Optimal reactive power dispatch of renewable energy based on primal-dual interior point filter method

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Optimal reactive power dispatch of renewable energy based on primal-dual interior point filter method

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Abstract. This paper proposes an optimal reactive power dispatch strategy of the renewable energy. It coordinates the different reactive power sources by considering the topological structure and the feeder lines impedance of the renewable energy. The primal-dual interior point filter method is utilized to solve such a nonlinear optimization problem and bind the voltage of the point of common coupling of the renewable energy to the reference value. The proposed strategy gives priority to the reactive power output of wind turbine generators to ensure the dynamic compensation devices could have enough reactive power reserves and meanwhile equipoises terminal voltage profiles among all the controlled wind turbine generators. The simulation results of an actual renewable energy in North China validate the control performance of the proposed optimization model and the effectiveness of the primal-dual interior point filter method.

1. Introduction
Wind power has become one of the most rapidly growing renewable energy sources due to its mature technology and rich resources over the past two decades. However, the increasing integration of wind farms has represented serious challenges for the power grids due to the random fluctuation feature of wind power. Most of the transmission system operators around the world have demanded extended reactive power supply capability of the wind farms for ensuring the security and stability of the power grids. According to these grid codes [1-3], the wind farms are required to be able to control the voltage profile at the point of common coupling (PCC) under steady-state operation condition.

In order to meet the control requirements of the PCC by employing the available reactive power sources (RPSs) within the wind farm, researchers in the past have investigated in the reactive power control of the wind farm. According to the features of different RPSs, the reactive power control methods in recent literatures can be mainly divided into two kinds, the shunt compensation devices control (SCDC) [4-5] and the wind turbine generators group control (WTGGC) [6-8]. The SCDC is generally used in the old-fashioned wind farms due to the fixed-speed wind turbine generators which don’t possess the reactive power regulation ability. Thus the centralized shunt compensation devices such as the capacitor banks and the static var compensator (SVC) installed in the substation of the wind farm are the only available RPSs to control the PCC. The WTGGC is proposed on the basis of the development of the variable-speed wind turbine generator such as the doubly-fed induction generators (DFIG) which can provide flexible reactive power to the grid. In this control method, the dispersed DFIGs in the wind farm are the only available RPSs and they are equivalently considered as a whole group to supply reactive support. Both the two control methods mentioned above ignore the topological structure and the feeder lines impedance of the wind farm, and the amount of reactive power adjustment of all RPSs within the wind farm is calculated according to the deviation of the
reference and the actual value of PCC by sensitivity method. On the basis of the above analysis, this paper proposes an optimal reactive power dispatch (ORPD) strategy of the wind farm aims at enhancing the SVC reactive power reserve and equiposing the DFIG terminal voltage profile.

The ORPD problem is a particular form of the optimal power flow, in which the purpose is to find the control settings of the RPSs to optimize the given objective functions simultaneously satisfying all equality and inequality constraints. Similarly to the full optimal power flow problem, the ORPD problem is a nonlinear, nonconvex and large scale optimization problem due to the power flow equality constraints. In order to achieve the better convergence, in this work the primal-dual interior point filter method (PDIPFM) which avoids the use of merit functions and the updating of penalty parameters is employed to solve the ORPD problem of the wind farm. The simulation results of an actual renewable energy in North China validate the control performance of the proposed optimization model and the effectiveness of the primal-dual interior point filter method.

2. Mathematical model
The objective functions and constraints of the ORPD of wind farm are formulated as follows.

2.1. Objective functions

2.1.1. DFIG terminal voltage balance index Both the impedance of the feeder lines and the reactive power output of the DFIGs will affect the DFIGs terminal voltage profiles. Keeping the DFIGs terminal voltage magnitude balanced and far away from the protection thresholds is an effective means to avoid the cascading trip-off of DFIGs. Thus the minimization of the voltage profiles unbalance of the DFIGs is one of the objectives in the ORPD of wind farm. The DFIG terminal voltage balance index can be expressed as

\[ f_d = \sum_{i=1}^{i \in \mathcal{N}_G} \left( U_{G_i} - U_{G_i}^{ref} \right)^2 \]  

(1)

where \( i \in \mathcal{N}_G \), \( \mathcal{N}_G \) is the set of the DFIGs in the wind farm; \( U_{G_i} \) and \( U_{G_i}^{ref} \) denote the actual voltage value and the voltage reference of the \( i \)-th DFIG, respectively.

2.1.2. SVC reactive power reserve index The flexible reactive power supplied by the SVCs during the disturbance can enhance the fault ride through capability of the wind farm. Thus the minimization of the consumption of the SVCs under the steady-state operation condition is significant for the security of the wind farm. The SVC reactive power reserve index can be expressed as

\[ f_q = \sum_{i=1}^{i \in \mathcal{N}_C} \left( Q_i - Q_i^{min} \right)^2 \]  

(2)

where \( i \in \mathcal{N}_C \), \( \mathcal{N}_C \) is the set of the SVCs in the wind farm; \( Q_i \), \( Q_i^{min} \), and \( Q_i^{max} \) denote the actual, the maximum and the minimum reactive power outputs of the \( i \)-th SVC, respectively.

2.2. Constraints
The constraints of the wind farm ORPD problem include the power flow equality constraints, the PCC voltage control constraint and the operating constraints.

2.2.1. Power flow equality constraints. The power flow equality constraints can be expressed as follows.

\[ \Delta P_i = P_{i1} - U_{i1} \sum_{j=1}^{N} U_j \left( G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) = 0 \]  

(3)

\[ \Delta Q_i = Q_{i1} - U_{i1} \sum_{j=1}^{N} U_j \left( G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) = 0 \]  

(4)

2
where \( i \in N_S \), \( N_S \) is the set of the total nodes of the wind farm; \( P_i, Q_i, U_i, \) and \( \theta_i \) are the active power injection, reactive power injection, the voltage magnitude and the voltage phase at node \( i \), respectively; \( G_{ij} \) and \( B_{ij} \) are the real and imaginary parts of the \( ij \)-th element of the admittance matrix, respectively.

### 2.2.2. PCC voltage control constraint

In the hierarchical voltage control system, the wind farm should control the voltage profile of PCC to the reference value given by the higher level control. The PCC voltage control constraint can be expressed as

\[
U_{PCC}^{\text{ref}} - U_{PCC}^\text{err} \leq U_{PCC} \leq U_{PCC}^{\text{ref}} + U_{PCC}^\text{err}
\]

where \( U_{PCC}^\text{err} \) denotes the permitted voltage control error of the PCC.

### 2.2.3. Operating constraints

The operating constraints are the upper and lower bounds of the control variables and the state variables which can be expressed as

\[
\begin{align*}
U_{i_{\min}} & \leq U_i \leq U_{i_{\max}} \\
\theta_{i_{\min}} & \leq \theta_i \leq \theta_{i_{\max}} \\
Q_{C_{i_{\min}}} & \leq Q_i \leq Q_{C_{i_{\max}}} \\
Q_{G_{i_{\min}}} & \leq Q_i \leq Q_{G_{i_{\max}}}
\end{align*}
\]

where generally \( U_{i_{\min}} = 0.9 \) p.u. and \( U_{i_{\max}} = 1.1 \) p.u. under the Per-unit system.

Considering the DFIGs can provide both the inductive reactive power (negative value) and the capacitive reactive power (positive value), in order to avoid the reactive power loss caused by the circular reactive power flow, the reactive power adjustment of each DFIG in the wind farm should have the same orientation, which can be expressed as

\[
\begin{cases}
[0, Q_{G_{i_{\max}}}] & \text{when } U_{PCC}^{\text{ref}} > U_{PCC} + U_{PCC}^\text{band} \\
[Q_{G_{i_{\min}}, 0}] & \text{when } U_{PCC}^{\text{ref}} < U_{PCC} - U_{PCC}^\text{band}
\end{cases}
\]

where \( U_{PCC}^\text{band} \) denotes the dead-band value of PCC voltage control.

### 2.3. Multi-objective optimization approach

In order to consider both the DFIG terminal voltage balance index and the SVC reactive power reserve index, the proposed ORPD problem is a multi-objective optimization problem. In order to avoid the choice of the weight coefficients, the proposed ORPD model is solved using the \( \varepsilon \)-constraint method and the SVC reactive power research index \( f_q \) is transformed into an inequality constraint due to its clear boundary. Therefore the proposed ORPD model can be expressed as

\[
\begin{array}{ll}
\min & f_q(\mathbf{x}) \\
\text{s.t.} & \Delta P_i(\mathbf{x}) \leq \varepsilon_q \\
& \Delta Q_i(\mathbf{x}) = 0 \\
& \mathbf{x} \leq \mathbf{x} \leq \mathbf{x} \\
\end{array}
\]

where \( \mathbf{x} \) denotes the vector of the control variables and dependent variables, \( \mathbf{x} \) and \( \mathbf{x} \) represent bounds on the variables; \( \varepsilon_q \) is the preset boundary of the SVC reactive power research index.

### 3. Primal-dual interior point filter method for wind farm ORPD problem

#### 3.1. The primal-dual barrier approach

We have developed a procedure to solve a general nonlinear optimization problem which is given in the form
\[ \min \ f(x) \]
\[ \text{s.t.} \] \[ e_e(x) = 0 \]
\[ c_i(x) \leq c_i(x) \leq \bar{c} \]
\[ \underline{x} \leq x \leq \bar{x} \]

where \( f(x) \) is the objective function, \( e_e(x) \) as the equality constraints, \( c_i(x) \) as the inequality constraints with the up bound \( \bar{c} \) and low bound \( \underline{c} \). The whole set of the constraints represent the feasible region for \( x \) within which the algorithm must reach a solution.

With the aid of the necessary slack variables \( s = (s_{e1}^T, s_{e2}^T, s_{a1}^T, s_{a2}^T)^T \), (\( s \geq 0 \)) to transform the inequality constraints into the equality constraints, we can apply a barrier method to (9) to form the following succession of sub-problems where \( \mu \) is known as the barrier parameter

\[ \min \ \varphi_\mu (x) \quad \Leftrightarrow \quad f(x) - \mu \sum_i \ln s_i \]

\[ \text{s.t.} \] \[ e_e(x) = 0 \quad \Leftrightarrow \quad e_e(x) - s_e - \underline{c} = 0 \]
\[ c_i(x) + s_{ci} - \bar{c} = 0 \]
\[ c_a(x) + s_a - \bar{x} = 0 \]

We now apply a primal-dual approach introducing the dual variables defined as \( z = \mu S^{-1} e \), where \( S \) is a matrix whose diagonal contains the elements of \( s_i \) and zero valued for the other elements, and \( e \) is a vector with all of its elements equal to 1. Equivalently, the solution of (10) can be interpreted as applying a homotopy method to the primal-dual equations

\[ r_\mu (x, s, \lambda, \eta) = r_\mu (w) = \begin{bmatrix} q(x) - A(x)^T \lambda - C_1 \eta + C_2^T \lambda - C_3^T \eta - z \\ c(x, s) \\ c_2(x, s) \\ S z - \mu e \end{bmatrix} = 0 \]

with the homotopy parameter \( \mu \), which is driven to zero. Here, \( \lambda \) and \( \eta \) correspond to the Lagrange multipliers for \( c(x, s) \) and \( c_a(x, s) \), respectively; \( q(x) \) is the gradient of \( f(x) \); \( A(x) \) is defined as the \( x \)-Jacobian of \( c(x, s) \), namely \( A(x) = \nabla_x c(x, s) \); \( C_1 = \nabla_s c_e(x, s) \), \( C_2 = \nabla_s c(x, s) \) and \( C_3 = -\nabla_s c_a(x, s) \), which are all constant matrices; \( w = (x^T, s^T, \lambda^T, \eta^T)^T \) is just a grouping of variables used in the algorithm. Note, that equations (11) for \( \mu = 0 \) together with "\( s, z \geq 0 \)" are the Karush-Kuhn-Tucker (KKT) conditions for the original problem (9). Those are the first order optimality conditions for (9) if constraint qualifications are satisfied.

Using the individual parts of the primal-dual equations (11), we define the optimality error for the barrier problem as \( E_\mu (w_\mu) = \|r_\mu (w_\mu)\|_\infty \). The overall algorithm terminates if an approximate solution \( \tilde{w}_\mu \) satisfying \( E_\mu (\tilde{w}_\mu) \leq \varepsilon_{tol} \) where \( \varepsilon_{tol} > 0 \) is the user provided error tolerance.

In order to solve the barrier problem (10) for a given fixed value \( \mu \) of the barrier parameter, the Newton’s method is applied to the primal-dual equations (11) in each global iteration \( k \). After removing \( \Delta z_k \) from this system (it can easily be demonstrated \( \Delta z_k = -S_k^{-1} Z_k \Delta x_k - z_k + \mu S_k^{-1} e \)), the search directions \( \Delta w_k \) are obtained from the linearization of (11) at \( w_k \), namely
where $H_k$ denotes the $x$-Hessian of $f(x) - \sum \lambda_i c_i(x,s)$. Once the direction $\Delta w_k$ along which to move has been obtained from (12), we have to calculate the step size $\alpha_k$, so that we can update our variables for the next iteration according to $w_{k+1} = w_k + \alpha_k \Delta w_k$.

In each iteration the barrier parameter is updated according to the following strategy

$$\mu_k = \max \left \{ \frac{\epsilon_{\text{tol}}}{10}, \min \{ \kappa_\mu \mu_{k-1}, \mu_{k-1} \} \right \}$$

where constants $\kappa_\mu \in (0,1), s_\mu \in (1,2)$. In this research work, the default parameters are used: $\kappa_\mu = 0.2$, $s_\mu = 1.5$, $\epsilon_{\text{tol}} = 10^{-6}$ and $\mu_0 = 0.1$.

3.2. The filter method

In this context of solving the barrier problem (10), two quantities $\vartheta_m = \vartheta(w_m)$ and $\theta_m = \theta(w_m)$ are chosen to represent the measure in the objective progress and the measure towards feasibility, which are expressed as

$$\vartheta = f(x) - \mu \sum s_i, \quad \theta = \begin{bmatrix} e(x,s) \\ e_s(x,s) \end{bmatrix}$$

Following this paradigm, we might consider a trial point $x_k(\alpha_k) = x_k + \alpha_k \Delta x_k$ during the backtracking line search to be acceptable, if it leads to sufficient progress toward either goal compared to the current iterate, if

$$\vartheta(x_k(\alpha_k)) \leq (1 - \gamma_\vartheta) \vartheta(x_k)$$

or

$$\theta(x_k(\alpha_k)) \leq \theta(x_k) - \gamma_\theta \theta(x_k)$$

holds for fixed constants $\gamma_\vartheta, \gamma_\theta \in (0,1)$.

The algorithm maintain a filter, a set $F_k \in \{ (\vartheta, \theta) \}$ for each iteration $k$. The filter $F_k$ contains those combinations of constraint violation values $\vartheta$ and the object function values $\theta$ that are prohibited for a successful trial point in iteration $k$: During the line search, a trial point $x_k(\alpha_k)$ is rejected if $(\vartheta(x_k(\alpha_k)), \theta(x_k(\alpha_k))) \in F_k$. We then say that the trial point is not acceptable to the current filter.

At the beginning of the optimization, the filter is initialized to

$$F_0 = \{ (\vartheta, \theta) : \theta \geq \theta_{\text{max}} \}$$

for some $\theta_{\text{max}}$, so that the algorithm will never allow trial points to be accepted that have a constraint violation greater than $\theta_{\text{max}}$. Later, the filter is augmented using the update formula

$$F_{k+1} = F_k \bigcup \{ (\vartheta, \theta) : \theta \geq (1 - \gamma_\theta) \theta(x_k) \land \vartheta \geq \vartheta(x_k) - \gamma_\vartheta \theta(x_k) \}$$

after every iteration. This procedure ensures that the algorithm cannot cycle between two points that alternatingly decrease the constraint violation and the barrier objective function.

3.3. Control flow of wind farm ORPD

The control flow using PDIPFM to solve the wind farm ORPD problem can be shown in Figure 1.
4. Case study and main results

4.1. Simulation system

Table 1. Information of feeder lines in the wind farm.

| Feeder Lines | Length/km | DFIG Numbers* | Feeder Lines | Length/km | DFIG Numbers |
|--------------|-----------|---------------|--------------|-----------|--------------|
| A            | 4.671     | 1-7           | J            | 9.269     | 84-92        |
| B            | 7.792     | 8-16          | K            | 6.94      | 93-102       |
| C            | 7.014     | 17-24         | L            | 4.069     | 103-109      |
| D            | 8.217     | 25-32         | M            | 6.259     | 110-118      |
| E            | 8.642     | 33-41         | N            | 11.375    | 119-131      |
| F            | 12.87     | 42-54         | O            | 11.96     | 132-143      |
| G            | 13.561    | 55-63         | P            | 18.14     | 144-152      |
| H            | 14.32     | 64-70         | Q            | 18.58     | 153-164      |
| I            | 15.65     | 71-83         |              | -         | -            |

*The DFIGs in one feeder line are numbered according to the distance from each generator to the PCC, the shorter distance corresponds to the smaller number.

In this paper, an actual wind farm in North China is employed to verify the validity and performance of the proposed strategy and algorithm. The installed capacity of the wind farm is 246
MW, and the structure of the simulation system is shown in Figure 2. This wind farm consists of 164 DFIGs each rated at 1.5 MW and they are connected to the 220kV infinity grid through seventeen 35kV feeder lines and two 120MVA transformers. There are two SVCs and both the regulating capacities are -20 (inductive) ~ 40 (capacitive) MVar. The distances from each DFIG to the PCC are uneven, and the information of the feeder lines in the wind farm is shown in Table 1.

In this paper, three different reactive power control modes of wind farm are considered for comparison purposes:

1) Mode I, the SCDC is adopted, only the SVCs in the substation take part in the PCC voltage control, the DFIGs operate at unity power factor and do not provide reactive power. The reactive power output of each SVC is according to the equal division shown in (2).

2) Mode II, the WTGGC is adopted, only the DFIGs take part in the PCC voltage control. The reactive power output of each DFIG is according to the equal division shown in (3).

3) Mode III, both the SVCs and the DFIGs take part in the PCC voltage control, and the reactive power of the RPSs are set in accordance with the ORPD strategy proposed in this paper.

The wind power, the reactive power and the voltage profile of the PCC in a time period of 24 hours before any reactive power control are shown in Figure 3 and Figure 4, respectively by solid line when the voltage of the infinity grid is 0.985 p.u.. The three control modes are employed to achieve the voltage control reference curve of the PCC in Figure 4 indicated by the red dotted line.

The algorithm was programmed in C++ and the simulation was run on a Core i3 2.1GHz laptop with 4Gbyte RAM.

4.2. Control performance comparison of different modes

4.2.1. Control performance comparison when wind power continuously changed

The control performances of the three different control modes for a time period of 24 hours are compared in this
part. The reactive power control programs are implemented every 30 seconds. The reactive power output of SVCs and DFIGs in different control modes is shown in Figure 5. The maximum terminal voltage of the DFIGs in different control modes is shown in Figure 6.

From Figure 5 and Figure 6, it can be seen that both the control performances of Mode I and Mode II are one-sided. The max terminal voltage of DFIGs in Mode I is relatively low because the DFIGs don’t take part in the reactive power control, but the output of the SVCs is the largest. In Mode II, the equal reactive power output of each DFIG brings not only the largest SVCs reserves but also the highest terminal voltage. In Mode III, the DFIGs group is given priority to providing the basic reactive power support in the proposed ORPD strategy for ensuring the SVCs have enough reactive power reserves. In addition, as can be seen from Figure 5, in order to achieve the same PCC voltage control purpose, the total reactive power output of the DFIGs group in Mode II is larger than the total reactive power output of the SVCs in Mode I. This is because the DFIGs group needs to output a little more reactive power to counterweigh the reactive loss caused by the impedance of the feeder lines and transformers.

4.2.2. Control performance comparison under two typical operating conditions

Two typical operating conditions at two typical time points of the time period mentioned above are studied in this part, they are

a) Operating condition A at the time point when the wind power output percentage of wind farm is 60% and the PCC voltage reference is 1.0 p.u.;

b) Operating condition B at the time point when the wind power output percentage of wind farm is 90% and the PCC voltage reference is 0.99 p.u..

The optimization results comparison of the three control modes under the two different operating conditions are shown in Table 2. The voltage magnitude and the reactive power output of each DFIG under different operating conditions are shown in Figure 7 and Figure 8, respectively.

| Operating Condition | Mode I | Mode II | Mode III |
|---------------------|--------|---------|----------|
|                     | $\sum Q_C$/MVar | $U_{G_{\text{max}}}$/p.u. | $\sum Q_G$/MVar | $U_{G_{\text{max}}}$/p.u. | $\sum Q_C$/MVar | $\sum Q_G$/MVar | $U_{G_{\text{max}}}$/p.u. |
| A                   | 39.2348 | 1.0381  | 41.2617  | 1.0594  | 7.4305  | 33.3644 | 1.0456 |
| B                   | 74.1635 | 1.0539  | 79.8167  | 1.0942  | 12.6332 | 65.9011 | 1.0734 |

From Figure 7(a) and Figure 8(a), it can be seen the tendency of the terminal voltage curves of the DFIGs on one feeder line in Mode II is that the longer the distance from the DFIG to the PCC is, the higher the terminal voltage will be. This will reduce the operating reliability of the DFIGs at the end of the long feeder lines because the large reactive power output of the DFIG will easily make the terminal voltage beyond the security limit. From Figure 7(b) and Figure 8(b), it can be seen that by considering the topological structure and the impedance of the feeder lines in Mode III, the reactive power output of each DFIG is unequal and the DFIG far away from the PCC will be required to provide less reactive power for equipoising the terminal voltage profiles of the whole wind farm.
The voltage magnitude of each DFIG

The reactive power output of each DFIG

**Figure 7.** The voltage magnitude and reactive power output of each DFIG in different control modes under condition A.

The voltage magnitude of each DFIG

The reactive power output of each DFIG

**Figure 8.** The voltage magnitude and reactive power output of each DFIG in different control modes under operating condition B.

### 4.3. Effectiveness of PDIPFM

**Table 3.** Iteration process of the wind farm ORPD problem under operating condition A.

| Iteration | Objective | Primal infeasibility | Dual infeasibility | Log(μ) |
|-----------|-----------|----------------------|--------------------|--------|
| 0         | 0         | 2.23×10^1           | 0                  | 0      |
| 1         | 152.1902  | 7.3×10^9            | 9.91×10^2          | -0.6   |
| 2         | 229.3922  | 2.07×10^3           | 7.06×10^1          | 0.4    |
| 3         | 186.4813  | 2.27×10^4           | 5.19×10^0           | -0.6   |
| 4         | 178.0463  | 2.02×10^4           | 2.08×10^0          | -2.1   |
| 5         | 178.1363  | 1.34×10^4           | 1.05×10^0          | -2.3   |
| 6         | 178.1363  | 1.30×10^4           | 3.97×10^2          | -3.4   |
| 7         | 178.1608  | 7.21×10^6           | 1.44×10^3          | -4.8   |
| 8         | 178.1613  | 1.09×10^7           | 1.99×10^5          | -6.8   |

In every implementation of the wind farm ORPD calculation, the nonlinear problem contains 828 variables, 664 equality constraints and 1 inequality constraint. The iteration processes of the wind farm ORPD problems under the operating A and B are shown in Table 3 and Table 4 respectively (the convergence tolerance is 10^-6). Ten times tests mean values of the solution time for the two operating conditions are 4.34 sec and 3.57 sec respectively. It can be seen from Table 3 and Table 4 that the
iteration counts of the two problems are stable when the calculation parameters changed. With the effectiveness of the filter method, in the iteration progresses algorithm doesn’t cycle between the two points decreasing the constraint violation and the objective function, and at least one of the two points will be decreased after every iteration.

Table 4. Iteration process of the wind farm ORPD problem under operating condition B.

| Iteration | Objective  | Primal infeasibility | Dual infeasibility | Log(μ) |
|-----------|------------|----------------------|--------------------|--------|
| 0         | 0          | 2.23×10^1            | 0                  | 0      |
| 1         | 201.8359   | 1.64×10^1            | 1.66×10^3          | -0.6   |
| 2         | 492.2925   | 1.06×10^2            | 2.98×10^2          | 0.7    |
| 3         | 468.6706   | 7.74×10^1            | 3.33×10^1          | -0.4   |
| 4         | 461.4612   | 3.04×10^0            | 1.47×10^0          | -1.5   |
| 5         | 462.1837   | 1.53×10^1            | 4.08×10^0          | -2.4   |
| 6         | 462.2045   | 1.59×10^2            | 2.66×10^3          | -4     |
| 7         | 462.2032   | 6.78×10^8            | 1.20×10^0          | -6     |
| 8         | 462.2032   | 1.43×10^12           | 2.48×10^10         | -11    |

5. Conclusions
The implementation of renewable energy reactive power control is an effective means of improving the voltage profiles of the nodes where large scale wind farms integrated. This paper proposes an ORPD strategy to coordinate the different RPSs within the wind farm by considering the topological structure and the feeder lines impedance of the wind farm. The ε-constraint method is employed to transform the multi-objective optimization model and the PDIPFM is utilized to solve such a nonlinear optimization problem. The simulation results from an actual wind farm show that besides binding the PCC voltage to the reference value, the proposed ORPD strategy can enhance the SVC reactive power reserve and equipoise the DFIG terminal voltage profile. The fast calculation speed and good robustness of PDIPFM also validate the feasibility of online applications of the proposed ORPD strategy.

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