Optimal Power Flow Preventive Control Considering Wind Farm Access

Fan Chen1, Zhiqing Liu2, Jifu Qiu3, Zhipeng Lu2, Ming Chen3, Qingda Niu3 and Xiaoming Dong1*

1 Key Laboratory of Power System Intelligent Dispatch and Control, Ministry of Education, Shandong University, Jinan, Shandong Province, 250061, China
2 State Grid Shandong Electric Power Company, Jinan, Shandong Province, 250001, China
3 Qingdao Electric Power Supply Company of State Grid Shandong Electric Power Company, Qingdao, Shandong Province, 266002, China
* Corresponding author’s e-mail: dongxiaoming@sdu.edu.cn

Abstract. Renewable energy access will be an important trend in the development of the future power grid. In order to analyze the uncertainty brought by wind power access and improve the safety of the grid during steady-state operation, this paper models the uncertainty of wind power. An optimal power flow model considering the risk of power and voltage overruns is established. The model takes the optimal cost of power generation as the goal, takes into account the influence of transformer tap adjustment on system network parameters, and the constraint conditions take into account unit power and safety constraints, it is solved by the primal dual interior point method. The effectiveness of the model and algorithm proposed in this paper is verified by the IEEE14 test system.

1. Introduction
With the continuous expansion of the scale of the power system and the integration of large-scale distributed power sources, the system structure and operation mode have become more complicated. The uncertainty of wind power fluctuations may cause problems such as branch power overrun and bus voltage overrun, which poses new challenges to the safe and stable operation of the power system [1-3]. In the traditional optimal power flow, the control variables are deterministic, but with the access of wind farms, optimal power flow prevention and control needs to consider the impact of wind power uncertainty.

The optimal power flow problem is derived on the basis of the classic economic dispatch theory, fully considering the safety constraints of the power network under normal conditions, and placing the economic dispatch in a safe framework [4], and the safety constraints optimal power flow is to add more safety constraints and more accident constraints on the basis of the former. Optimal power flow preventive control is to find an economical and safe operating state, so that the grid can operate normally under safety constraints and anticipated accidents. Current preventive control mainly focuses on N-1 verification of all transmission lines of the system, and does not fully consider wind power. The influence of bus voltage and branch power fluctuation caused by field access can easily lead to more optimistic evaluation results [5,6].
At present, the literature has carried out research on some of the above problems. Literature [7] uses multi-scenario technology to model the uncertainty of wind power and load. On this basis, a bi-level stochastic power generation and transmission planning model that takes into account the N-1 safety network constraints is established, which improves the ability to absorb wind power and model solving efficiency. Literature [8] improves on the traditional optimal power flow of safety constraints based on fault severity ranking, uses improved overload risk indicators to replace traditional severity indicators, and proposes a new type of security constraint optimal power flow based on fault overload risk indicators ranking algorithm. Literature [9] uses Benders decomposition method to decompose the reactive power optimization planning problem into two sub-problems of investment and operation, and uses the interior point method to solve the operation sub-problem.

Current research does not consider the risk of system overruns caused by wind farm power fluctuations. This paper proposes a safety-constrained optimal power flow (SCOPF) model that takes into account the steady-state operation constraints with the optimal cost of power generation. In the steady-state constraints, the influence of branch power and bus voltage fluctuations are considered. The control methods in SCOPF include the output of thermal power units, the taps of on-load tapping transformers, and load shedding when necessary, this article adopts the proto-dual interior point method and adds the predictive correction part to speed up the simplified calculation and model convergence.

2. Uncertainty modeling and processing

2.1. Wind power model

This article mainly considers the uncertainty of wind power and the risk of branch power and bus voltage overrun caused by power fluctuations. In short-term or online analysis and evaluation studies considering the uncertainty of wind power, the results of short-term predicted power plus the prediction error of random fluctuations are used to describe the wind farm model. The uncertainty of wind power under this situation is mainly reflected in the forecast random fluctuations of error. This paper uses the normal distribution model to describe the error distribution of wind power. It is believed that the probability density function of wind power prediction error obeys the normal distribution with an expected value of 0. The error interval of predicted power meeting the 95% probability level can be obtained according to 2 times of the standard deviation of statistical data. As shown in formula (1):

\[ \varepsilon_w \sim \mathcal{N}(0, \delta_w^2) \]  \hspace{1cm} (1)

Where: \( \varepsilon_w \) is a random variable, which represents the wind power forecast error, \( \delta_w \) is the standard deviation of the wind power forecast error.

2.2. Equivalent branch power and bus voltage fluctuation

Let \( M \) denote the bus voltage phase angle and the bus voltage amplitude, \( W \) denote the injected power of each bus, and \( N \) denote the active and reactive power of the branch, then the power flow equation and branch power equation can be expressed as:

\[
\begin{align*}
W &= f(M) \\
N &= g(M)
\end{align*}
\]  \hspace{1cm} (2)

Take the system steady-state operating point \((M_0, N_0)\) as the reference point, perform taylor expansion of the above formula, and keep the constant term and the first order term. Taking into account the influence of wind power fluctuations, taking \( \Delta W \) as the random disturbance, the corresponding disturbances of \( M \) and \( N \), \( \Delta M \) and \( \Delta N \), can be obtained:

\[
\begin{align*}
\Delta M &= f_0^{-1}\Delta W = S_0\Delta W \\
\Delta N &= G_0f_0^{-1}\Delta W = T_0\Delta W
\end{align*}
\]  \hspace{1cm} (3)

Where: \( f_0 \) is the Jacobian matrix of power flow calculation, \( S_0 \) is the sensitivity matrix of bus voltage to bus injection power, \( G_0 \) is the sensitivity matrix of branch power to bus voltage, \( T_0 \) is the sensitivity matrix of branch power to bus injection power.

From the relationship between the second-order semi-invariant and the variance and expectation in the random variable, we can get:
\[ g_2 = \alpha_2 - \alpha_1^2 \] (4)

Where: \( g_2 \) is the second-order semi-invariant, \( \alpha_2 \) is the second-order moment of origin, which is the variance of the random variable, \( \alpha_1 \) is the first-order moment of origin, which is the expectation of the random variable.

Known from the homogeneity of semi-invariants:
\[
\begin{align*}
\Delta M^{(2)} &= S^{(2)} \Delta W^{(2)} \\
\Delta N^{(2)} &= T^{(2)} \Delta W^{(2)}
\end{align*}
\] (5)

Where: \( \Delta M^{(2)} \) is the second-order semi-invariant of the bus voltage, \( \Delta N^{(2)} \) is the second-order semi-invariant of the branch power, \( \Delta W^{(2)} \) is the second half of the bus injected power Order semi-invariant, \( S^{(2)} \) and \( T^{(2)} \) are respectively composed of the powers of each element in \( S \) and \( T \).

It can be seen that through the linearization of a certain point of the power flow equation, the fluctuation of wind power can be converted into the fluctuation of bus voltage and branch power, a small range of fluctuations can be regarded as approximately normal distribution, so that the fluctuation of bus voltage and branch power is approximately normal distribution characteristics:
\[
\begin{align*}
\varepsilon_\text{line} &\sim N(0, \delta^2_\text{line}) \\
\varepsilon_\text{vm} &\sim N(0, \delta^2_\text{vm})
\end{align*}
\] (6) (7)

Where: \( \varepsilon_\text{line} \) is the standard deviation of the branch power distribution, \( \varepsilon_\text{vm} \) is the standard deviation of the bus voltage distribution.

3. SCOPF Preventive Control Model Considering System Over-limit Risk Constraint

The core purpose of preventive control is to ensure the safe and normal operation of the power grid even when wind power is disturbed. This is reflected in the addition of security constraints to constraints. Another purpose of grid operation is to ensure the optimal cost, that is, the fuel cost of the generator set is the smallest, so this is the highest priority target \( f_1 \). In addition, a quadratic penalty function \( f_2 \) is used to deal with the discrete quantity introduced by the transformer tap. \( f_2 \) is load shedding in urgent case which is used to respond to the system control in emergency situations, the original dual interior point method is used to solve the optimization model. The objective function of the SCOPF model is shown in formula (8):
\[
\begin{align*}
\text{Min } f(u_0) &= \sum_{i=1}^{N_G} a_i P_{G0_i}^2 + b_i P_{G0_i} + c_i + \sum_{i=1}^{N_t} \frac{1}{2} (1 - t_i) t_i + \sum_{i=1}^{N_p} d_i (P_{L0} - P_{Li}) \\
t_i &= \frac{T_i - T_{i-1}}{T_i - T_{i-1}}, \quad T_0 \leq T_i \leq T_T
\end{align*}
\] (8) (9)

Where: \( N_G \) is the set of thermal power plants, \( N_t \) is the set of load bus, \( N_p \) is the set of branches. If the branch contains a transformer, the transformation ratio is adjustable, \( P_{Gi} \) is the active power of generator \( i \), \( P_{L0} \) is the initial load distribution, \( c_i \) are the economic parameters of generator \( i \), \( T_i \) is the transformation ratio of the transformer, \( T_T \), \( T_T \) represent the discrete value of the adjacent grading to which \( T_i \) belongs.

Constraints include equality constraints, that is, the balance equation of active and reactive power, and inequality constraints, that is, the active and reactive power of each thermal power unit, the active and reactive power of the load, the transformer transformation ratio, the power constraints of branch power, Constraints on the magnitude of bus voltages, etc.

1) Equality constraint of power balance
\[
\begin{align*}
\Delta P_i &= P_{Gi} - P_{Li} - [V_i \sum_{i \neq j}^N V_j(G_{ij}\cos \theta_{ij} + B_{ij}\sin \theta_{ij}) - V_i^2 \sum_{i \neq j}^N t_j G_{ij}] \\
\Delta Q_i &= Q_{Gi} - Q_{Li} - [V_i \sum_{i \neq j}^N V_j(G_{ij}\sin \theta_{ij} - B_{ij}\cos \theta_{ij}) - V_i^2 \sum_{i \neq j}^N t_j B_{ij} - \frac{1}{2} b_{ij})]
\end{align*}
\] (10) (11)

Considering the regulation function of the transformer, the power flow equation is rewritten as the above formula. In the formula: \( P_{Li}, Q_{Li} \) are the load bus power, \( t_{ij} \) is the transformation ratio between bus \( i \) and \( j \), \( b_{ij} \) is the sodium value of electricity between bus \( i \) and \( j \), \( Q_{Gi} \) is the generator set \( \theta_{ij} \) is the voltage phase angle difference between bus \( i \) and \( j \).
The wind farm connected to the system is regarded as a \( PQ \) bus, and the wind farm adopts a constant power factor control method. The reactive power of the wind turbine is proportional to the active power, and the expression is:

\[
Q_W = P_W \tan(\varphi)
\]

(12)

Where: \( P_W \) is the expected active power of the wind farm, \( Q_W \) is the expected reactive power of the wind farm, \( \varphi \) is the power factor angle.

2) Inequality constraints of control variables:

\[
P_{Gi,\min} \leq P_i \leq P_{Gi,\max} \quad i \in N_b
\]

(13)

\[
Q_{Gi,\min} \leq Q_i \leq Q_{Gi,\max} \quad i \in N_b
\]

(14)

\[
T_{ij,\min} \leq T_{ij} \leq T_{ij,\max} \quad T_{ij} \in N_l
\]

(15)

\[
P_{li,\min} \leq P_{li} \leq P_{li,\max} \quad i \in N_b
\]

(16)

\[
Q_{li,\min} \leq Q_{li} \leq Q_{li,\max} \quad i \in N_b
\]

(17)

3) Inequality constraints on state variables:

\[
V_{i,\min} \leq V_i \leq V_{i,\max} \quad i \in N_b
\]

(18)

\[
-P_{li,\max} \leq P_{ij} \leq P_{li,\max} \quad P_{ij} \in N_l
\]

(19)

Taking into account the fluctuations caused by the injected power of wind power, it is necessary to adjust the values of the state variables in the safety constraints. The bus voltage amplitude and branch power mentioned in the previous section are approximately normal distribution, combined with the 2sigma principle, that is, the probability of random variable distribution in \((\mu - 2\sigma, \mu + 2\sigma)\) is 0.9544.

Modify the formula (17)-(19) as follows:

\[
-P_{li,\max} \leq P_{ij} + 2\delta_{\text{line}} \leq P_{li,\max} \quad P_{ij} \in N_l
\]

(20)

\[
V_{i,\min} \leq V_i + 2\delta_{\text{vm}} \leq V_{i,\max} \quad i \in N_b
\]

(21)

\[
V_{i,\min} \leq V_i - 2\delta_{\text{vm}} \leq V_{i,\max} \quad i \in N_b
\]

(22)

\[
\delta_{\text{line}}^2 = S^{(2)} \Delta W^{(2)}
\]

(23)

\[
\delta_{\text{vm}}^2 = T^{(2)} \Delta W^{(2)}
\]

(24)

The sensitivity matrix corresponding to \( S \) and \( T \) in the formula is updated with each iteration. By dynamically adjusting the value of each state quantity, the system can obtain economically optimal control variables. It should be noted that the preventive SCOPF model constructed in this article does not consider whether the operating point of the system after the accident still meets the safety constraints.

The predictive control model proposed in this paper belongs to a nonlinear programming problem, and the interior point method is a very effective and fast optimization algorithm for solving large-scale nonlinear programming problems. The interior point method has the advantages of processing inequality constraints, fast convergence speed, and initial point selection is not sensitive and other advantages. By introducing the slack variable, the inequality constraint can be changed to the equality constraint, and then the barrier function is constructed to solve the inequality constraint with the slack variable, finally the lagrange multiplier method is used to convert the original problem into a dual problem. The prediction-correction part is added to the iteration to reduce the number of iterations and improve the convergence characteristics.

4. Case analysis

This paper uses the IEEE14 test example. As shown in the Figure 1, the modified system includes 14 bus and 20 transmission lines, 3 generators are located at bus 1, 2, and 6, and 2 phase modifiers are located at bus 3 and 8. The unit economic parameters are shown in Figure 1. A wind farm with a rated power of 80MW is connected to bus 10, and the wind power factor is -0.98, and the wind power forecast error obeys normal distribution, the standard deviation is \( \sigma = 0.15 \), and the expected expected power of wind power is 50MW, to cover 95% of the prediction error distribution, the upper and lower limits of wind power distribution are selected as \([\mu - 2\sigma, \mu + 2\sigma]\). It should be noted that there is no loss of load shedding under normal operation. The program is realized by matlab programming.
This paper compares the optimal power flow distribution ignoring wind power fluctuations and considering wind power fluctuations. The power and fuel cost of each unit, the bus voltage amplitude and standard deviation, the branch power distribution and fluctuation are shown in Table 1, Table 2 and Table 3:

Table 1 Unit power and cost.

| Generator bus | Active power/MW | Reactive power/MW | Fuel costs/$ |
|---------------|-----------------|------------------|--------------|
|               | OPF             | SCOPF            | OPF          | SCOPF            | OPF     | SCOPF     |
| 1             | 225.7           | 212.8            | -17          | -17              | 857.7   | 852.8     |
| 2             | 24.93           | 36.7             | 18.46        | 17.28            | 135.003 | 180.0     |
| 3             | -               | -                | 19.94        | 18.13            | -       | -         |
| 6             | 20              | 23.3             | 17.43        | 19.56            | 120.4   | 134.0     |
| 8             | -               | -                | 10.44        | 13.21            | -       | -         |

It can be seen from Table 1 that after considering the impact of wind power fluctuations on system safety, the active and reactive power of the generating units has changed, and part of the economy has been sacrificed. The reason is that after considering wind power fluctuations, the safety constraint range of the system has become smaller, and the operating state of the system has changed.

Table 2 Branch power and transformer ratio.

| Branch number | From and To bus | Branch power/MW | Power variance /MW | Rated power/MW | Transformer ratio |
|---------------|-----------------|-----------------|-------------------|----------------|-----------------|
|               |                 | OPF SCOPF       | OPF SCOPF         | OPF SCOPF      | OPF SCOPF       |
| 1             | 1-2             | 155.86 142.56   | 32.8 26.2         | 200            | -               |
| 4             | 2-4             | 49.93 42.33     | 13.33 11.6        | 80             | -               |
| 8             | 4-7             | 23.83 23.83     | 18.49 20.1        | 60             | 0.98 0.96       |
| 9             | 4-9             | 13.63 13.63     | 10.55 9.2         | 60             | 0.97 0.95       |
| 10            | 5-6             | 30.17 28.13     | 16.67 14.3        | 60             | 0.93 0.93       |

It can be seen from Table 2 that when only the expected value of wind power is considered at the system reference point, the system branch power does not exceed the limit, however, the fluctuation of wind power makes the branch power normally distributed within a certain range. The standard deviation can reveal that some branches have a certain risk of overload. By adjusting the power of the generators, the power injection distribution of the system is changed, and the transformer ratio is changed to adjust
the network parameters of the system, so as to optimize the expected power value of the branch and its distribution characteristics.

Table 3 Bus voltage and variance.

| Bus number | Bus voltage /pu | Voltage variance /pu |
|------------|-----------------|----------------------|
|            | OPF              | SCOPF                | OPF                  | SCOPF                |
| 4          | 1.022            | 1.028                | 0.0084               | 0.0073               |
| 7          | 1.060            | 1.053                | 0.0074               | 0.0068               |
| 13         | 0.943            | 0.948                | 0.0018               | 0.0016               |
| 14         | 0.940            | 0.943                | 0.0066               | 0.0062               |

It can be seen from Table 3 that the voltage of the partial load bus is close to the constraint boundary (the upper and lower limits of the voltage of the PQ bus are 1.06pu and 0.94pu). After the wind farm is connected, a large amount of reactive power is consumed, which will cause nearby bus (13, 14) the voltage amplitude is reduced, and there is a risk of over-limit, the voltage stability can be improved by changing the reactive power source.

5. Conclusions

This paper establishes an optimal power flow prevention and control model that considers the risk of exceeding the limit, to ensure that the branch power and bus voltage after connecting to the wind farm system can meet the safety requirements under the fluctuation of wind power. The primal dual interior point method is used to solve this nonlinear optimization problem. In addition, it can be seen from the analysis results of the calculation example that the access of a wind farm will affect the voltage amplitude of the nearby area, and it is particularly important to configure reactive power sources reasonably, the distribution of state variables caused by wind power fluctuations will affect the safety of the system and should fully consider the impact of wind power fluctuations on system safety constraints.

Acknowledgments

This work was supported by the Natural Science Foundation of Shandong Province, China (Grant No. ZR2020ME195).

References

[1] Li, S., Jiang, B.P., Jiang, D.R. (2011) Optimal load shedding algorithm based on the minimum load margin calculation method. Journal of Chongqing University of Technology, 25: 29-32.
[2] Wu, D.X. (2015) Research on the optimal load shedding strategy of power system with risk assessment. Taiyuan University of Technology.
[3] Mao, S.J, Jia, Y.B., Zhang Q. (2019) Research on emergency control methods considering the severity of heating of overloaded lines. Power System Protection and Control, 47: 34-42.
[4] Wang, B., Fang, W.L., Luo X.Z. (2011) A fast algorithm for optimal machine load shedding scheme under emergency control. Power System Technology, 35: 82-87.
[5] Bi, Z.D., Wang J.Q., Han, Z.X. (2002) Fast load shedding algorithm based on the sensitivity of numerical integration method. Power System Technology, 1: 4-7.
[6] Wang, J.Q., Wang W.S, Zhu Z.Q., Xia D.Z. (1997) Optimal load shedding algorithm for power systems. Automation of Electric Power Systems, 1: 36-38.
[7] Wang, Z.P., Zhu, S.X, Wang T., Qin H.X. (2020) Stratified optimization load shedding strategy for receiving end power grid. Transactions of China Electrotechnical Society, 35: 1128-1139.
[8] Wang, G., Cai, X.G, Ma P. (2005) Research on load shedding algorithm to minimize power loss. Proceedings of the Chinese Society of Electrical Engineering, 1: 48-53.
[9] Cao S.G., Yang Y.H, Yu E.k. (1996) The cost of power shortage and its estimation method. Power System Technology, 11: 72-74.