Coherence Effects on Power and Loads of Multi-Rotor Wind Turbines

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Abstract: Wind power prediction research shows that it is difficult to accurately and effectively estimate the probability distribution (PD) of wind power. When only partial information of the wind power probability distribution function is available, an optimal available transfer capability (ATC) assessment strategy considering the uncertainty on the wind power probability distribution is proposed in this paper. As wind power probability distribution is not accurately given, the proposed strategy can efficiently maximize ATC with the security operation constraints satisfied under any wind power PD function case in the uncertainty set. A distributional robust chance constrained (DRCC) model is developed to describe an optimal ATC assessment problem. To achieve tractability of the DRCC model, the dual optimization, S-lemma and Schur complement are adopted to eliminate the uncertain wind power vector in the DRCC model. According to the characteristics of the problem, the linear matrix inequality (LMI)-based particle swarm optimization (PSO) algorithm is used to solve the DRCC model which contains first and second-order moment information of the wind power. The modified IEEE 30-bus system simulation results show the feasibility and effectiveness of the proposed ATC assessment strategy.

Keywords: transmission system; wind power; available transfer capacity; uncertainty; distributional robust; linear matrix inequality (LMI)

1. Introduction

Wind power energy has become one of the fastest growing renewable energies in recent years. However, the intermittency, randomness and unpredictability of wind power increase the power volatility of the transmission system [1]. With increasing uncertainty in the transmission system, the available transfer capability (ATC) of the transmission system will be influenced greatly. Currently, the wind power prediction accuracy, which to a certain extent has a prediction error, is limited, and it is difficult to obtain the accurate probability distribution function wind power. To improve the security of the transmission system, the wind power uncertainty should be considered in the ATC assessment. Therefore, the probability distribution uncertainty of wind power should be considered to carry out robust and economical ATC assessment strategies [2,3].
In recent years, the research topic of ATC assessment with consideration of wind power uncertainty has seen much activity. The genetic algorithm [4,5], particle swarm optimization [6], optimal power flow method [7], probability analytical method, stochastic programming method [8], Monte Carlo simulation [9,10], and the enumeration method [11] were adopted for this purpose. For describing the wind power uncertainty, the statistical probability method [12–15] and scene analysis method [16] are adopted. Both of these methods assume that the probability distribution function of wind speed or wind power is determined. In [12], under the determined wind power probability distribution function, the Monte Carlo simulation sampling method is adopted to simulate renewable energy output, and the ATC of transmission system is calculated using optimal power flow under specific grid system status, constraints and parameters. Luo et al. [16] employed the Latin hypercube sampling and scenes cluster analysis to assess ATC with large wind power integration. Shayesteh et al. [17] and Huang et al. [18] assumed that the probability distribution function of wind power is normally distributed. In [18], the ATC assessment problem is described as a kind of chance constrained optimization problem. However, the above proposed statistical probability method and scene analysis method did not consider the uncertainty of the wind power probability distribution function. Due to the fact that the probability distribution function of wind power which is used to describe the uncertainty is also uncertain, the ATC assessment methods mentioned in [12–18] may be ineffective.

In wind-integrated transmission systems, due to the fact that the wind power prediction technology is limited, adding the geographical complexity, the climate variability and other factors, it is difficult to accurately and effectively estimate the probability distribution function of wind power. Instead, only partial wind power information is available, such as the first and second order moment information [19]. In the prior scenario-based simulation methods and probabilistic analysis methods, wind speeds are assumed to follow a normal distribution [20,21], beta distribution [22,23], Laplace distribution [24,25], Cauchy distribution [26] or other probability distribution functions [27]. However, there is no such uniform probability distribution that is suitable to describe the wind power in all different situations. Based on the available partial information, the exact probability distribution of the wind power even cannot be obtained. Instead, the probability distribution is uncertain and related to a special set of distributions. Therefore, as the above scenario analysis method or probability analytical method do not take this uncertainty into account, they cannot ensure the effectiveness of the ATC assessment strategies.

With the above background, the motivation for this work was to optimize the ATC assessment for wind integrated transmission systems with consideration of all the possible wind power probability distributions. The ATC assessment problem is described as a distributional robust chance constrained (DRCC) model. The dual optimization, Schur complement and S-lemma [28,29] are adopted to eliminate the random variables, and then convert the probabilistic DRCC model into a deterministic model. The linear matrix inequality (LMI)-based particle swarm optimization (PSO) algorithm is used to solve the problem according to its characteristics. This optimization strategy can efficiently maximize the ATC of the transmission system with consideration to all the possible wind power probability distributions with the security operation constraints satisfied. The simulation and analysis of the modified IEEE 30-bus test system verify the feasibility and effectiveness of the proposed strategy.

The rest of this paper is organized as follows: Section 2 introduces the ATC assessment optimization model for wind-integrated transmission systems, which include the chance constrained optimal ATC assessment model and the DRCC optimal ATC assessment model. The solving method for DRCC optimal ATC assessment model, which includes the reformulation of distributional robust chance constraints, the modeling for branch power and node voltage constraints and the determination model for DRCC, is presented in Section 3. Section 4 gives the LMI-based PSO algorithm for the optimal ATC assessment model. Section 5 provides numerical example and case studies. Finally, conclusions are drawn in Section 6.
2. Optimal Available Transfer Capability (ATC) Assessment Model

2.1. Traditional Chance Constrained Optimal Available Transfer Capability (ATC) Assessment Model

For optimal ATC assessment for wind integrated transmission systems considering the uncertainty on the wind power probability distribution chance constrained programming is employed to avoid the operational scheme being limited by small probability events and satisfy the security constraints of the transmission system. The chance constrained optimal ATC assessment model is as follows: the objective function is to maximize the all tie-line power output between a given interface, say, from area \(a\) to area \(b\) [29]:

\[
ATC = \max \sum P_{a\rightarrow b} \tag{1}
\]

where \(P_{a\rightarrow b}\) denotes all tie-line power output from area \(a\) to area \(b\).

2.1.1. Active and Reactive Power Balance Constraint

\[
P_W + P_G - P_D - S_{IJ}P_L = 0 \tag{2}
\]
\[
Q_W + Q_c + Q_G - Q_D - S_{IJ}Q_L = 0 \tag{3}
\]

where \(P_W\) and \(Q_W\) denote the active and reactive power output of wind farms, respectively; \(P_G\) and \(Q_G\) denote the active and reactive power output of conventional generators, respectively; \(P_D\) and \(Q_D\) denote active and reactive loads, respectively; \(P_L\) and \(Q_L\) denote the active and reactive power flow, respectively; \(Q_c\) indicates the actual capacity of reactive power compensators; \(S_{IJ}\) denotes the node branch incidence matrix, which is defined as:

\[
S_{IJ} = \begin{cases} 
1 & \text{if link } IJ \text{ starts at node } I \\
-1 & \text{if link } IJ \text{ ends at node } I \\
0 & \text{else}
\end{cases}
\]

2.1.2. Conventional Unit Generating Capacity Constraints

\[
P_{G,\min} \leq P_G \leq P_{G,\max} \tag{4}
\]
\[
Q_{G,\min} \leq Q_G \leq Q_{G,\max} \tag{5}
\]

where \(P_{G,\max}\) and \(P_{G,\min}\) denote the upper and lower active power limits of conventional generation, respectively; \(Q_{G,\max}\) and \(Q_{G,\min}\) denote the upper and lower reactive power limits of conventional generation, respectively.

2.1.3. Active and Reactive Wind Power Output Constraints

\[
0 \leq P_W \leq P_{W,\max} \tag{6}
\]
\[
0 \leq Q_W \leq Q_{W,\max} \tag{7}
\]

where \(P_{W,\max}\) and \(Q_{W,\max}\) represent the maximum active and reactive power output of corresponding wind farms, respectively.

2.1.4. Chance Constraints of Node Voltage

\[
Pr\{V_{\min} \leq V \leq V_{\max}\} \geq \beta \tag{8}
\]
where $V, V_{\text{max}}$ and $V_{\text{min}}$ represent the actual voltage amplitude, upper limit and lower limit of voltage amplitude, respectively. $Pr_\phi$ is the probability under $\phi$, where $\phi$ is a placeholder for a probability distribution; $\beta$ is the confidence level.

2.1.5. Chance Constraints of Branch Power

$$Pr_\phi \{ |P_L| \leq P_{L,\text{max}} \} \geq \beta$$

where $P_{L,\text{max}}$ indicates the upper limit of branch power.

Random variables $P_W$ and $Q_W$ exist in the chance constrained optimal ATC assessment model, thus the node voltage and branch power constraints become complicated. The traditional approach to solve the above chance constraints is to use Boole’s inequality [28] to convert these problems into a single chance-constrained problem. The Monte-Carlo sampling method is adopted under the given probability distribution function. However, this method is only efficient if the wind power probability distribution is defined and comprehensively described.

2.2. Distributional Robust Chance Constrained Model

Due to the fact that the wind speed prediction accuracy is limited, the wind speed fluctuates significantly at different seasons over a year, even during different hours over a day. Besides that, geography and climate influence the wind speed a lot. There is lots of uncertain information about wind power and the decision-makers can not get all the information about the probability distribution of wind power. Instead, partial information on wind power such as the first and second order moments can be collected from the historical data. Denote the active output expectations and covariance matrix of $m$ wind farms are $\mu = [\mu_1, \ldots, \mu_m]^T$ and $\Gamma$, respectively. Define $\Xi = \{ P_W \in \mathbb{R}^m : 0 \leq P_W \leq P_{W,\text{max}}, Q_W \in \mathbb{R}^m : 0 \leq Q_W \leq Q_{W,\text{max}} \}$. Denote $\Phi_\Xi(\mu, \Gamma)$ as the set of all the distributions whose mean and covariance are $\mu$ and $\Gamma$.

The wind probability distribution function may be any one of set $\Phi_\Xi(\mu, \Gamma)$, and the predetermined node voltage and branch power constraints should be satisfied under all possible wind power probability distributions.

Therefore, the distributional robust chance constrained model is adopted to describe the optimal ATC assessment problem. When the probability distribution of random variables is uncertain distributional robust chance constrained programming is an effective way to solve such problems [22].

In the node voltage constraints in Equation (8) and branch power constraint in Equation (9), since the probability distribution of the random vector $P_W$ and $Q_W$ are uncertain, $P_W$ and $Q_W$ can be any possible realization under the set $\Phi_\Xi(\mu, \Gamma)$, therefore wind power output influences the node voltage and branch power. Therefore, the infimum is introduced in Equations (8) and (9) in the distributional robust chance constrained model to express that for any possible probability distribution function, branch power and node voltages should satisfy the constraints, which is shown in Equations (10) and (11), where $\inf_{\phi \in \Phi_\Xi(\mu, \Gamma)} Pr_\phi \{ A \}$ represents the minimum probability of $A$ under all possible probability distributions.

$$\inf_{\phi \in \Phi_\Xi(\mu, \Gamma)} Pr_\phi \{ V_{\text{min}} \leq V \leq V_{\text{max}} \} \geq \beta$$

(10)

$$\inf_{\phi \in \Phi_\Xi(\mu, \Gamma)} Pr_\phi \{ |P_L| \leq P_{L,\text{max}} \} \geq \beta$$

(11)

If the probability distribution of wind power isn’t specified, the optimal ATC assessment programs should meet the pre-set confidence level for node voltage and branch power under any possible probability distribution function of set $\Phi_\Xi(\mu, \Gamma)$. The difficulty in solving the model is how to handle constraints in Equations (10) and (11) with system node voltage and branch power constraints satisfied when only first and second moment of wind power PD are given.

It is impossible to accurately estimate the wind power probability distribution function in the optimal ATC assessment model as analyzed above. The solving process for distributional robust chance constrained ATC assessment model is as follows: firstly, the wind power vector is separated into active and reactive power balance Equations (2) and (3). Secondly, employing the node voltage and reactive power model [30,31], the branch power constraints and node voltage constraints are expressed as a function of wind power. Thirdly, dual optimization, S-lemma and Schur complement are adopted to eliminate the random variable. Finally, the probabilistic based constraints are converted into deterministic constraints.

3.1. Reformulation of Distributional Robust Chance Constraints

Rewrite the node voltage constraints in Equation (10) as follows:

\[
\inf_{\mathbf{\Phi} \in \Phi_{2}(\mu, \Gamma)} \ln \Phi \left\{ \left| V - \frac{V_{\max} + V_{\min}}{2} \right| \leq \left( \frac{V_{\max} - V_{\min}}{2} \right) \right\} \geq \beta
\]

\[
\Leftrightarrow \inf_{\mathbf{\Phi} \in \Phi_{2}(\mu, \Gamma)} \ln \Phi \left\{ |\Delta V| \leq \left( \frac{V_{\max} - V_{\min}}{2} \right) \right\} \geq \beta \tag{12}
\]

Employing the node voltage and reactive power model [31], \( \Delta V = J\Delta Q \), where \( \Delta V \) is the voltage vector increment, \( \Delta Q \) is the node reactive power injection increment, \( J \) is the contraction of Jacobian matrix \( V - Q \). The Newton-Raphson power flow calculation method is adopted in this paper. The core idea is to gradually linearize the nonlinear equations using the Taylor series expansion method. If the initial value is chosen appropriate, which means the first derivative of the initial value is relatively small in the equation, and the second order and higher order term can be omitted. Here in the equation \( \Delta V = J\Delta Q \), \( \Delta Q \) is the last correction term which can meet the real value of the power balance equation.

The specific power flow calculation of \( \Delta V = J\Delta Q \) is as follows:

1. Give the initial value of \( Q(\lambda) \) and \( V(\lambda) \), where \( \lambda = 0 \) at the beginning, it denotes the initial value.
2. Substitute \( Q(\lambda) \) and \( V(\lambda) \) into the power balance equation [31] to calculate the correction term \( \Delta V(\lambda) \) and \( \Delta Q(\lambda) \).
3. Iteration stops when \( \Delta V(\lambda) = J\Delta Q(\lambda) \), otherwise, go to Step (4).
4. Use \( \Delta V(\lambda) \) and \( \Delta Q(\lambda) \) to correct \( Q(\lambda) \) and \( V(\lambda) \), then obtains \( Q(\lambda + 1) \) and \( V(\lambda + 1) \), let \( \lambda = \lambda + 1 \), go back to Step (2).

Here, \( \Delta V = J(Q_{W} + Q_{G} - Q_{D} - S_{NL}^{T}Q_{L}) \). Substitute \( \Delta V \) into the node voltage constraint in Equation (12) and eliminate the random variable. Equation (12) can be reformulated as Equation (13), where \( \text{Prob}_{1}(Q_{G}) \) denotes the maximum probability value which satisfies the node voltage constraint under all possible wind power probability distributions:

\[
\text{Prob}_{1}(Q_{G}) = \inf_{\mathbf{\Phi} \in \Phi_{2}(\mu, \Gamma)} \ln \Phi \left\{ \left| \left( \frac{Q_{W} + Q_{G} - Q_{D} - S_{NL}^{T}Q_{L}}{1} \right) \right| \leq \left( \frac{V_{\max} - V_{\min}}{2} \right) \right\} \geq \beta
\]

\[
\Leftrightarrow \text{Prob}_{1}(Q_{G}) = \inf_{\mathbf{\Phi} \in \Phi_{2}(\mu, \Gamma)} \ln \Phi \left\{ \left| \frac{Q_{W}}{1} \right| \leq \left( \frac{V_{\max} - V_{\min}}{2} \right) \right\} \geq \beta \tag{13}
\]

Let \( \left[ J(Q_{G} - Q_{D} - S_{NL}^{T}Q_{L}) \right] = F_{1}(Q_{G}) \), \( z_{1} = \left[ Q_{W} \right]^{T} \), rewrite Equation (13) as:

\[
\text{Prob}_{1}(Q_{G}) = \inf_{\mathbf{\Phi} \in \Phi_{2}(\mu, \Gamma)} \ln \Phi \left\{ \left| F_{1}(Q_{G})z_{1} \right|^{2} \leq \left( \frac{V_{\max} - V_{\min}}{2} \right)^{2} \right\} \geq \beta \tag{14}
\]
Let \( \begin{bmatrix} T_{ij}^T & \cdot \end{bmatrix} \cdot (P_G - P_D) \right] = F_2(P_G), \ z_2 = [P_W 1]^T, \) where \( T_{ij}^T \) is the power transmission distribution coefficient matrix [31]. The active power flow \( P_L \) can be formulated as follows [31]:
\[
P_L = (T_{ij}^T) \cdot (P_W + P_G - P_D)
\]
\[
= \begin{bmatrix} (T_{ij}^T) \cdot (P_G - P_D) \end{bmatrix} \cdot \begin{bmatrix} P_W \\ 1 \end{bmatrix}
\]
(15)

Thus, recall \( \inf \{ F_{\Phi} \in \Phi_{\mathcal{G}(\mu, \Gamma)}Pr_{\Phi} \{ A \} \}, \) denote \( \text{Prob}_2(P_G) \) as the maximum probability value which satisfies the branch active power constraint under all possible wind power probability distributions:
\[
\text{Prob}_2(P_G) = \inf \{ F_{\Phi} \in \Phi_{\mathcal{G}(\mu, \Gamma)}Pr_{\Phi} \{ [F_2(P_G)z_2]^2 \leq (P_{L_{\max}})^2 \} \} \geq \beta
\]
(16)

### 3.2. Determination Model for Distributional Robust Chance Constraint

According to the dual theory [20], \( \text{Prob}_1(Q_G) \) and \( \text{Prob}_2(P_G) \) in Equations (14) and (16) correspond to the optimal value of sub-optimization problem in Equations (17) and (18), respectively. The detailed derivation is shown in Appendix A:

\[
\begin{aligned}
\text{Prob}_1(Q_G) &= \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} \left( N \cdot M_{k1} \right) \\
\text{s.t. } & z_1^T M_{k1} z_1 \geq 1, \forall z_1 \in \left\{ \left[ F_1(Q_G) z_1 \right]^2 \leq \left( \frac{V_{\max} - V_{\min}}{2} \right)^2 \right\} \cap \Xi \\
& z_1^T M_{k1} z_1 \geq 0, \forall z_1 \in \Xi
\end{aligned}
\]
(17)

\[
\begin{aligned}
\text{Prob}_2(P_G) &= \inf_{M_{k2} = M_{k2}^T \in \mathbb{R}^{m+1}} \text{Tr} \left( N \cdot M_{k2} \right) \\
\text{s.t. } & z_2^T M_{k2} z_2 \geq 1, \forall z_2 \in \left\{ [F_2(P_G) z_2]^2 \leq (P_{L_{\max}})^2 \right\} \cap \Xi \\
& z_2^T M_{k2} z_2 \geq 0, \forall z_2 \in \Xi
\end{aligned}
\]
(18)

where \( \text{Tr}(\cdot) \) denotes the trace operations, \( N = [\Gamma + \mu \mu^T, \mu; \mu^T, 1] \). \( M_{k1} \) and \( M_{k2} \) are symmetric matrices containing all the dual variables.

In a similar way, employing the dual optimization, S-lemma and Schur complement [20,21], the random wind power in the optimization model is eliminated [28], and Equations (17) and (18) are converted into linear matrix inequalities as shown in Equations (19) and (20). The detailed derivation is shown in Appendix B:

\[
\begin{aligned}
\text{Prob}_1(Q_G) &= \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} \left( N \cdot M_{k1} \right) \\
\text{s.t. } & \tau_{k1} \geq 0, \ l_1 = 1, \ldots, m \\
& \tau_{k2} \geq 0 \\
& \tau_{k3} \geq 0, \ l_1 = 1, \ldots, m \\
& M_{k1} + \sum_{l=1}^{m} \tau_{k1} l W_{l1} \geq 0 \\
& \left[ M_{k1} - \text{diag} \left( 0, 1 - \tau_{k2} l \left( \frac{V_{\max} - V_{\min}}{2} \right)^2 \right) + \sum_{l=1}^{m} \tau_{k3} l W_{l} \right] \geq 0
\end{aligned}
\]
(19)
where in matrix $W_l \in \mathbb{R}^{(m+1) \times (m+1)}$ the $(l_1, l_1)$-th element is 1, and the $(l_1, m+1)$-th and $(m+1, l_1)$-th element is $-Q_{W,max,l_1}/2$, the rest of the elements is 0, and there are $m$ wind farms. The maximum reactive power output of the $l_1$-th wind farms is $Q_{W,max,l_1}$.

$$\begin{aligned}
\forall (i, j) \in (10) \text{ and } (11) \qquad \text{to replace the node voltage constraint in Equation (10) and branch power constraint in Equation (11), the DRCC deterministic model is shown in the following equation:}
\end{aligned}$$

$$\text{Prob}_2 (P_G) = \inf_{M_{k2} = M_{k2}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \times M_{k2})$$

$$\text{s.t.} \quad \tau_{k1,l_2} \geq 0, \quad l_2 = 1, \ldots, m$$

$$\tau_{k2,l_2} \geq 0$$

$$\tau_{k3,l_2} \geq 0, \quad l_2 = 1, \ldots, m$$

$$M_{k2} + \sum_{l=1}^{m} \tau_{k1,l_2} W_l, W_l \geq 0$$

$$M_{k2} - \text{diag} \left(0, 1 - \tau_{k2,l_2} \left(P_{L,max}\right)^2\right) + \sum_{l=1}^{m} \tau_{k3,l_2} W_l W_l^T \tau_{k2,l_2} \geq 0$$

$$\tau_{k2,l_2} \geq 0$$

In matrix $W_l \in \mathbb{R}^{(m+1) \times (m+1)}$, the $(l_2, l_2)$-th element is 1, and the $(l_2, m+1)$-th and $(m+1, l_2)$-th element is $-P_{W,max,l_2}/2$, the rest of the elements is 0, and there are $m$ wind farms. The maximum active power output of the $l_2$-th wind farms is $P_{W,max,l_2}$.

Substitute Equations (19) and (20) into the DRCC optimal ATC assessment model (Equations (1)–(7), (10) and (11)) to replace the node voltage constraint in Equation (10) and branch power constraint in Equation (11), the DRCC-ATC deterministic model is shown in the following equation:

$$\begin{aligned}
\max \sum P_{a-b} \quad \inf_{M_{k2} = M_{k2}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k2}) \geq \beta, \quad \inf_{M_{k4} = M_{k4}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k4}) \geq \beta \\
\text{S.T.} \quad P_G, Q_G \in \mathbb{R}^n; \quad P_{G,\min} \leq P_G \leq P_{G,\max} \\
\quad Q_{G,\min} \leq Q_G \leq Q_{G,\max} \\
\quad \tau_{k1,l_1} \geq 0, \quad \tau_{k2,l_2} \geq 0, \quad \tau_{k3,l_3} \geq 0, \quad \tau_{k4,l_4} \geq 0, \quad l_1, l_2, l_3, l_4 = 1, \ldots, m \\
\quad M_{k2} + \sum_{l=1}^{m} \tau_{k1,l_2} W_l \geq 0, \quad M_{k2} + \sum_{l=1}^{m} \tau_{k3,l_2} W_l \geq 0 \\
\quad \tau_{k2,l_2} F_1 (Q_G) \geq 0 \\
\quad M_{k2} - \text{diag} \left(0, 1 - \tau_{k2,l_2} \left(P_{L,max}\right)^2\right) + \sum_{l=1}^{m} \tau_{k3,l_2} W_l W_l^T \tau_{k2,l_2} \geq 0 \\
\quad \tau_{k2,l_2} \geq 0
\end{aligned}$$

After the above derivations, it is obvious that the wind power $P_W$ and $Q_W$ do not exist in the optimization problem in Equation (21), and only the first and second moment information of the wind power probability distribution function is needed.

4. **Linear Matrix Inequality (LMI)-Based Particle Swarm Optimization (PSO) Algorithm for Available Transfer Capability (ATC) Assessment Problem**

The optimal ATC assessment in Equation (21) only needs the first and second order moments of the wind power probability distribution information. It is relatively difficult to solve the nonlinear problem as it includes LMI and nonlinear constraints. The PSO algorithm [32] is used in this paper to solve the problem in Equation (21).

Particle swarm optimization was first proposed by Eberhart and Kennedy. The design of the PSO algorithm is as follows: initialize a group of random particles, each particle represents a candidate solution. The particles update themselves through tracking the personal best position and the optimal solution for the entire population called global minimum, the position of the best particle that give the best fitness value in the entire population. The PSO algorithm has a clear searching direction and it converges quickly at the beginning, however, the PSO algorithm can easily fall into local minimum of convergence speed and precision during the course of evolution. Thus we combine the immune
algorithm and PSO, which is expected to address the convergence speed shortcomings of the local minimum of the PSO.

In the PSO updating process, the particles which have high fitness value will be retained. However, if such particles are too concentrated, it can easily fall into a local optimum. Those particles which have lower fitness value but maintain good evolutionary trends will not be eliminated, so the vaccination strategy based on the diversity of concentration mechanism can efficiently ensure all fitness levels by maintaining a certain concentration. The specific procedures are as follows:

$$D(x_i) = \frac{1}{\sum_{j=1}^{\text{num}} |f(x_i) - f(x_j)|}, \quad i = 1, 2, \ldots, \text{num}$$  

where $$x_i$$ and $$f(x_i)$$, $$i = 1, 2, \ldots, \text{num}$$, refer to the i-th particle and the fitness value of the i-th particle, respectively. num refers to particle number.

The probability of the particle concentration is defined as follows:

$$\text{Prob}(x_i) = \frac{\frac{1}{D(x_i)}}{\sum_{i=1}^{\text{num}} \frac{1}{D(x_i)}} = \frac{1}{\sum_{i=1}^{\text{num}} \sum_{j=1}^{\text{num}} |f(x_i) - f(x_j)|}, \quad i = 1, 2, \ldots, \text{num}$$  

We can see from the above equation that, if particle $$j$$ is similar to particle $$i$$, then $$\text{Prob}(x_j)$$ is less, which means the chance of particle $$i$$ to be chosen is less. If the particle $$j$$ is more different from particle $$i$$, then $$\text{Prob}(x_j)$$ is larger. Therefore, the particles have higher diversity.

Immune selection is inspired by the biological immune system. The biological immune system is an intricate network of specialized tissues, organs, cells, and chemicals with the capability of distinguishing entities within the body as “self” or “non-self” and eliminating those that are non-self. If the fitness value of particles is inferior to those of their parent, then the vaccination process is canceled, otherwise, the particles are retained.

The specific flow chart for the LMI-based PSO algorithm for ATC assessment is shown in Figure 1. The specific procedures are as follows:

1. Input grid original parameters, the first and second order moments of the wind power, PSO control parameters and control variables. The branch power and node voltage constraints in Equations (10) and (11) can be converted into LMI form as shown in Equations (19) and (20).
2. Initialization: set the initial solution $$P_G^0$$ and $$Q_G^0$$, calculate the fitness value, and let the iteration counter $$K = 0$$.
3. Parameter optimization: substitute $$P_G = P_G^K$$ and $$Q_G = Q_G^K$$ into sub-problems in Equations (19) and (20). Solve the resulting LMI problem and obtain the optimal solution $$\tau_{11}^{K}$$, $$\tau_{21}^{K}$$, $$\tau_{31}^{K}$$, and set $$\tau_{12}^{K} = \tau_{21}^{K}$$, $$\tau_{22}^{K} = \tau_{32}^{K}$$, $$\tau_{33}^{K} = \tau_{13}^{K}$$.
4. Optimal decision: substitute $$\tau_{11}^{K}$$, $$\tau_{21}^{K}$$, $$\tau_{22}^{K}$$, $$\tau_{31}^{K}$$, $$\tau_{32}^{K}$$, $$\tau_{33}^{K}$$ into Equation (21), solve the matrix positive condition and power flow calculation to obtain the updated optimal solution $$P_G^K$$ and $$Q_G^K$$, and the corresponding objective value $$\sum P_{a\rightarrow b}^*$$.
5. Vaccine selection and immune selection are defined as shown in Equations (22) and (23), the particle $$P_{G,i}$$, $$Q_{G,i}$$ with high $$\text{Prob}(P_{G,i}, Q_{G,i})$$ value would be selected, and set $$P_G^{K+1} = P_G^K$$ and $$Q_G^{K+1} = Q_G^K$$, $$\sum P_{a\rightarrow b}^{K+1} = \sum P_{a\rightarrow b}^*$$.
6. Termination: If the iteration counter $$K$$ meets the predefined value, then the final optima $$P_G^{K+1}$$, $$Q_G^{K+1}$$ and $$\sum P_{a\rightarrow b}^{K+1}$$ are obtained, and the algorithm ends. Otherwise, let $$K = K + 1$$, and repeat Steps (3) and (4).
5. Numerical Example

The modified IEEE 30-bus transmission system used for simulation calculation is shown in Figure 2. It is divided into three regions, and the revised system includes six conventional generators, the specific parameters of which are shown in Table 1. There are 22 P-Q buses (where bus 11 and bus 24 are reactive power compensation points, the compensation step is 0.048), one balance bus (bus 1), and the rest are P-V buses. Upper and lower limits of node voltage are 1.1 pu (per unit) and 0.95 pu. There are 41 branches in the transmission system. The transformer parameters are shown in Table 2. There are six wind farms integrated to the transmission system, which are connected to the grid at bus 3, 16, 23, 26, 27 and 28.

To illustrate the validity of the proposed strategy, we compare the results of the DRCC optimal ATC assessment (DRCC-ATC) model and the TCC optimal ATC assessment (TCC-ATC) model. Wind power is assumed to follow the normal distribution in the TCC model. In order to analyze the impact of wind power on the optimal ATC assessment, we test the ATC assessment strategy under different confidence levels and covariance values.
To compare the distributional robust chance constrained ATC (DRCC-ATC) model and the traditional chance constrained ATC (TCC-ATC) model, we set the expectation of wind power probability distribution to 2.0 MW, and the covariance of the wind power probability distribution to 0.4 MW². The optimal values of the DRCC-ATC model and the TCC-ATC model under different confidence levels are shown in Figure 3.

**Table 1. Generator parameters and limits.**

<table>
<thead>
<tr>
<th>Node</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>8</th>
<th>11</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{G,max}$ (MW)</td>
<td>139</td>
<td>58</td>
<td>35</td>
<td>21</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>$P_{G,min}$ (MW)</td>
<td>130</td>
<td>32</td>
<td>30</td>
<td>13</td>
<td>17</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 2. Transformer parameters and limits.**

<table>
<thead>
<tr>
<th>Branch No.</th>
<th>$T_{max}$</th>
<th>$T_{min}$</th>
<th>Tap Ratio</th>
<th>Unit Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.1</td>
<td>0.9</td>
<td>17</td>
<td>0.0125</td>
</tr>
<tr>
<td>12</td>
<td>1.1</td>
<td>0.9</td>
<td>17</td>
<td>0.0125</td>
</tr>
<tr>
<td>15</td>
<td>1.1</td>
<td>0.9</td>
<td>17</td>
<td>0.0125</td>
</tr>
<tr>
<td>36</td>
<td>1.1</td>
<td>0.9</td>
<td>17</td>
<td>0.0125</td>
</tr>
</tbody>
</table>

Figure 2. The modified IEEE 30-bus test system.

To compare the distributional robust chance constrained ATC (DRCC-ATC) model and the traditional chance constrained ATC (TCC-ATC) model, we set the expectation of wind power probability distribution to 2.0 MW, and the covariance of the wind power probability distribution to 0.4 MW². The optimal values of the DRCC-ATC model and the TCC-ATC model under different confidence levels are shown in Figure 3.

![Figure 3. Optimal ATC obtained by the DRCC and TCC models for the modified IEEE 30-bus system.](image)

Figure 3 illustrates the effect of the confidence level on the ATC. It is shown in Figure 3 that with increasing confidence level, the ATC obtained by the DRCC and TCC both gradually decrease to satisfy the security constraints caused by the wind power uncertainty. For a given confidence level, the ATC under the DRCC model is smaller than that of the TCC model. In the DRCC model, the node voltages and branch power should meet the constraints at a given confidence level under any given wind power probability distribution. In the TCC model, the node voltage and branch power should meet the constraint at a given confidence level for only one kind of wind power probability distribution. Therefore, the DRCC model argues for a more rigid security constraint for the wind-integrated transmission system, which results in a smaller ATC when this model is employed.

5.2. Available Transfer Capability (ATC) under Different Expectations of Wind Power Probability Distribution, Where Covariance = 0.4 MW²

Figure 4 illustrates the relationship between ATC and the wind power probability distribution expectation. Given the same covariance of wind power PD and confidence level, we compare ATC values under different expectations of wind power probability. We can find in Figure 4 that with the increase of the confidence level, ATC gradually decreases. When the confidence level increases, ATC decreases to avoid breaking the security constraints.
Where Expectation = 2.0 MW, the smaller the corresponding.

5.3. Available Transfer Capability (ATC) under Different Covariance of Wind Power Probability Distribution, Where Expectation = 2.0 MW

Figure 5 illustrates the relationship between ATC and the covariance of the wind power probability distribution. Given the same expectation of wind power PD and confidence level, we compare ATC under different covariances of wind power probability. We can find that the greater the covariance is, the smaller the corresponding ATC is. If the covariance is greater, which means the fluctuation range of wind power is increased, therefore the branch flow and node voltage change more, which results in an ATC decrease under more strict security constraints.

Figure 4. ATC under different expectations of wind power PD for the modified IEEE 30-bus system, where the covariance = 0.4 MW².

Figure 5. ATC under different wind power covariances for the modified IEEE 30-bus system, where expectation = 2.0 MW.

In the actual wind integrated transmission system operation, the transmission system should set a reasonable confidence level according to the actual situation with the security satisfied to thus obtain an effective ATC assessment scheme.
6. Summary

This paper proposes an ATC evaluation strategy considering the uncertainty on the wind power due to the fact that the exact probability distribution of wind power is not given. With respect to the fact that the partial information such as the first and second order moments of wind power probability distribution can be collected from historical data, a DRCC model is presented for ATC assessment. The proposed method can meet the system requirements for security operation under any possible wind power probability distribution. The DRCC model is converted into a deterministic model. For solving the deterministic model, the PSO algorithm based on the LMI is employed. The effectiveness and feasibility of the proposed optimal ATC evaluation strategy method is verified through numerical examples. In modeling the ATC assessment strategy for a wind integrated transmission system, it is more in accord with the actual engineering situation using the apparent power in the branch power and node voltage model, which we will concentrate on in future research work.

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Author Contributions: All the authors contributed to this work. Jun Xie designed the study, developed the mathematical model, performed the analysis and checked the overall logic of this work. Lu Wang developed the DRCC based ATC assessment model, set the simulation environment and performed the simulations. Qiaoyan Bian contributed to the conceptual approach and provided important comments on the modeling and analysis. Xiaohua Zhang contributed towards the optimization algorithm. Dan Zeng contributed towards the LMI based PSO algorithm. Ke Wang contributed towards the distributional robust chance constrained optimal ATC assessment modeling framework.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Dual Problem of Node Voltage Constraints

Prob1 (QG) in Equation (13) can be regarded as a sub-optimization problem, the decision variable is QG. The dual problem of sub-optimization problem is as follows:

\[
\begin{align*}
\text{Prob}_1 (Q_G) & = \inf_{M_{k1} = M_{k1}' \in \mathbb{R}^{m+1}} \operatorname{Tr} (N \cdot M_{k1}) \\
\text{s.t.} & \quad z_1^T M_{k1} z_1 \geq 1, \forall z_1 \in \left\{ [F_1 (Q_G) z_1]^2 \leq \left( \frac{V_{\max} - V_{\min}}{2} \right)^2 \right\} \cap \Xi \\
& \quad z_1^T M_{k1} z_1 \geq 0, \forall z_1 \in \Xi
\end{align*}
\]

where \( \operatorname{Tr}(\cdot) \) denotes the trace operation, \( N = [\Gamma + \mu \mu^T, \mu; \mu^T, 1] \), \( M_{k1} \) is a symmetric matrix including all the dual variables.

\textbf{Proof.} Denote the measurable indicator function \( I_S(z_1) = z_1^T F_1^T (Q_G) F_1 (Q_G) z_1 - \left( \frac{V_{\max} - V_{\min}}{2} \right)^2 \leq 0 \), random variables \( z_1 = \begin{bmatrix} Q_W & 1 \end{bmatrix}^T \). Consider the maximum expectations of measurable function \( I_S(z_1) \) under all possible probability distribution.

\[
\theta (z_1) = \sup_{\phi \in \Phi_\Xi (\mu, \Gamma)} E_\phi \left\{ I_S (z_1) \right\}
\]

where \( \phi \) is the probability distribution of \( z_1 \). Denote \( \Phi_\Xi (\mu, \Gamma) \) as the set of all the distributions whose mean and covariance are \( \mu \) and \( \Gamma \).
\( \theta (z_1) \) in Equation (A2) can be expressed in integral form as follows [29]:

\[
\theta (z_1) = Z^D = \sup_{f \in M_+ R^m} \int I_z (z_1) \phi (dz_1) \\
\text{s.t.} \quad \int \phi (dz_1) = 1 \\
\int z_1 \phi (dz_1) = \mu \\
\int z_1 z_1^T \phi (dz_1) = \Gamma + \mu \mu^T
\]

(A3)

where \( M_+ \) represents the cone of nonnegative Borel measures on \( \mathbb{R}^m \). Note that the first constraint forces \( \phi \) to be a probability measure. The other two constraints enforce consistency with the given first- and second-order moments, respectively.

The following problem in Equation (A4) is the dual problem in Equation (A3), which matches the strong duality theorem, which means that \( Z^D = Z^P \).

\[
\begin{align*}
Z^D &= \inf_{y_0, y, Y} \left( y_0 + y^T \mu + \text{Tr} (\Gamma + \mu \mu^T) \right) \\
\text{s.t.} & \quad y_0 \in \mathbb{R}, y \in \mathbb{R}^m, Y = Y^T \in \mathbb{R}^{m \times m} \\
& \quad y_0 + y^T z_1 + \text{Tr} z_1 z_1^T Y \geq I_S (z_1), \forall z_1 \in \mathbb{R}^m
\end{align*}
\]

(A4)

where \( y_0 \in \mathbb{R}, y \in \mathbb{R}^m, \) and \( Y \in S^k \) are the dual variables of the first, second and third constraint in Equation (A4), respectively.

Therefore, we can get the optimal value of the original problem \( \theta_{wc} \) by solving the dual problem \( Z^D \).

Define the following variables:

\[
M_{k1} = \begin{bmatrix} Y & \frac{1}{2} y & \frac{1}{2} y \\ \frac{1}{2} y & y_0 \end{bmatrix}, \quad N = \begin{bmatrix} \Gamma + \mu \mu^T & \mu \\ \mu^T & 1 \end{bmatrix}
\]

The dual question \( Z^D \) can be rewritten as [29]:

\[
\begin{align*}
Z^D &= \inf_{M_{k1} \in S^{k+1}} \text{Tr} (N, M_{k1}) \\
\text{s.t.} & \quad z_1^T \begin{bmatrix} 1 & M_{k1} \end{bmatrix} \begin{bmatrix} z_1 & 1 \end{bmatrix}^T \geq I_S (z_1)
\end{align*}
\]

(A5)

\( \text{Prob}_1 (Q_G) \) in Equation (12) is:

\[
\text{Prob}_1 (Q_G) = \sup_{\phi} \{ F_1 (Q_G) z_1 \}^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2
\]

(A6)

Consider the range of \( Q_w \) is \( \Xi \), \( I_S (z_1) \) is the indicator function which indicates \( [F_1 (Q_G) z_1]^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \).

\[
I_S (z_1) = I_S (z_1) = \begin{cases}
1, & z_1 \in \left[ [F_1 (Q_G) z_1]^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right] \cap \Xi \\
0, & z_1 \in \left[ [F_1 (Q_G) z_1]^2 < \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right] \cap \Xi
\end{cases}
\]

(A7)
Thus:

$$Pr_{\Phi} \left\{ [F_1(Q_G)z_1]^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right\} = E_{\Phi} \left\{ I_S(z_1) \right\}$$  \hspace{1cm} (A8)

According to Equations (A5) and (A7), we can obtain that:

$$\begin{align*}
\left\{ \begin{array}{l}
\text{Prob}_1(Q_G) = \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k1}) \\
s.t. \ z_1^T M_{k1} z_1 \geq I_S(z_1), \forall z_1 \in \Xi
\end{array} \right.
\end{align*}$$  \hspace{1cm} (A9)

According to the definition of the indicator function in Equation (A7), the constraints in Equation (A9) can be written as:

$$\begin{align*}
\left\{ \begin{array}{l}
z_1^T M_{k1} z_1 \geq 1, \forall z_1 \in \left\{ [F_1(Q_G)z_1]^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right\} \cap \Xi \\
z_1^T M_{k1} z_1 \geq 0, \forall z_1 \in \Xi
\end{array} \right.
\end{align*}$$  \hspace{1cm} (A10)

Combining Equation (A9) with Equation (A10), the optimal value of $\text{Prob}_1(Q_G)$ is:

$$\begin{align*}
\left\{ \begin{array}{l}
\text{Prob}_1(Q_G) = \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k1}) \\
s.t. \ z_1^T M_{k1} z_1 \geq 1, \forall z_1 \in \left\{ [F_1(Q_G)z_1]^2 \geq \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right\} \cap \Xi
\end{array} \right.
\end{align*}$$  \hspace{1cm} (A11)

Appendix B. Eliminate Random Vector and Convert Matrix Inequalities

The random vector $z_1$ in constraints in Equation (A11) can be eliminated according to the S-lemma. The Equation (A11) is converted into the matrix inequalities according to Schur complement.

$$\begin{align*}
\left\{ \begin{array}{l}
\text{Prob}_1(Q_G) = \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k1}) \\
s.t. \ \tau_{k1, l_1} \geq 0, \ l_1 = 1, \ldots, m \\
\tau_{l2, l_1} \geq 0 \\
\tau_{k3, l_1} \geq 0, \ l_1 = 1, \ldots, m \\
M_{k1} + \sum_{l_1=1}^{m} \tau_{k3, l_1} W_{l_1} \geq 0 \\
M_{k1} - \text{diag} \left( 0_m, 1 - \tau_{k2, l_1}, \left[ \frac{V_{\text{max}} - V_{\text{min}}}{2} \right]^2 + \sum_{l_1=1}^{m} \tau_{k3, l_1} W_{l_1} \right) \tau_{k2, l_1} F_1(Q_G) \tau_{k2, l_1}^T \\
\geq 0
\end{array} \right.
\end{align*}$$

Proof. Rewrite the second constraint in Equation (A11) as:

$$z_1^T M_{k1} z_1 \geq 0, \forall z_1 \in \Xi = \left\{ z_1 \in \mathbb{R}^m : z_1^T W_{l_1} z_1 \leq 0, \ l_1 = 1, \ldots, m \right\}$$  \hspace{1cm} (B1)

In matrix $W_{l_1} \in \mathbb{R}^{(m+1) \times (m+1)}$, the $(l_1,l_1)$th element is 1, the $(l_1,m+1)$th and $(m+1,l_1)$th element is $-Q_{W,\text{max},l_1}/2$, the rest of the elements is 0. There are $m$ wind farms. The maximum output power of the $l_1$th wind farms is $Q_{W,\text{max},l_1}$.

Notice the constraint condition of Equation (B2):

$$\begin{align*}
\exists \tau_{k1, l_1} \geq 0, \ l_1 = 1, \ldots, m \\
M_{k1} + \sum_{l_1=1}^{m} \tau_{k1, l_1} W_{l_1} \geq 0
\end{align*}$$  \hspace{1cm} (B2)
According to the S-lemma, Equation (B1) is satisfied if and only if Equation (B2) is satisfied. And when $m = 1$, Equation (B2) is equal to Equation (B1). Meanwhile, the first constraint in constraint in Equation (A11) can be written as:

$$z_1^T (M_{k1} - \text{diag} (0_m, 1)) z_1 \geq 0$$

$$\forall z_1 \in \left\{ -z_1^T \left[ F_1^T (Q_G) F_1 (Q_G) - \text{diag} \left( 0_n, \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right) \right] z_1 \leq 0 \right\} \cap \Xi$$  \hspace{1cm} (B3)

Apply the S-lemma to eliminate the random variables $z_1$ in Equation (B3), Equation (B3) is satisfied if and only if Equation (B4) is satisfied.

$$\begin{cases}
\exists \tau_{k2, l_i} \geq 0, \\
\exists \tau_{k3, l_i} \geq 0, \ l_i = 1, \ldots, m \\
M_{k1} - \text{diag} (0_m, 1) - \\
\tau_{k2, l_i} \cdot \left[ F_1^T (Q_G) F_1 (Q_G) - \text{diag} \left( 0_n, \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right) \right] + \sum_{l_i=1}^{m} \tau_{k3, l_i} W_{l_i} \geq 0
\end{cases}$$  \hspace{1cm} (B4)

Apply the Schur complement, rewrite Equation (B4) as:

$$\begin{cases}
\exists \tau_{k2, l_i} \geq 0, \\
\exists \tau_{k3, l_i} \geq 0, \ l_i = 1, \ldots, m \\
M_{k1} - \text{diag} (0_m, 1) - \\
\tau_{k2, l_i} \cdot \left[ F_1^T (Q_G) F_1 (Q_G) - \text{diag} \left( 0_n, \left( \frac{V_{\text{max}} - V_{\text{min}}}{2} \right)^2 \right) \right] + \sum_{l_i=1}^{m} \tau_{k3, l_i} W_{l_i} \geq 0
\end{cases}$$  \hspace{1cm} (B5)

Thus, the optimal solution to sub-optimization problem in Equation (A11) is:

$$\begin{cases}
\text{Prob}_1 (Q_G) = \inf_{M_{k1} = M_{k1}^T \in \mathbb{R}^{m+1}} \text{Tr} (N \cdot M_{k1}) \\
\text{s.t.} \ \tau_{k1, l_i} \geq 0, \ l_i = 1, \ldots, m \\
\tau_{k2, l_i} \geq 0 \\
\tau_{k3, l_i} \geq 0, \ l_i = 1, \ldots, m \\
M_{k1} + \sum_{l_i=1}^{m} \tau_{k1, l_i} W_{l_i} \geq 0 \\
M_{k1} - \text{diag} (0_m, 1 - \tau_{k2, l_i} \left[ V_{\text{max}} - V_{\text{min}} \right]/2)^2 \right) + \sum_{l_i=1}^{m} \tau_{k3, l_i} W_{l_i} \geq 0
\end{cases}$$  \hspace{1cm} (B6)

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