$  \hspace{1em} (4)

where

$$\frac{1}{\lambda^4} = \frac{1}{\lambda + 0.089\beta} \frac{0.035}{\beta^3 + 1}$$  \hspace{1em} (5)

Figure 1 shows characteristic curve of wind energy utilization coefficient. As shown in Figure 1, for a specific angle pitch, it always exits a maximum power utilization factor, where the tip speed ratio is called the optimal tip speed ratio. The decrease of the pitch angle leads to the increase of the maximum value of power utilization factors. When β = 0 and λ = 8, the maximum value of power utilization factor of the system is 0.48. From the formula for calculating the mechanical energy, we can notice that the higher the value of C_p, the more wind power can capture. Therefore, by adjusting the tip speed ratio, the power utilization coefficient can be kept at the maximum. The above results revealed that the maximum power control of direct drive SPMSG wind power system is comparable to the speed control of SPMSM under the rated wind speed.

**SPMSG modeling**

According to the basic principle of the vector control technology of magnetic field orientation, the dynamic equations of a three-phase SPMSG are shown in the rotating d-q reference frame as35:

$$\begin{align*}
    u_d &= L_d \frac{di_d}{dt} + R_d i_d - L_q \omega_l i_q \\
    u_q &= L_q \frac{di_q}{dt} + R_q i_q + L_d \omega_l i_d + \omega_l \psi_f
\end{align*}$$  \hspace{1em} (6)

where u_d and u_q are the stator voltages in the d-q reference frame, i_d and i_q are the stator currents in the d-q reference frame, ψ_f is the magnetic flux, R_d is the stator resistance, ω_l is the rotor electrical pulsation. The inducances of d-q axes are equal, L_d = L_q = L.

The electromagnetic torque in the d-q reference frame is given as35:

$$T_e = \frac{3}{2} n_p \psi_f i_q$$  \hspace{1em} (7)

where n_p is the pair of poles.

Under generator operation, the mechanical equation is represented as28:

$$J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m$$  \hspace{1em} (8)

where ω_m is rotor mechanical speed of the turbine, J is the combined moment of inertia of generator and turbine (kg m²), B is viscous friction coefficient (kg m²/s), T_m is the drive torque produced by the wind (N m), and T_e is electromagnetic torque.

**Control scheme**

**Design of SPMSG’s ESO**

The speed loop of SPMSG system could be generalized as follows2,29:

$$\begin{align*}
    \frac{dx(t)}{dt} &= f(x, t) + d(t) + bu(t) \\
    y(t) &= x(t)
\end{align*}$$  \hspace{1em} (9)

Where y(t), b, u(t), f(x, t), d(t) denote output signal, control gain, input signal, unknown function, and external disturbances respectively.

Let z_1(t) = x(t), z_2(t) = f(x, t) + d(t), so that the model of ESO could be described as follow:

$$\begin{align*}
    \frac{dz_1(t)}{dt} &= z_2(t) - \beta_1 (z_1(t) - x(t)) + bu(t) \\
    \frac{dz_2(t)}{dt} &= -\beta_2 (z_2(t) - x(t))
\end{align*}$$  \hspace{1em} (10)

The parameter u(t) is observed estimate of x(t), y(t) expresses estimate of y(x(t), y(t) = x(t), then the following equation can be obtained:

$$z_1(t) - x(t) = y_e(t) - y(t)$$  \hspace{1em} (11)

Equation (12) can be expressed as following state space model:
Therefore, the ADRC of SPMSG can be expressed as:
\[
\begin{align*}
\frac{dz_1}{dt} &= z_2 - 2p(z_1 - \omega_m) + bu \\
\frac{dz_2}{dt} &= -p^2(z_1 - \omega_m)
\end{align*}
\] (19)

The corresponding linear control law can be designed as:
\[
\begin{align*}
u_0 &= k_p(\omega_m - z_1) \\
u &= u_0 - \frac{z_2}{b_c}
\end{align*}
\] (20)

where, \(z_1\) is the estimates of status of the system, \(z_2\) is the lumped disturbances of the system, \(\omega_m\) is the desired output, \(b\) is the control gain \(u\) is the q-axis current given, \(u_0\) is the output of the feedback controller.

### Design of model-compensation ADRC for SPMSG’s speed loop

Because the external environment suddenly changes, the WECS will undergo a sudden change, which will cause a change of the torque \(T_m\), the moment of inertia \(J_v\), viscous friction coefficient \(B\), and control gain \(b\) of ADRC. Therefore, the total disturbance of wind power generation system mainly includes modeling error, torque estimation error, moment of inertia estimation error and control gain estimation error.

In this paper, a model synthesis compensation strategy is proposed for the disturbance caused by the estimation of torque, moment of inertia, \(J_v\), viscous friction coefficient \(B\), and control gain \(b\) of ADRC.

According to equation (18) can be given as follows:
\[
\frac{d\omega_m}{dt} = \left(\frac{T_m}{J} - \frac{B}{J}\omega\right) - b_i\omega_c = \left(\frac{T_{em}}{J_e} - \frac{B}{J_e}\omega_c\right) - b_i\omega_c + \left[\left(\frac{T_m}{J} - \frac{B}{J}\omega - \frac{1.5n\psi_f}{J}\omega_c\right) -\left(\frac{T_{em}}{J_e} - \frac{B}{J_e}\omega_c - \frac{1.5n\psi_f}{J_e}\omega_c\right)\right]
\] (21)

where \(T_{em}\), \(\omega_c\), \(J_e\), \(b_c\) are used to estimate \(T_m\), \(\omega\), \(J\), and \(-b_0\).

According to equations (19) and (20), the model-compensation ADRC, can be designed as:
\[
\begin{align*}
\frac{dz_1}{dt} &= z_2 - 2p(z_1 - \omega) + f(\omega_c, J_c, T_{em}, i_q, B_c) + b_iu \\
\frac{dz_2}{dt} &= -p^2(z_1 - \omega)
\end{align*}
\] (22)

The control law can be designed as:
\[
u = k_p(\omega^* - z_1) - (z_2 + f(\omega_c, J_c, T_{em}, i_q, B_c))/b_c
\] (23)

Where \(f(\omega_c, J_c, T_{em}, i_q, B_c) = \frac{T_{em}}{J_e} - \frac{B}{J_e}\omega_c - \frac{1.5n\psi_f}{J_e}\omega_c\).

Consider \(d\) as the lumped disturbance, it can be expressed as:
\[
z_2 = d = \left[\frac{T_m}{J} - \frac{B}{J}\omega\right] - \left[\frac{T_{em}}{J_e} - \frac{B}{J_e}\omega_c\right] + (b_c + b_0)i_q
\] (24)

where \(b_c\) is an estimate of \(-b_0\).
The parameter $b_c$ of the speed controller when inertia $J$ varies, $b_c$ is theoretically supposed to be tuned with the change of inertia, such as $b_c = \frac{3}{2}m\dot{\psi}_f/J_c$. However, the control saturation has to be considered. To ensure the performance of this adaptive control scheme, a practical performance relationship between $b_c$ and inertia $J_c$ should be obtained.

$$b_c = b_m + a\left(\frac{3}{2}m\dot{\psi}_f/J_c - b_m\right)$$  \hspace{1cm} (25)

Where $a$ is Gain factor, $b_c \subseteq [q_1, q_2], q_1 > 0, q_2 > 0, b_m$ is the identification value at the basic speed.

According to the equation (24), if $\omega = \omega_c$, $J_c = J$, $T_{em} = T_m$, $B = B_c$, $b_c = b_0$, then $\hat{d} < d$. It is very important to reduce the disturbance estimator of ESO to improve its estimation performance. If we can identify $T_{em}$, $J_c$, and $b_c$ accurately, then $\hat{d}$ can reduce to 0.

**Design of Inertia Identification, Torque and viscous friction coefficient Observation**

Considering the change of system inertia caused by environment change in wind power system, equation (26) shows the estimation equation of inertia$^{15}$:

$$\left\{ \begin{array}{l}
\delta J_c(n) = -\lim_{n \to \infty} \frac{\int_{r_1(n)}^{r_2(n)} T_{e}(t) \cdot T_{e}(t) dt}{\int_{r_1(n)}^{r_2(n)} r_1(t) dt} \\
J_c(n) = J_c(n) + \delta J_c(n)
\end{array} \right. \hspace{1cm} (26)$$

Where $T_{e}(t)$ is the estimated disturbance torque, integral of $r_1(t)$ is the state variable, $J_c(n)$ is the estimated value of inertia, $\delta J_c(n)$ is the estimated inertia variation during the sampling period $nT$.

Figure 2 shows the diagram of inertia and torque estimation, where $T_{e}(s) = J_s \lambda s^2 + \lambda s + T_s$, $\lambda$ is the observer pole.

According to the equation (16), when inertia and torque are known, viscous friction coefficient $B_c(n)$ can be expressed as:

$$B_c(n) = \frac{T_s \cdot T_{em}(n) - 1.5m\dot{\psi}_f i_q(n) + J_c(n)\omega_c(n) - 1 - J_c(n)\omega_c(n)}{T_s \cdot \omega_c(n)}$$ \hspace{1cm} (27)

Where $B_c(n)$, $T_{em}(n)$, $i_q(n)$, $\omega_c(n)$, and $J_c(n)$ are estimated value during the sampling period $nT$, $T$ is the sampling time.

**Design of SPMSG’s model predictive current control**

First, literature$^{16-24}$ all show that current predictive control has higher system bandwidth than PI. Therefore, this paper designs current predictive control strategy instead of PI control. Then, the current predictive control strategy is designed in this paper for the sudden change of external environment, such as the sudden change of wind speed and moment of inertia, which is different from the application of PMSM.

As the current is the state variable, the state equation of SPMSG can be obtained according to equation (6) as shown:

$$\frac{di}{dt} = Ai + Bu + D$$ \hspace{1cm} (28)

where $i = [i_d, i_q]^T$, $u = [u_d, u_q]^T$, $A = \begin{bmatrix} -R_s/L & \omega_c \\ -\omega_c & -R_s/L \end{bmatrix}$, $B = \begin{bmatrix} 1/L & 0 \\ 0 & 1/L \end{bmatrix}$, and $D = \begin{bmatrix} 0 \\ -\dot{\psi}_f \omega_c/L \end{bmatrix}$.

In this paper, control period, current sampling period and inverter switching period of the servo system are all $T$, so after discretization, the state equation of SPMSG is shown in equation (29).

$$i(x + 1) = L(x)i(x) + M(x)u(x) + N(x)$$

$$i(x) = [i_d(x), i_q(x)]^T$$, $u(x) = [u_d(x), u_q(x)]^T$,

$$L(x) = \begin{bmatrix} 1 - TR_s/L & T\omega_c(x) \\ -T\omega_c(x) & 1 - TR_s/L \end{bmatrix}$$,

$$M(x) = \begin{bmatrix} T/L & 0 \\ 0 & T/L \end{bmatrix}$$,

$$N(x) = \begin{bmatrix} 0 \\ -T\dot{\psi}_f \omega_c(x)/L \end{bmatrix}$$ \hspace{1cm} (29)

In this paper, SPMSG current at next moment can follow the current command value without delay. At the same time, we design the loss function to measure the
control performance of the algorithm. The loss function of current predictive control is designed:

\[ J_c = |i'_q(x) - i_q(x + 1)| + |i'_d(x) - i_d(x + 1)| \] (30)

In order to make the selection of reference voltage output of \( u'(x) \) regulator accurate, the value of loss function can be minimized, that is, the actual current \( i(x + 1) \) at the \( x + 1 \) time is as close to the current instruction \( i'(x) \) at the current moment as possible, make: \( i'(x) = i(x + 1) \) (where \( i(x + 1) \) is the current value calculated according to equation (29) at the \( x + 1 \) moment).

According to equation (29), the reference output voltage \( u'(x) \) at the current moment is shown as:

\[ u'(x) = M^{-1}(x)[i'(x) - L(x) i(x) - N(x)] \] (31)

Considering the direct cause of current delay is that the reference output voltage \( u'(x) \) usually lags one cycle before being applied to SPMSG. The reference voltage \( u'(x + 1) \) at the \( x + 1 \) moment is calculated at the \( x \) moment and applied to SPMSG at the beginning of the \( x + 1 \) moment. Therefore, the influence of system delay on current predictive control can be eliminated theoretically.

The calculation equation of \( u'(x + 1) \) at the \( x \) moment is shown as:

\[ u'(x + 1) = M^{-1}(x)[i'(x) - N_s(x + 1) - L_c(x + 1) i_c(x + 1)] \] (32)

In the wind power generation system, the change of inertia or the sudden change of wind speed will affect the speed prediction in the current prediction process, according to equation (16), the prediction of rotor mechanical speed \( \omega_{r,c}(x + 1) \) at the \( x + 1 \) time can be designed as:

\[
\begin{align*}
\omega_{r,c}(x + 1) &= \left(1 - \frac{B}{J_c(x)}\right) \omega_r(x) \\
&\quad + \frac{n}{J_c(x)} (T_{em}(x) + b_s(x) i_s(x))
\end{align*}
\] (33)

where \( M_{c}^{-1}(x + 1) = M^{-1}(x) = \begin{bmatrix} T/L & 0 \\ 0 & T/L \end{bmatrix} \),

\[
\begin{align*}
i'(x + 1) &= \begin{bmatrix} i'_r(x + 1) \\ i'_s(x + 1) \end{bmatrix} \\
L_c(x + 1) &= \begin{bmatrix} 1 - TR_s/L & T\omega_{r,c}(x + 1) \\ -T\omega_{r,c}(x + 1) & 1 - TR_s/L \end{bmatrix} \\
M(x) &= \begin{bmatrix} T/L & 0 \\ 0 & T/L \end{bmatrix} \\
N_s(x + 1) &= \begin{bmatrix} 0 \\ -T\phi_i/\omega_{r,c}(x + 1)/L \end{bmatrix}.
\end{align*}
\]

The calculation equation of \( i_c(x + 2) \) at the \( x \) moment is shown as:

\[ i_c(x + 2) = i_c(x + 1) + h_c(x) \] (34)

\[ j(x) = \gamma \begin{bmatrix} e(x) \\ \sigma \end{bmatrix} \]

where \( h_c(x) = \gamma \begin{bmatrix} e(x) \\ \sigma \end{bmatrix} \) is a designed observer, \( \gamma = \text{diag}(\gamma_1, \gamma_2) \), \( \gamma_1, \gamma_2 \) are parameters to be designed, \( e(x) = i(x) - i_c(x), \sigma = [\sigma_1, \sigma_2]^T, \sigma_1, \sigma_2 \) are tiny values.

Through equation (32), the calculation of \( u'(x + 1) \) can be completed at \( x \) time, and \( u'(x + 1) \) can be used to SPMSG at the beginning of the \( x + 1 \) moment. Thus, the effect of time delay on current control performance is reduced. Figure 3 shows the time delay compensation of model predictive current control. Figure 4 shows the scheme of SPMSG based on model compensation ADRC + MPC.

**Simulation results and analysis**

In this paper, based on MATLAB Simulink simulation software, the model of the designed composite controller is analyzed, and the simulation verification is given. In order to more truly simulate the specific characteristics of wind speed in practical application, the actual operating conditions of wind power generation system under gust, gradual wind, random wind and natural wind are mainly studied. The control performance of the composite controller under the four wind speeds is studied, and compared with the traditional ADRC, model compensated ADRC as well as model compensated ADRC + MPC. Table 1 shows wind turbine’s parameters used in this paper.

In this paper, basic wind speed is 4 m/s, the gradual, random, gust, and natural wind speeds are used to simulate wind speeds. The natural wind is combination of gradual wind, base wind and random wind and gust wind. The wind speed chart is shown in Figure 5.

**The wind simulations**

**Case 1: Simulation of the gradual wind.** The gradual wind shows characteristics of slow changes in wind speed.

Figure 6 shows the speed tracking effect of the three control strategies at this wind speed. Figure 7 shows the output response comparison curves of the three control strategies under the gradual condition.
Table 1. Main parameters of wind turbines.

| SPMSG parameters          | Value     | Wind Turbine parameters                  | Value     |
|---------------------------|-----------|------------------------------------------|-----------|
| Stator inductance L(H)    | $7.2 \times 10^{-3}$ | Permanent magnetic flux (Wb) | 0.175     |
| Rated power (kW)          | 7.5       | Rated voltage (V)                        | 380       |
| Rotor inertial (kg/m²)    | $2 \times 10^{-3}$ | Pole pairs                               | 4         |
| Viscous coefficient (kg/m²/s) | $7.2 \times 10^{-5}$ | Stator resistance (Ω)                    | 3.1       |
| Wind Turbine parameters   |           |                                          |           |
| Optimum tip speed ratio   | 8         | Maximum power coefficient                | 0.48      |
| Basic wind speed (m/s)    | 4         | Rated wind speed (m/s)                   | 37.5      |
| Rated speed (r/s)         | 25        | Turbine blade radius (m)                 | 1.5       |
| Air density (kg/m³)       | 1.25      |                                          |           |

Figure 4. The scheme of SPMSG based on model compensation ADRC + MPC.

Figure 5. Wind speed charts.

Figure 6. The gradual wind tracking performance.
Case 2: Simulation of the gust wind. The gust wind is characterized by sudden changes in wind speed. So gust wind can be expressed by cosine function.

Figure 8 shows the speed tracking effect of three control strategies under this wind speed. Figure 9 shows the output response comparison curve of three control methods in this speed.

Case 3: Simulation of the random wind. The random noise wind speed can simulate the randomness of wind without rules.

Figure 10 shows the speed tracking effect of three control methods under random wind speed. Figure 11 shows the output response comparison curve of three control methods in this speed.

Case 4: Simulation of the natural wind. The natural wind contains above four kinds of wind, which has strong variability and randomness.

Figure 7. The gradual wind controller output response comparison.

Figure 8. The gust wind tracking performance.

Figure 9. The gust wind controller output response comparison.

Figure 10. The random wind tracking performance.

Figure 11. The random wind controller output response comparison.
Figure 12 shows the speed tracking effect of the three control methods under this wind speed. Figure 13 shows the output response comparison curves of the three control strategies at this speed.

In this paper, we use integral of absolute error (IAE) performance index to estimate the control performance of tracking performance are list in Table 2. It can be seen that the IAE of the model-compensation ADRC + MPC scheme are much smaller than that under the traditional ADRC scheme and model-compensation ADRC scheme.

**Simulation analysis**

It can be seen from Figures 6 and 8 that when the wind is gradual or gust wind, the wind changes steadily, the disturbance is not large and the system effect is no big gap. Figures 6 and 8 show that the control effect of the compound control strategy is better than that of ADRC and Model-compensation ADRC. Figure 7 shows that under the condition of gradual wind speed, the model-compensation ADRC + MPC control strategy can track the actual wind speed quickly and accurately, and the control quantity $i_q$ is less than the effects of ADRC and model-compensation ADRC. Figure 9 shows that under the condition of gust wind speed, the system output response is is evidently gap. At the same time, Figures 6 and 8 show that the control effect of model-compensation active disturbance rejection controller is better than that of ADRC.

Figures 10 and 12 show the tracking effect when the wind speed changes greatly. It can be seen from the figure that when the environment changes severely, the composite controller adopts the inertia identification adaptive controller for speed compensation, and adopts the model predictive current control to speed up the current loop tracking speed and reduce the delay, which can quickly track the wind speed, and the control effect is excellent. Figures 11 and 13 show that the control quantity $i_q$ is smaller than ADRC and model-compensation ADRC. At the same time, it can be seen from Figures 10 and 12 that the model-compensation ADRC control effect is better than ADRC control effect.

The above simulation results show that the compound control algorithm designed in this paper can speed up the response speed of the current loop and reduce the delay of the current loop, at the same time, adding an active disturbance rejection control algorithm to the speed loop has stronger anti-disturbance ability and better robustness. It has better control effect in wind power generation control system.

**Table 2.** The absolute error (IAE) interval index of different control methods in natural wind field.

| Controller          | ADRC | Model-compensation ADRC | Model-compensation ADRC + MPC |
|---------------------|------|-------------------------|--------------------------------|
| IAE                 | 1613.8 | 1324.5                  | 688.9                          |

**Conclusion**

In this paper, ADRC technology, inertia identification technology and model predictive current control technology are combined, and the maximum power tracking control of the change of the torque and the moment of inertia for direct-drive permanent magnet synchronous
wind turbine system is realized by designing a composite controller. In the paper, the composite controllers are designed separately. ADRC estimates disturbance of the whole system in real time and gives the estimated value of disturbance. The observer is used to calculate the real-time torque and moment of inertia, and model-compensation ADRC is designed to compensate ADRC. The model predictive current control technology for the sudden change of external environment is designed to speed up the response speed of the current loop, and eliminate the delay of the current loop system. Finally, a simulation analysis is given in this paper, and the simulation results verify the effectiveness of the designed composite controller. The control strategy used in this paper improves the performance of the control system, but compared with PI, it also increases the complexity of the control system. In practical application, it can be selected according to the system memory and system control accuracy.

CRediT authorship contribution statement
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ORCID iDs
Hong-Jun Shi https://orcid.org/0000-0002-9594-296X
Xu-Chen Nie https://orcid.org/0000-0003-0462-8703

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