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Optimal Active Power Control Based on MPC for DFIG-based Wind Farm Equipped with Distributed Energy Storage Systems

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Abstract
An optimal active power control scheme based on model predictive control (MPC) is proposed for a doubly-fed induction generator (DFIG)-based wind farm equipped with distributed energy storage systems (ESSs). A two-stage optimal control scheme is proposed. In the first stage, the power reference of each WT and the total power command of ESSs are generated, aiming to reduce the fatigue load of WTs by minimizing variations of thrust force and shaft torque. In the second stage, the charge/discharge power of ESSs are optimized to achieve the fair power sharing and maximize the capacity margin. An MPC based optimization problem is formulated for the constrained multiple input and multiple output (MIMO) wind farm system. The dynamics of converters and WTs are taken into account by the MPC. With the proposed control scheme, the active power references are optimized between WTs and ESSs according to their local wind conditions. Fatigue loads of WTs are reduced efficiently by coordinating the DFIG-based WTs and distributed ESSs. A wind farm with 10 DFIG-based WTs was used to validate the control performance of the proposed optimal active power control scheme.

Keywords: DFIG, distributed ESSs, fatigue loads, MPC

1. Introduction
To meet the increasing demand for renewable energy, wind power has been developing rapidly. Due to fluctuations of wind power, high penetration of wind power poses considerable challenges to power system operation [1], [2]. To comply with specific grid code requirements [3], efficient optimal control for wind farms should be developed. The wind farm controller receives the power dispatch command from the transmission system operator (TSO) and available wind power information from individual wind turbines (W Ts). The primary control objective of dispatch schemes for wind farms is active power tracking [4], [5]. For the active power control, the proportional distribution (PD) or proportional-integral (PI) control is...
widely adopted in modern wind farms due to its simple implementation, which also takes into account the available power [6]. But the PD or PI control cannot obtain an optimal solution for wind farms. When a wind farm is required to limit its power production, WTs inside the wind farm have the freedom to vary their active power output according to their local wind condition. The wind farm controller can generate optimal active power references for WTs to achieve optimal control while meeting the dispatch command [7]. Fatigue load refers to the forces and moments experienced by WTs that considerably affect their service lifetime [8]. To reduce the fatigue load, the wind farm controller should dynamically regulate WT power references to adapt to current disturbances induced by turbulence [9]. An improved multi-model optimal control scheme was proposed in [10] and [11] for wind farms with variable speed pitch-regulated WTs, which considers generator rotational speed and mechanical shaft torque in addition to power tracking. In [12], a model predictive control (MPC)-based coordinated active and reactive power control scheme was developed to reduce fatigue loads of WTs while keeping bus voltages within the feasible range. A parametric programming-based control scheme was proposed in [13] to minimize fatigue loads of WTs while meeting the TSO requirements. In [14], a distributed control strategy was proposed to minimize fatigue loads of WTs while maintaining the global power set-point by coordinating neighboring WTs. In [15] and [16], an MPC-based optimal control scheme is proposed for wind farms equipped with a centralized energy storage system (ESS). The wind farm controller coordinates the active power outputs among the WTs and centralized ESS to achieve a better performance on fatigue loads minimization of wind farms.

ESS is considered as an effective tool for enhancing flexibility and controllability of wind farms. ESS can efficiently maintain safe operation of power grids, balance supply and demand sides, enhance fault ride-through ability, and damp short-term power oscillations [17]. However, considering the increasing number and size of wind farms, the requirements for the centralized ESS are high. The failure of a centralized ESS will result in secure issues for wind farms. Compared with the centralized ESSs, the distributed ESSs could be more robust and flexible in case of failures. Moreover, only a much small capacity DC/DC converter is added to boost voltage at each WT and the grid-side converter of the WT is shared, imply better cost-saving. Several studies have been conducted on WTs with distributed ESSs [18]-[27]. Ref. [21] considered the integration of a short-term supercapacitor energy storage device in a DFIG design to smooth the fast wind-induced power variations while reinforcing the dc bus during transients. Ref. [22] presented a decoupled active and reactive power control strategy for the DFIG system with a supercapacitor energy storage system. The aims are to enhance the low voltage ride through (LVRT) capability and damping of the DFIG system. In [23], a coordinated control method was proposed to coordinate the operation of the DFIG, supercapacitor, battery, and load. Ref. [24] presented a control system to achieve coordinated operation of a grid connected doubly fed induction generator (DFIG)-based WT and lead-acid battery ESS. In [25], a constant power control scheme was proposed for a DFIG wind farm, and each DFIG is equipped with an ESS at the DC link. This scheme enables the wind farm to effectively participate in the unit commitment, active power and frequency regulation of the grid. An energy management strategy was proposed in [26] for a flywheel-based energy storage system. The aim is to smooth the power injected into the grid from a variable speed WT. In [27], a control strategy was proposed for a wind power conversion system equipped with a flywheel storage system, aiming to regulate the dc-link voltage against both input power surges/sags from a WT or sudden changes of load.

According to the above studies, most of studies on fatigue loads minimization of wind farms only consider the optimal control of the wind farm itself or with a centralized ESS. There is no study on optimal active power control of wind farms with distributed ESSs. Most of studies only use the WT mechanical system model for optimal active power control to reduce fatigue loads. The dynamic response of the WT converter is neglected. For the studies of WTs equipped with distributed ESSs, the proposed control schemes are mainly carried out at the WT level. Without optimal control, a wind farm with distributed ESS cannot realize optimal operation.

Therefore, an optimal active power control scheme based on MPC is proposed for a DFIG-based wind farm equipped with distributed ESSs. The incremental dynamic models of the converter, ESS, and WT mechanical system are presented in detail. To minimize fatigue loads as much as possible, this control scheme is divided into two stages. In the first stage, the wind farm controller regulates DFIGs to track the power reference while reducing fatigue loads by minimizing the variations of the thrust force and shaft...
torque of WTs, and generates a total power reference for the ESSs. In the second stage, the controller coordinates the distributed ESSs inside the wind farm to keep the state-of-charge (SOC) of each ESS close to the average value and track the total active power reference for the ESSs from the first stage control.

The main contribution of this paper is the design of a two stages optimal active power control scheme for a large-scale wind farm with distributed ESSs. The DFIGs, converters, and ESSs are optimally coordinated to minimize fatigue loads of WTs and maintain the SOC of ESSs close to the average value to provide flexibility. An MPC based optimization problem is formulated for the constrained multiple input and multiple output (MIMO) wind farm system, which consider the dynamics of the WT mechanical model and converters. With the proposed control scheme, the active power references are optimized among the WTs and ESSs according to their local wind conditions. With the distributed ESSs, the equivalent operation range of the WTs active power output is increased. It can realize a better control performance.

The paper is organized as follows. Section 2 provides an overview of the proposed optimal active power control scheme. The model of the DFIG wind farm equipped with distributed ESSs is presented in Section 3. The coordinated control scheme is described in Section 4. The simulation results are presented and discussed in Section 5, followed by conclusions.

2. Control Scheme Architecture

2.1. Wind Farm Configuration

Fig. 1 shows the typical configuration of a wind farm that is connected to the external alternating current (AC) grid through a transmission cable. The on-load tap changer (OLTC) is at the high-voltage/medium-voltage (HV/MV) transformer at the point of connection (POC). The MV side is connected to several feeders. Several WTs are connected to a feeder and placed at a distance of 4 km.

![Fig. 1. Configuration of a wind farm.](image)

2.2. Control Concept

Fig. 2 shows the structure of the proposed control scheme. The active power reference at the POC of the wind farm is decided by the system operator and delivered to the wind farm controller. The wind farm controller is designed in a centralized manner based on the MPC, which is divided into the DFIG control block and ESSs control block.

The DFIG and ESS control blocks operate sequentially in each control period. The DFIG control block coordinates all DFIGs in the wind farm to track the power reference from the TSO while reducing the fatigue loads of WTs, caused by the variations of the shaft torque and thrust force of WTs. The total charge/discharge power capacity of the ESSs is considered in this block. This block generates the optimal active power reference for each DFIG and the total power reference for the ESS control block. The ESS control block optimally coordinates the ESSs inside the wind farm to drive the SOCs of the ESSs to converge to the average value and track the total ESS power reference from the DFIG control block.
3. DFIG System Model

Fig. 3 shows the configuration of a DFIG-based WT equipped with an ESS. The WT is connected to the DFIG through a gearbox. The DFIG stator is directly connected to the wind farm collector system. The rotor is connected to the AC grid through a back-back pulse-width modulation (PWM) converter, which consists of a rotor side converter (RSC), a grid-side converter (GSC), and an ESS. The rating of the converter is typically set as 25%–30% of the DFIG nominal power. The type of the energy storage unit (ESU) is lead-acid battery. The ESU is connected to the DC link of the converter through a DC/DC converter, which regulates charge/discharge power to store excessive wind power or release power to track the dispatch command from the TSO. The active and reactive power of the DFIG is controlled independently.

Fig. 3. Configuration of a DFIG WT equipped with ESS

3.1. RSC Model

The primary task of the RSC is controlling the active and reactive power output of a DFIG. The control strategy implemented in the RSC realizes the decoupled control of active and reactive power, which is achieved by rotor current regulation in a stator flux-oriented synchronously rotating reference frame. The d-axis of the reference frame is oriented along with the stator flux vector. The RSC control scheme is shown in Fig. 4.

The stator and rotor voltage in the dq-axis frame can be expressed as,

\[ u_{ds} = -R_s i_{ds} + \frac{d\psi_{ds}}{dt} - (\omega_s - \omega_r) \psi_{qs}. \]  
\[ u_{qs} = -R_s i_{qs} + \frac{d\psi_{qs}}{dt} + (\omega_s - \omega_r) \psi_{ds}. \]  
\[ u_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega_r) \psi_{qr}. \]  

Fig. 2. Control structure.
where \( u_{ds}, u_{qs}, u_{dr}, \) and \( u_{qr} \) are the stator and rotor voltage in the dq-axis frame, respectively, \( i_{ds}, i_{qs}, i_{dr}, \) and \( i_{qr} \) are the stator and rotor current in the dq-axis frame, respectively, \( \psi_{ds}, \psi_{qs}, \psi_{dr}, \) and \( \psi_{qr} \) are the stator and rotor flux in the dq-axis frame, respectively, \( \omega_s \) is the system angular speed, and \( \omega_r \) is the rotor angular speed. The stator and rotor flux in the dq-axis frame can be expressed as,

\[
\psi_{ds} = -L_s i_{ds} + L_m i_{dr},
\]

\[
\psi_{qs} = -L_s i_{qs} + L_m i_{qr},
\]

\[
\psi_{dr} = -L_m i_{ds} + L_r i_{dr},
\]

\[
\psi_{qr} = -L_m i_{qs} + L_r i_{qr}.
\]

where \( L_m \) is the mutual inductance of the stator and the rotor, \( L_s \) is the stator inductance, and \( L_r \) is the stator inductance. The total active power generated by the DFIG can be divided into two parts: the active power from the stator, and the active power from the rotor which is injected into the wind farm collector system through the RSC. Therefore,

\[
P_g = P_s + P_r.
\]

where \( P_g \) is the total active power generated by the DFIG, \( P_s \) is the active power from the stator, and \( P_r \) is the active power from the rotor. \( P_s \) is controlled by regulating rotor q-axis current, which can be expressed as,

\[
P_s = \frac{3L_m \psi_m \omega_s}{2L_s} i_{qr}.
\]

where \( \psi_m \) is the stator flux. The rotor absorbs active power from the AC grid when the DFIG operates in the sub-synchronous speed mode, and releases active power when the DFIG operates in the super-synchronous speed mode. Then, the rotor active power can be expressed as,

\[
P_r = -s_g P_s,
\]

where \( s_g \) is the slip ratio. In general, the time constant of the outer active power loop is considerably smaller than the inner current loop. The dynamic performance of the inner current loop can be described as a first-order lag function. Thus, the RSC model can be simplified as shown in Fig. 5.

Define \( \Delta i_{qr}, \Delta P_g, \Delta P_{ref}, \) and \( \Delta P_{int} \) as,

\[
\Delta i_{qr} = i_{qr} - i_{qr,0},
\]

\[
\Delta P_g = P_g - P_{g,0},
\]

\[
\Delta P_{ref} = P_{ref} - P_{ref,0},
\]

\[
\Delta P_{int} = P_{int} - P_{int,0}.
\]
where \( P_{\text{ref}} \) is the active power reference for the DFIG, \( P_{\text{int}} \) is the integral of the error between \( P_{\text{ref}} \) and \( P_g \), \( i_{qr,0} \), \( P_{g,0} \), \( P_{\text{ref},0} \), and \( P_{\text{int},0} \) are the initial value of \( i_{qr} \), \( P_g \), \( P_{\text{ref}} \), and \( P_{\text{int}} \), respectively. Then, the incremental state space model of the RSC can be derived as,

\[
\Delta i_{qr} = \frac{1}{1 + sT_{ir}} \left( k_{p,r} + k_{i,r} \right) (\Delta P_{\text{ref}} - \Delta P_g),
\]

\[
\Delta P_g = \frac{1}{1 + sT_{fr}} \left( 1 - s \right) \left( \frac{3L_m \psi_m \omega_s}{2L_s} \right) \Delta i_{qr},
\]

\[
\Delta P_{\text{int}} = \frac{\Delta P_{\text{ref}} - \Delta P_g}{s}.
\]

where \( k_{p,r} \) and \( k_{i,r} \) are the proportional and integral gains of the proportional-integral (PI) controller of the outer loop, respectively, \( T_{ir} \) is the time constant of the inner loop, and \( T_{fr} \) is the active power filter time constant of the DFIG. The state space model is represented in a matrix form as,

\[
\Delta \dot{x}_r = A_r \Delta x_r + B_r \Delta u_r,
\]

\[
A_r = \begin{bmatrix} -\frac{1}{T_e} & 0 & (1 - s \frac{3L_m \psi_m \omega_s}{2L_s}) \frac{1}{T_e} \\ -1 & 0 & 0 \\ -\frac{1}{T_{ir}} & \frac{1}{T_{ir}} & -\frac{1}{T_{ir}} \end{bmatrix},
B_r = \begin{bmatrix} 0 \\ 1 \frac{V_g}{T_e} \end{bmatrix}.
\]

### 3.2. GSC Model

The GSC is to regulate the DC link voltage and provide a certain degree of reactive power support for the wind farm collector system. The control strategy implemented in the GSC realizes decoupled control of the DC voltage and reactive power, which is achieved by grid current regulation in a grid voltage-oriented synchronously rotating reference frame. The d-axis of the reference frame is oriented along with the grid voltage vector. Because the impact of the GSC active power output is small, the details of the GSC model are not described.

### 3.3. ESS Model

The ESS is storing excessive wind power when the active power dispatch command is less than the available wind power, and releasing power when the active power dispatch command is higher than the available wind power. The ESS consists of a lead-acid battery and a two-quadrant DC/DC converter. The topology of the DC/DC converter is shown in Fig. 6.

In Fig. 6, \( U_{\text{ESS}} \) is the terminal voltage of the ESU, \( V_1 \) and \( V_2 \) are the insulated gate bipolar transistor (IGBT) switches, \( D_1 \) and \( D_2 \) are the diodes, \( i_{dc} \) is the charge/discharge current from the ESS to the DC link, \( u_{dc} \) is the voltage of the DC link, and \( i_L \) is the charge/discharge current of the ESU. The DC/DC converter can operate in the buck or boost mode, depending on the status of the two IGBT switches. If the switch \( V_1 \) is close and \( V_2 \) is open, the DC/DC converter is operated in the boost mode. The power flows from the DC link to the ESU. If the switch \( V_1 \) is open and \( V_2 \) is close, the DC/DC converter is operated in the boost mode. The battery charges power to the inductance \( L \). The power flows from the battery to the DC link when \( V_2 \)
The energy change in the ESS can be regarded as the integral of the charge and discharge power. Then, the energy stored in the ESS can be expressed as,

\[ C_{\text{ESS}} = C_{\text{ESS,0}} - \int P_{\text{ESS}} dt. \]  

(20)

where \( C_{\text{ESS}} \) is the energy stored in the ESS, \( C_{\text{ESS,0}} \) is the initial energy, and \( P_{\text{ESS}} \) is the charge/discharge power of the ESS. In reality, the ESS has losses, e.g., refrigeration systems increase heat load, which leads to power losses, because the temperature is reduced to store excessive energy [28]. Then, (12) is replaced by,

\[ C_{\text{ESS}} = C_{\text{ESS,0}} - \int P_{\text{ESS}} dt - \eta L C_{\text{ESS,0}}. \]  

(21)

where \( \eta \) is the loss coefficient. The typical double closed-loop control is used. Define \( P_{\text{ESS}}^{\text{ref}} \) as the active power reference for the ESS. The DC/DC converter control scheme is shown in Fig. 7.

The active power reference of the ESS is compared with the actual measurement. A PI controller is used to generate the inner loop current references. The duty cycle of the IGBT is obtained by the inner loop PI controller. Generally, the dynamic response of the inner loop is between 5-10 times slower than the switching frequency. Considering the fast dynamics of the inner control loop, it can be simplified as a first-order lag function. The DC/DC converter control loop is shown in Fig. 8.

where \( k_{d,p} \) and \( k_{d,i} \) are the proportional and integral gains of the PI controller of the outer loop, respectively, \( T_{id} \) is the time constant of the inner loop, and \( T_{id}^{\text{ref}} \) is the time constant of the active power filter of the DC/DC converter. Define \( \Delta C_{\text{ESS}}, \Delta \eta, \Delta P_{\text{ESS}}, \Delta P_{\text{ESS}}^{\text{ref}}, \text{ and } \Delta P_{\text{ESS}}^{\text{ref}} \) as,
\[ \Delta C_{\text{ESS}} = C_{\text{ESS}} - C_{\text{ESS},0}, \]  
(22)  
\[ \Delta i_L = i_L - i_{L,0}, \]  
(23)  
\[ \Delta P_{\text{ESS}} = P_{\text{ESS}} - P_{\text{ESS},0}, \]  
(24)  
\[ \Delta P_{\text{ref}}^{\text{ESS}} = P_{\text{ref}}^{\text{ESS}} - P_{\text{ref}}_{\text{ESS},0}, \]  
(25)  
\[ \Delta P_{\text{int}}^{\text{ESS}} = P_{\text{int}}^{\text{ESS}} - P_{\text{int}}_{\text{ESS},0}. \]  
(26)

where \( P_{\text{int}}^{\text{ESS}} \) is the integral of error between \( P_{\text{ref}}^{\text{ESS}} \) and \( P_{\text{ESS}}, i_{L,0}, P_{\text{ESS},0}, P_{\text{ref}}_{\text{ESS},0} \), and \( P_{\text{int}}_{\text{ESS},0} \) are the initial value of \( i_L, P_{\text{ESS}}, P_{\text{ref}}^{\text{ESS}}, \) and \( P_{\text{int}}^{\text{ESS}}, \) respectively. Then, the incremental state space model of the DC/DC converter can be derived as,

\[ \Delta \dot{C}_{\text{ESS}} = - \Delta P_{\text{ESS}} - P_{\text{ESS},0}, \]  
(27)  
\[ \Delta i_L = \frac{1}{1 + s T_{\text{id}}} (k_p^{\text{d}} + \frac{k_p^{\text{id}}}{s}) (\Delta P_{\text{ref}}^{\text{ESS}} - \Delta P_{\text{ESS}}), \]  
(28)  
\[ \Delta P_g = \frac{1}{1 + s T_{\text{fd}}} U_{\text{ESS}} \Delta i_L, \]  
(29)  
\[ \Delta P_{\text{int}} = \frac{\Delta P_{\text{ref}}^{\text{ESS}} - \Delta P_{\text{ESS}}}{s}. \]  
(30)

The state space model is represented in a matrix form as,

\[ \Delta x_E = A_E \Delta x_E + B_E \Delta u_E + E_E, \]  
(31)  
\[ \Delta y_E = C_E \Delta x_E. \]  
(32)

where

\[ \Delta x_E = \begin{bmatrix} \Delta C_{\text{ESS}}, \Delta P_{\text{ESS}}, \Delta P_{\text{int}}^{\text{ESS}}, \Delta i_L \end{bmatrix}^T, \]
\[ \Delta u_E = \Delta P_{\text{ref}}^{\text{ESS}}, \Delta y_E = \Delta C_{\text{ESS}}, \]
\[ A_E = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & -\frac{1}{T_a} & 0 & \frac{U_{\text{ESS}}}{T_a} \\ 0 & -1 & 0 & 0 \\ 0 & \frac{i_p}{T_a} & \frac{i_p}{T_a} & -\frac{1}{T_a} \end{bmatrix}, \]
\[ B_E = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \]
\[ E_E = \begin{bmatrix} -P_{\text{ESS},0} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \]
\[ C_E = \begin{bmatrix} 1, 0, 0, 0 \end{bmatrix}. \]

3.4. WT Mechanical System Model

The nonlinear variable speed WT system developed by the National Renewable Energy Laboratory (NREL) is used in this paper [29], [30]. Because the change rate of the pitch angle has a big impact on the state of the WT during the wind farm control period, the dynamics of the pitch actuator should be considered.
According to the analytical approach in [31], the WT mechanical system model can be expressed as,

\[
\begin{align*}
\Delta \beta &= \frac{K_{c,0}}{T_6 K_{r,0}} \Delta \beta^{ref} - \frac{1}{T_6} \Delta \theta + \frac{K_{c,0}}{T_6} (\theta_0 - \theta_0), \\
\Delta \theta^{ref} &= \frac{K_p}{T_4} \Delta \omega_t - (\frac{K_p}{T_4} - K_i) \Delta \omega_t + K_i (\omega_{t,0} - \omega_{t,0}^{\text{meas}}), \\
\Delta \omega_t &= \frac{\eta J_g \omega t}{J_1} \Delta \beta + \frac{\eta J_g \omega t}{J_1} \Delta \omega_g + \frac{\eta^2}{\mu J_g \omega t^2} \Delta \omega_t \\
&- \frac{\eta}{\mu J_g \omega t^2} \Delta P_{g,0} + \frac{\eta}{J_4} (T_{g,0} - \eta J_4 \omega_0), \\
\Delta \omega_0 &= \frac{1}{T_1} \Delta \omega_0 - \frac{1}{T_1} \Delta \omega_1, \\
\Delta T_s &= \frac{\eta J_g K_{rT}}{J_1} \Delta \beta + \frac{\eta^2 J_g K_{rT}}{J_1} \Delta \omega_g, \\
&- \frac{\eta J_g P_{g,0}}{\mu J_g \omega_0} \Delta \omega_t + \frac{\eta J_g}{\mu J_g \omega_0} \Delta P_{g,0}^{\text{ref}}, \\
\Delta F_1 &= K_{gF} \Delta \beta + K_{gF} \Delta \omega_g.
\end{align*}
\]

where \(\theta\) is the pitch angle of the WT, \(\theta_0\) is the initial pitch angle of the WT, \(\beta = K_c \theta, \omega_t\) is the generator speed, \(\omega_{t,0}\) is the initial measured generator speed, \(\omega_t\) is the filtered speed, \(\omega_{t,0}\) is the initial filtered speed, \(T_s\) is the shaft torque, \(F_1\) is the thrust force, \(T_a\) is the aerodynamic torque, \(T_{g,0}\) is the initial aerodynamic torque, \(T_g\) is the generator torque, \(T_{g,0}\) is the initial generator torque, \(\eta_g\) is the gear box ratio, and \(J_1 = J_g + \eta^2 J_g\) is the equivalent mass obtained by the merging rotor mass \(J_g\) and generator mass \(J_p\) and \(J_1\) denote the proportional and integral gains of the pitch controller, respectively, \(K_{c,0} = K_0 + 2 \eta K_{r,0}\) and \(K_0\) and \(K_1\) are constant. \(K_{rT}, K_{gT}, K_{gF}\) are the coefficients derived from the Taylor approximations of \(T_s\) and \(F_1\) at the initial operating point.

Define \(K_{\text{RSC}} = (1 - s) \frac{M_{\omega_0^{\text{rated}}}}{2 T_2 T_4} \). Then, combine with the RSC model, the incremental state-space DFIG WT model around an operating point can be formulated as,

\[
\begin{align*}
\Delta x_w &= A_w \Delta x_w + B_w \Delta u_w + E_w, \\
\Delta y_w &= C_w \Delta x_w.
\end{align*}
\]

where \(\Delta x_w = [\Delta P_g, \Delta P_{\text{m}}, \Delta i_{q}, \Delta \beta^{ref}, \Delta \beta, \Delta \omega_t, \Delta \omega_{t,0}, \Delta \omega_{g,0}]^T, \Delta u = \Delta P_{g,0}^{\text{ref}}, \text{ and } \Delta y_w = [\Delta T_s, \Delta F_1, \Delta P_g]^T\). The state-space model matrices are,

\[
A_w = \begin{bmatrix}
-\frac{1}{T_6} & 0 & K_{gT} & 0 & 0 & 0 & 0 \\
-\frac{1}{T_6} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{T_4} & \frac{\eta}{J_4} & -\frac{1}{T_4} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{K_{r,0}}{T_6} & -\frac{1}{T_6} & K_t \\
0 & 0 & 0 & \frac{K_{r,0}}{T_6} & -\frac{1}{T_6} & 0 & 0 \\
-\frac{\eta}{\mu J_g \omega_0} & 0 & 0 & \frac{\eta J_4}{J_1} & \frac{\omega_t}{J_1} & -\frac{1}{J_1} & K_{gF} \\
0 & 0 & 0 & 0 & \frac{1}{T_1} & -\frac{1}{T_1} & 0 \\
\end{bmatrix}
\]
3.5. Wind Farm Model

Denote $N_T$ as the set of DFIG WTs. The continuous state space model of a wind farm can be formulated as,

$$
\Delta \dot{x}_{wf} = A_{wf} \Delta x_{wf} + B_{wf} \Delta u_{wf} + E_{wf},
$$

$$
\Delta y_{wf} = C_{wf} \Delta x_{wf},
$$

where

$$
\Delta x_{wf} = \begin{bmatrix} \Delta x_{total}^{ESS}, \Delta P_{total}^{ESS}, \Delta P_{total}^{ESS, int}, \Delta \phi_L, \Delta \chi_{w,E}^{[N]}, \Delta \chi_{E,E}^{[N]} \end{bmatrix}^T,
$$

$$
\Delta u_{wf} = \begin{bmatrix} \Delta P_{ESS, total}^{pref}, \Delta P_{ESS, int}^{pref}, \Delta P_{ESS,1}^{pref}, \ldots, \Delta P_{ESS,N_T}^{pref} \end{bmatrix}^T,
$$

$$
\Delta y_{wf} = \begin{bmatrix} \Delta y_{w,1}, \Delta y_{w,2}, \ldots, \Delta y_{w,N_T} \end{bmatrix}^T,
$$

$$
A_{wf} = \text{diag} \left[ A_{E, E, w, 1}, \ldots, A_{E, w, [N]}, A_{E, 1, w, E}, \ldots, A_{E, 1, [N]} \right],
$$

$$
B_{wf} = \text{diag} \left[ B_{E, E, w, 1}, \ldots, B_{E, w, [N]}, B_{E, 1, w, E}, \ldots, B_{E, 1, [N]} \right],
$$

$$
E_{wf} = \text{diag} \left[ E_{E, E, w, 1}, \ldots, E_{E, w, [N]}, E_{E, 1, w, E}, \ldots, E_{E, 1, [N]} \right],
$$

$$
C_{wf} = \text{diag} \left[ C_{E, E, w, 1}, \ldots, C_{E, w, [N]}, C_{E, 1, w, E}, \ldots, C_{E, 1, [N]} \right],
$$

where $C_{total}^{ESS}$ is the total energy inside the ESSs, $P_{total}^{ESS}$ is the total charge/discharge power of the ESSs, $P_{total}^{ESS, int}$ is the sum of $P_{total}^{ESS, int}$, $P_{total}^{ESS}$ is the sum of the charge/discharge current of the ESSs, and $P_{total}^{ESS, total}$ is the total active reference for the ESSs. The discrete state-space model can be derived from the continuous model, which is,

$$
\Delta x_{wf}(k+1) = A_{wf,d} \Delta x_{wf}(k) + B_{wf,d} \Delta u_{wf}(k) + E_{wf,d},
$$

$$
\Delta y_{wf}(k) = C_{wf,d} \Delta x_{wf}(k). \tag{44}
$$

4. Coordinated Control for Wind Farm Equipped with Distributed ESSs

The wind farm controller coordinates both the WTs and ESSs in the wind farm. ESSs are controlled to track the TSO dispatch command and maintain the SOC within the secure operation range. When the dispatch command is less than the total available wind power in the wind farm, the ESSs will store the excessive wind power. When the dispatch command is higher than the total available wind power in the wind farm, the ESSs are set to compensate for power mismatching between generation and demand. The coordinated control scheme for the wind farm equipped with distributed ESSs has two stages. In the first stage, the wind farm controller drives DFIGs to track the power reference while reducing the fatigue loads by minimizing variations of the thrust force and shaft torque of WTs, which consider the total available active power of ESSs. In the second stage, the controller coordinates the distributed ESSs inside the wind farm to keep the SOC of each ESS close to the average.
4.1. Energy Management for ESSs

The SOC of each ESS should be kept within the secure operation range. For the \( i \)th ESS, 
\[
SOC_{\text{min}} \leq SOC_i \leq SOC_{\text{max}},
\]
where \( SOC_i \) is the SOC of the \( i \)th ESS, \( SOC_{\text{min}} \) and \( SOC_{\text{max}} \) are the minimum and maximum SOC of the ESS, respectively. For the ESS charge mode, the available charge energy \( C_{\text{ESS,charge,},i} \) can be expressed as,
\[
C_{\text{charge,},i} = \xi (SOC_{\text{max}} - SOC_i) C_{\text{rated,},i},
\]
where \( C_{\text{rated,},i} \) is the rated capacity of the \( i \)th ESS, and \( \xi \) is a ratio for the available energy, which ensure that an ESS does not use all the energy in each control period. For the ESS discharge mode, the available discharge energy \( C_{\text{discharge,},i} \) can be expressed as,
\[
C_{\text{discharge,},i} = \xi (SOC_i - SOC_{\text{min}}) C_{\text{rated,},i},
\]

Then, considering the charge/discharge power limits of the DC/DC converter, the available charge/discharge power \( P_{\text{charge,},i} \) \( P_{\text{discharge,},i} \) can be expressed as,
\[
P_{\text{charge,},i} = \begin{cases} \frac{C_{\text{charge,},i} \Delta t}{C_{\text{rated,},i}} & \text{if } \frac{\Delta t}{C_{\text{charge,},i} \Delta t} \leq P_{\text{lim,},i} \text{ESS} \\ P_{\text{lim,},i} \text{ESS} & \text{if } \frac{\Delta t}{C_{\text{charge,},i} \Delta t} \geq P_{\text{lim,},i} \text{ESS} \end{cases}
\]
\[
P_{\text{discharge,},i} = \begin{cases} \frac{C_{\text{discharge,},i} \Delta t}{C_{\text{rated,},i}} & \text{if } \frac{\Delta t}{C_{\text{discharge,},i} \Delta t} \leq P_{\text{lim,},i} \text{ESS} \\ P_{\text{lim,},i} \text{ESS} & \text{if } \frac{\Delta t}{C_{\text{discharge,},i} \Delta t} \geq P_{\text{lim,},i} \text{ESS} \end{cases}
\]
where \( P_{\text{lim,},i} \text{ESS} \) is the power output limit of the ESS, and \( \Delta t \) is the control period. The total available charge/discharge active power for all ESSs \( P_{\text{charge,},\text{total}} \) \( P_{\text{discharge,},\text{total}} \) can be expressed as,
\[
P_{\text{charge,},\text{total}} = \sum_{i=1}^{\text{\#E}} P_{\text{charge,},i} \text{ESS},
\]
\[
P_{\text{discharge,},\text{total}} = \sum_{i=1}^{\text{\#E}} P_{\text{discharge,},i} \text{ESS},
\]

4.2. Objective Function for the First Stage

The MPC is a widely used control method. In the MPC, the control input is obtained by solving a discrete-time optimal control problem over a given horizon. An optimal control input sequence is generated and only the first control in the sequence is applied. The principle of the MPC is illustrated in Fig. 9. The control period is \( T_c \), and the prediction horizon is \( T_p \). The control actions are only changed at the beginning of the control period and maintained within the control period.

![Fig. 9. Principle of MPC.](image-url)
The SOC level of ESSs should be kept close to the SOC reference. To limit the SOC of all ESSs within the range close to the medium SOC level as much as possible, the first control objective is to maintain the total energy stored in the ESSs close to the medium level. The second objective is to minimize the fluctuation of the shaft torque, which is transmitted through the gearbox. The oscillatory transient of the shaft torque causes microcracks in the material, which can further lead to the component failure. The third objective is to minimize the fluctuation of the thrust force. For the tower structure, the WT tower may be excited by the thrust force caused by the wind flowing on the rotor. The oscillatory transient leads to an undesired nodding of the tower, causing fatigue of the WT tower. Accordingly, the cost function is expressed as,

$$\min \sum_{i=1}^{\mathcal{N}_T} \sum_{k=1}^{N_p} \| C_{\text{ESS},i}(k) - \eta_i C_{\text{ESS,0}} \|_2^2 + \| \Delta T_{\text{s},i}(k) \|_2^2 + \| \Delta F_{\text{t},i}(k) \|_2^2 .$$  (52)

where \( N_p \) is the predictive steps of MPC, \( C_{\text{ESS,0}} \) is the medium energy of the total ESS capacity, \( Q_C \) is a weighting factor for minimizing the deviation of energy storage to its medium value, \( Q_T \), and \( Q_F \) are the weighting factors for minimizing the variations of shaft torque and thrust force, respectively. For a wind farm, the total active power output should track the power reference from the TSO as,

$$\sum_{i=1}^{\mathcal{N}_T} \sum_{k=1}^{N_p} || C_{\text{ESS},i}(k) - \eta_i C_{\text{ESS,0}} \|_2^2 ,$$  (53)

where \( P_{\text{pref}} \) is the active power reference for the DFIG wind farm. For the \( P_{\text{total}} \), the constraint is as,

$$-P_{\text{charge, max}} \leq P_{\text{total}} \leq P_{\text{discharge, max}} \ .$$  (54)

For a WT, the available power constraint is,

$$0 \leq P_{\text{avg},i} \leq P_{\text{avg},i}, \forall i \in \mathcal{N}_T .$$  (55)

where \( P_{\text{avg},i} \) is the available wind power for the \( i \)th WT.

### 4.3. Objective Function for the Second Stage

In the second stage, the optimization problem is formulated to coordinate all active power outputs of the distributed ESSs inside the wind farm, which aims to keep the SOC of each ESS close to the average while tracking the total active power reference from the first stage control. With the stage second control, all ESSs can achieve a fair active power output according their SOCs level. Accordingly, the cost function is expressed as,

$$\min \sum_{i=1}^{\mathcal{N}_T} \sum_{k=1}^{N_p} || C_{\text{ESS,j}}(k) - \eta_i C_{\text{ESS,j}}^0 \|_2^2 .$$  (56)

For the \( i \)th ESS, the charge power reference constraint is,

$$-P_{\text{charge, max}} \leq P_{\text{ESS,i}} \leq P_{\text{discharge, max}} \ , \forall i \in \mathcal{N}_T .$$  (57)

The total charge/discharge active power output for the wind farm should track the total ESS power reference from the first stage control as,

$$\sum_{j=1}^{\mathcal{N}_T} P_{\text{ESS,j}} = P_{\text{total}} \ .$$  (58)
5. Case Study

5.1. Test System

In this section, a wind farm with 10×5 MW DFIG WT equipped with distributed ESSs is used to demonstrate the performance of the proposed control scheme. The wind field model that considers turbulences and wake effects is generated from SimWindFarm, a toolbox for dynamic wind farm modelling, simulation and control. The wind farm control is carried out in every 1 s. In order to examine the performance of the proposed control method, the simulation results are compared with the results based on the centralized optimal active power control scheme without ESSs in [31]. The parameters of the simulation system are listed in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{WF}}^{\text{rated}}$</td>
<td>WT rated capacity (MW)</td>
<td>5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Gearbox ratio</td>
<td>97</td>
</tr>
<tr>
<td>$J_g$</td>
<td>Generator inertia (kg m²)</td>
<td>534.116</td>
</tr>
<tr>
<td>$J_t$</td>
<td>Rotor inertia (kg m²)</td>
<td>35444067</td>
</tr>
<tr>
<td>$\mu_g$</td>
<td>Generator efficiency</td>
<td>0.944</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density (kg/m³)</td>
<td>1.2231</td>
</tr>
<tr>
<td>$R$</td>
<td>Rotor blade length (m)</td>
<td>63</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Filter time constant (s)</td>
<td>0.6</td>
</tr>
<tr>
<td>$T_{\theta}$</td>
<td>Pitch angle time constant (s)</td>
<td>0.1</td>
</tr>
<tr>
<td>$K_P$</td>
<td>Proportional gain of the pitch control</td>
<td>0.2143</td>
</tr>
<tr>
<td>$K_I$</td>
<td>Integral gain of the pitch control</td>
<td>0.0918</td>
</tr>
<tr>
<td>$K_0$</td>
<td>Constant</td>
<td>1</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Constant</td>
<td>2.1323</td>
</tr>
<tr>
<td>$\omega_{\text{g}}^{\text{rated}}$</td>
<td>Rated generator speed (rad/s)</td>
<td>122.91</td>
</tr>
<tr>
<td>$f_{\text{nom}}$</td>
<td>Rated collect system frequency (Hz)</td>
<td>60</td>
</tr>
<tr>
<td>$p$</td>
<td>Generator pole-pairs number</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 2. Converter, ESS, and control parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{rated RSC}}$</td>
<td>RSC rated capacity (MW)</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{\text{rated GSC}}$</td>
<td>GSC rated capacity (MW)</td>
<td>2.0</td>
</tr>
<tr>
<td>$P_{\text{rated DC}}$</td>
<td>DC converter rated capacity (MW)</td>
<td>0.5</td>
</tr>
<tr>
<td>$K^p_{r,p}$</td>
<td>Proportional gain of the RSC</td>
<td>1</td>
</tr>
<tr>
<td>$K^i_{r,i}$</td>
<td>Integral gain of the RSC</td>
<td>100</td>
</tr>
<tr>
<td>$T_{ir}$</td>
<td>inner loop time constant of the RSC (s)</td>
<td>0.01</td>
</tr>
<tr>
<td>$T_{fr}$</td>
<td>filter time constant of the RSC (s)</td>
<td>0.001</td>
</tr>
<tr>
<td>$K^p_{d,p}$</td>
<td>Proportional gain of the DC/DC converter</td>
<td>1</td>
</tr>
<tr>
<td>$K^i_{d,i}$</td>
<td>Integral gain of the DC/DC converter</td>
<td>50</td>
</tr>
<tr>
<td>$T_{id}$</td>
<td>inner loop time constant of the DC/DC converter (s)</td>
<td>0.01</td>
</tr>
<tr>
<td>$T_{fd}$</td>
<td>filter time constant of the DC/DC converter (s)</td>
<td>0.001</td>
</tr>
<tr>
<td>$U_{\text{rated ESS}}$</td>
<td>Rated terminal voltage of the battery (V)</td>
<td>50</td>
</tr>
<tr>
<td>$C$</td>
<td>Rated capacity of the battery (Ah)</td>
<td>100</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Ratio for the available energy</td>
<td>0.2</td>
</tr>
<tr>
<td>$T_c$</td>
<td>control period (s)</td>
<td>1</td>
</tr>
<tr>
<td>$T_p$</td>
<td>prediction horizon (s)</td>
<td>5</td>
</tr>
</tbody>
</table>

5.2. Control Performance

The performance of the proposed control scheme is tested in this subsection. WT8 is selected as the representative DFIG-based WT to illustrate the results. The total simulation time is set as 600 s. Fig. 10 shows the total available wind power and the dispatch command from the TSO. The total available wind power fluctuates between 40 MW to 50 MW during $t = 0$ − 280 s. During $t = 280$ − 480 s, the available wind power reaches the rated power. After $t = 480$ s, the total available wind power gradually decreases. The dispatch command is set as 25 MW during $t = 0$ − 250 s. The wind farm operates in the constant power output mode. Then the dispatch command increases within the ramp limit during $t = 250$ − 350 s. The wind farm operates in the ramping mode. After $t = 350$ s, the dispatch command is set as 50 MW. The wind farm operates in the maximum power point tracking (MPPT) mode. Fig. 11 shows the wind speed of WT8.

Fig. 10. Total available wind power and the dispatch command.

Figs. 12 and 13 show the variations of $T_s$ and $F_i$ of WT8. Because the ESSs relax the active power constraints for DFIGs, the shaft torque variations with the ESSs are considerably smaller than that without ESSs control scheme in both the constant power output and ramping modes. During $t = 0$ − 250 s, $T_s$ with the ESSs fluctuates around 1.5 MNM, and $T_s$ without the ESSs fluctuates around 2 MNM. From $t = 400$ − 500 s, the wind farm is operated in the MPPT. Because the ESSs provide active power support for the wind...
The performance of the shaft torque variation is also better than that without the ESSs control scheme. From $t = 500 - 600$ s, the variations of $T_s$ with the ESSs are nearly the same as those without the ESSs. The DFIGs nearly operate in the MPPT mode due to the active power output limit of ESSs and decreasing available wind power. Thrust force variations with the ESSs are slightly smaller than those without the ESSs control scheme for $t = 0 - 500$ s. The performance is nearly the same from $t = 500 - 600$ s.

The variations of the shaft torque and thrust force of WT8 are also quantified by the standard deviations $\sigma(\Delta T_s)$ and $\sigma(\Delta F_t)$, which are listed in Tables 3 and 4, respectively. During $t = 0 - 250$ s, the standard deviation of $\sigma(\Delta T_s)$ with the ESSs is 0.260 MNM, which is reduced by 52.2% compared with that without the ESSs (0.544 MNM). During $t = 400 - 600$ s, when the wind farm is operated in the MPPT, the standard deviation of $\sigma(\Delta T_s)$ with the ESSs is 0.607 MNM, which is also better than that without the ESSs (0.640 MNM). In the entire control period, the standard deviation of $\sigma(\Delta T_s)$ with ESSs has a 14.0% reduction compared with that without the ESSs. The standard deviation of $\sigma(\Delta F_t)$ has a 2.5% reduction compared with that without the ESSs in the entire control period.

Fig. 14 shows the SOCs of ESSs. The SOC constraints are set as from 0.3 to 0.7. The initial SOC of ESS 1, 3, 5, and 8 is set as 0.45, 0.47, 0.56, and 0.4, respectively. The remaining initial SOCs of the ESSs are set as 0.5. From $t = 0 - 50$ s, all of the ESSs’ SOCs converge to a common value. During $t = 0 - 350$ s, the available wind power is higher than the dispatch command. The SOCs of the ESSs is limited within the range of close to the medium SOC levels. The SOCs fluctuate at approximately 0.5.
Table 3. Standard deviation $\sigma(\Delta T_s)$ of WT8

<table>
<thead>
<tr>
<th>$v_{avr}$ (m/s)</th>
<th>noESS$\sigma(\Delta T_s)$ (MN)</th>
<th>ESS$\sigma(\Delta T_s)$ (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-250 s</td>
<td>13.4</td>
<td>0.544</td>
</tr>
<tr>
<td>250-400 s</td>
<td>15.3</td>
<td>0.283</td>
</tr>
<tr>
<td>400-600 s</td>
<td>10.1</td>
<td>0.640</td>
</tr>
<tr>
<td>Total</td>
<td>12.9</td>
<td>0.470</td>
</tr>
</tbody>
</table>

Table 4. Standard deviation $\sigma(\Delta F_t)$ of WT8

<table>
<thead>
<tr>
<th>$v_{avr}$ (m/s)</th>
<th>noESS$\sigma(\Delta F_t)$ (MN)</th>
<th>ESS$\sigma(\Delta F_t)$ (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-250 s</td>
<td>13.4</td>
<td>0.253</td>
</tr>
<tr>
<td>250-400 s</td>
<td>15.3</td>
<td>0.172</td>
</tr>
<tr>
<td>400-600 s</td>
<td>10.1</td>
<td>0.255</td>
</tr>
<tr>
<td>Total</td>
<td>12.9</td>
<td>0.236</td>
</tr>
</tbody>
</table>

From $t = 350 – 500$ s, the ESSs have to deliver power to track the dispatch command because the available wind power is occasionally lower than dispatch command. The SOCs are maintained at 0.45. After 500 s, the SOCs decrease due to the decreasing available wind power and the unchanged dispatch command. In the last 40 s, the SOCs are maintained at 0.3 because no additional energy output is available to track the dispatch command.

The active power output of WT8 and ESS8 is shown in Fig. 15. During $t = 0 – 50$ s, ESS8 is operated in the charge mode because the initial SOC is lower than the average SOC. ESS8 hits the maximal charge power limit (0.5MW). During $t = 50 – 300$ s, the power output of the ESSs fluctuates between -0.5 MW and 0.5 MW to keep the SOC within the range close to the medium SOC level. During $t = 300 – 520$ s, the charge/discharge power is reduced, which fluctuates around 0. From $t = 520 – 600$ s, the ESSs deliver the maximum power to track the dispatch command. Fig. 16 shows the active power output of the wind farm. Compared with the dispatch command in Fig. 10. During $t = 0 – 520$, the wind farm can accurately track the dispatch command. During $t = 520 – 600$ s, due to the decreasing available wind power and the unchanged dispatch command, the active power output of the wind farm is reduced. However, with the ESSs, the wind farm can accurately track the dispatch command until the ESSs release all available energy stored above the minimum limit.
Fig. 17 shows the terminal voltage of WT8. Since the WT active power outputs with and without the ESSs are different, the voltage performances are different. During $t = 0 - 250$ s, the voltage of WT8 with the ESSs is kept at about 1.005 p.u., which is lower than that without the ESSs (1.007 p.u.). During $t = 350 - 500$ s, the voltage performances are similar. During $t = 480 - 550$ s, since the active power output of the wind farm with the ESSs is higher than that without the ESSs, the voltage with ESSs is higher than that without the ESSs. The electrical torque of DFIG8 is shown in Fig. 18. During $t = 0 - 250$ s, the variations of the electrical torque with the ESSs fluctuate around 0.015 MNM, and the variations of the electrical torque without the ESSs fluctuate around 0.02 MNM. During $t = 350 - 600$ s, the variations with the ESSs and without the ESSs are similar.

Fig. 19 shows the rotor angular speed of DFIG8. The angular speed fluctuates around 1200 rmp during $t = 0 - 550$ s. During $t = 350 - 500$ s, the angular speed decreases to around 1140 rmp due to the available wind power increasing. Figs. 20-21 show the q-axis current of the stator and rotor, respectively. The variations of the q-axis current with ESSs are lower than that without the ESSs, which are similar as the variation performances of the shaft torque. The q-axis current of the stator is nearly proportional to the q-axis current of the rotor. The active power output of the DFIG stator can be efficiently controlled by regulating the q-axis current of the rotor.
Fig. 18. Electrical torque of DFIG8.

Fig. 19. Angular speed of DFIG8.

Fig. 20. q-axis current of DFIG8 stator.

Fig. 21. q-axis current of DFIG8 rotor.

6. Discussion

In this section, the optimal active power control scheme for the DFIG-based wind farm equipped with distributed ESSs is discussed.

The distributed ESSs are used for enhancing flexibility and controllability of the DFIG-based wind farm. With the ESSs, fatigue loads of WTs can be reduced efficiently. Case study shows that the performances of fatigue loads minimization with the ESSs are better than that without the ESSs. Fatigue loads can be
reduced by optimizing the active power output according their local wind condition. With the ESSs, the equivalent operation range of the WT active power output can be increased.

The optimal active power control scheme proposed in this paper can effectively manage the ESSs. When the dispatch command is less than the total available wind power, the SOC of all ESSs can be kept within the range of close to the medium SOC levels. And the fair active power output among ESSs is achieved by using the second stage optimal control. When the dispatch command is higher than the total available wind power, the ESSs are controlled to keep SOC close to their average level while providing active power to balance the mismatch. Since the dynamic control model of the ESS converter and their active power output constraints are considered in the optimal control scheme, the control accuracy of the ESS is acceptable.

Compared with a wind farm without the ESSs, the biggest disadvantage is the cost. However, compared with a centralized ESS, since less electronic devices are needed, the cost for electronic devices is reduced.

7. Conclusion

In this paper, an optimal active power control scheme based on the MPC is designed for the DFIG-based wind farm equipped with distributed ESSs. The proposed scheme coordinates power outputs among the DFIG-based WTs and distributed ESSs inside the wind farm. A MPC based optimization problem is formulated, which considers the WT mechanical models and converter dynamic response model. The active power references are optimized and redistributed among the WTs and ESSs according to their local wind conditions. The wind farm operator can not only minimize fatigue loads, but also manage the charge/discharge power of all ESSs to maintain the SOC at the average value. Case studies show that the control scheme can efficiently reduce the fatigue loads by minimizing the variations of thrust force and shaft torque and keeping the ESSs’ SOC close to the average value. The proposed optimal active power control scheme is suitable for the real-time control of large-scale wind farms. Through the distributed ESSs, the wind farm controller can more flexibly regulate WTs inside the wind farm.

Appendix

Optimal Active Power Control for a Wind Farm Without ESSs

Firstly, the centralized controller minimizes the variation of the shaft torque and thrust force of the WTs to reduce fatigue loads. Secondly, a fair active power sharing among the WTs within a wind farm is also considered. Accordingly, the cost function is expressed as,

$$
\min \sum_{j=1}^{N_T} \sum_{k=1}^{N_p} \| P_{g,j}(k) - P_{pd,j} \|^2_Q + \| \Delta T_{sw}(k) \|^2_Q + \| \Delta F_{sw}(k) \|^2_Q
$$

(59)

where $Q_p$ is a weighting factor for minimizing the deviation of power reference to its proportional value, and $P_{pd,j}$ is the proportional dispatch (PD) power reference for the $i$th WT according to its available power, which can be calculated by,

$$
P_{pd,i} = \alpha_{pd} P_{WF}^{ref}, \quad \alpha_{pd} = \frac{P_{avi}^{vi}}{P_{WF}^{ref}}
$$

(60)

For the wind farm, the total active power output should track the power reference from the TSO,

$$
\sum_{j=1}^{N_T} P_{g,j}^{ref} = P_{WF}^{ref}
$$

(61)

For a WT, the available power limit is as,

$$
0 \leq P_{g,j}^{ref} \leq P_{avi}^{vi}, \forall i \in N_T.
$$

(62)
References


