Emergency Control Strategy for Line Overload Considering Power Source and Load Fluctuation

Zhiqing Liu 1*, Fei Wang 2, Jifu Qiu 3, Fan Chen 4, Zhipeng Lu 1, Ming Chen 3, Qingda Niu 3 and Xiaoming Dong 4

1 State Grid Shandong Electric Power Company, Jinan, Shandong Province, 250001, China
2 Dezhou Electric Power Supply Company of State Grid Shandong Electric Power Company, Dezhou, Shandong Province, 253011, China
3 Qingdao Electric Power Supply Company of State Grid Shandong Electric Power Company, Qingdao, Shandong Province, 266002, China
4 Key Laboratory of Power System Intelligent Dispatch and Control, Ministry of Education, Shandong University, Jinan, Shandong Province, 250061, China
* Corresponding author’s e-mail: 201934269@mail.sdu.edu.cn

Abstract. Uncertain factors such as the integration of renewable energy into the grid and load fluctuations have brought more risks to the safe dispatch of the grid. The random power flow is used to calculate the impact of distributed power sources and load fluctuations on the grid, and to quantify the probability distribution of line power, which can avoid the drawbacks of deterministic power flow that cannot fully reflect the line overload risk. Combining the line overload level with the traditional load shedding method can effectively prevent the system from cascading failures caused by the risk of line overload, improve the optimistic calculation results caused by the load shedding strategy in emergency situations that cannot consider source load fluctuations, and make the grid control more safe and reliable.

1. Introduction
With the continuous integration of renewable energy and multiple loads, the source-load side volatility of the power system is increasing. As an important emergency control to ensure the safe operation of the power grid, load shedding can prevent the system voltage from collapsing, prevent the line power from exceeding the limit, maintain the dynamic and transient stability of the system [1]. However, deterministic power flow calculations and load shedding calculations are difficult to account for the influence of uncertain factors on the system, and cannot meet the safety control requirements of the system in emergency situations.

Probabilistic load flow (PLF) can comprehensively consider various uncertain factors such as transmission lines, loads, and power generation to obtain the probability distribution of system state quantities. Compared with traditional deterministic power flow calculations, random power flow can be more comprehensive reflect the operating status of the system, using it for load-shedding calculations can formulate scheduling strategies better and provide strong support for system real-time decision-making and risk assessment [2-5]. Literature [6] proposed the application of multi-objective planning theory to study the calculation of the minimum load shedding that takes into account the difference in
load importance in power grid planning. Literature [7] combined the superposition theorem and the proportional distribution principle to propose a new power flow tracking algorithm, and apply it to line overload emergency control, to eliminate the overload under the condition of as little load shedding as possible, to prevent the occurrence of cascading failures, and ensure that normal circuits are not overloaded. Literature [8] proposes an interval minimum load shedding calculation method that accurately solves the interval number of system minimum load shedding under interval load, which provides a new idea for the study of system security under interval uncertain information.

It can be seen that the above load shedding method based on static analysis research is mainly aimed at the load shedding control of large power grid nodes, and does not take into account wind, solar power and load fluctuations. Based on the above problems, this article based on semi-invariant and Gram-Charlier series proposes a load shedding calculation method that takes into account source load fluctuations, which combines the line overload rate with traditional load shedding calculations to avoid overly optimistic evaluation results. And the validity and accuracy of the proposed method are verified by an example.

2. Source-load fluctuation model and random power flow calculation

2.1. Wind power probability model

Considering the randomness and volatility of wind speed, many models have been proposed in previous studies to simulate the probability distribution of wind speed: Weibull distribution, Rayleigh distribution, LogNormal distribution, Gumbel distribution, etc. Among them, the Weibull distribution is generally recognized as the probability distribution most consistent with the statistical law of wind speed. Weibull distribution is a single-peak two-parameter distribution function cluster, and its probability density expression is:

\[ f(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right] \]  

Where: \( v(v > 0) \) is the wind speed, \( c(c > 0) \) is the scale parameter, which represents the average wind speed in the area, \( k(k > 0) \) is the shape parameter, which represents the distribution characteristics of wind speed.

At present, the mainstream wind turbines used are doubly-fed wind turbines, and the relationship between active power and wind speed basically satisfies the classic wind power conversion expression:

\[ f(P_w) = \begin{cases} 
0 & v \leq v_i, v \geq v_0 \\
k_1 v + k_2 & v_i \leq v \leq v_r \\
P_r & v_r \leq v \leq v_0 
\end{cases} \]  

Where: \( v_i \) is the cut-in wind speed, \( v_r \) is the rated wind speed, \( v_0 \) is the cut-out wind speed, \( P_r \) is the rated active power of the wind turbine, \( k_1 = P_r/(v_r - v_i) \), \( k_2 = -P_r v_i/(v_r - v_i) \).

In the constant power factor control mode, the reactive power of the wind turbine is proportional to the active power, and the expression is:

\[ Q_w = P_w \tan (\phi) \]  

Where: \( \phi \) is the power factor angle.

2.2. Load power probability model

The prediction accuracy of load power is higher than that of wind power. In current research on random power flow, it is generally believed that load power obeys a normal distribution, and its probability density function is expressed as:

\[ f(P_L) = \frac{1}{\sqrt{2\pi} \sigma_{PL}} \exp \left( -\frac{(P_L - \mu_{PL})^2}{2\sigma_{PL}^2} \right) \]

\[ f(Q_L) = \frac{1}{\sqrt{2\pi} \sigma_{QL}} \exp \left( -\frac{(Q_L - \mu_{QL})^2}{2\sigma_{QL}^2} \right) \]  

Where: \( \mu_{PL} \) is the average active power, \( \sigma_{PL} \) is the standard deviation of active power, \( \mu_{QL} \) is the average reactive power, \( \sigma_{QL} \) is the standard deviation of reactive power.
Where: $P_L$ and $Q_L$ are load active power and load reactive power respectively, $\mu_{P_L}$ and $\mu_{Q_L}$ are the expected values of load active and reactive power respectively, $\sigma_{P_L}$ and $\sigma_{Q_L}$ are the standard deviation of load active and reactive power respectively.

2.3. Photovoltaic power probability model
Studies have shown that the solar irradiance generally obeys Beta distribution in a short time, and the probability density of solar irradiance is:

$$f \left( \frac{r}{r_{\max}} \right) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \left( \frac{r}{r_{\max}} \right)^{\alpha-1} \left( 1 - \frac{r}{r_{\max}} \right)^{\beta-1}$$  \hspace{1cm} (5)

Where: $\alpha$ and $\beta$ are shape parameters, which can be obtained from the mean and variance of solar irradiance in a short time, $\Gamma$ is the Gamma function, $r$ and $r_{\max}$ are the actual irradiation intensity and maximum irradiation intensity in a short time.

After the solar intensity is determined, the power of the photovoltaic power station can be determined by the following formula:

$$P_S = r \times A \times \eta$$  \hspace{1cm} (6)

Where: $A$ is the total area of photovoltaic panels, $\eta$ is the photoelectric conversion efficiency. When the photovoltaic power station is connected to the grid, the power factor of the inverter is generally maintained close to 1, so its reactive power can be ignored.

2.4. Stochastic power flow calculation
The stochastic power flow calculation adopts the method based on semi-invariant and Gram-Charlier series expansion. Through the semi-invariant of node voltage amplitude and phase angle, line active and reactive power, the probability density and probability of each state variable are obtained by series expansion distributed. Let $X$ represent the voltage phase angle of the pq and pv nodes and the voltage amplitude of the pq node, $W$ represent the injected power of each node, $Z$ represent the active and reactive power of each line. Then the power flow equation can be expressed as:

$$\begin{align*}
W &= f(X) \\
Z &= g(X)
\end{align*}$$  \hspace{1cm} (7)

At the system reference point $(X_0, Z_0)$, perform Taylor expansion of the power flow equation in polar coordinate form and keep only the constant term and the first order term, and take the random disturbance quantities of $X, W, Z$: $\Delta X, \Delta W, \Delta Z$, and get:

$$\begin{align*}
\Delta X &= J^{-1} \Delta W = S \Delta W \\
\Delta Z &= G \Delta X = G J^{-1} \Delta W = T \Delta W
\end{align*}$$  \hspace{1cm} (8)

Where: $J$ is the Jacobian matrix of the last iteration in the power flow calculation, $G$ is the first-order partial derivative of branch power versus voltage, $S$ is the sensitivity matrix of node voltage versus node injection power, $T$ is the sensitivity matrix of branch power versus node injected power.

$\Delta W$ is composed of wind power $\Delta W_G$, load $\Delta W_L$ and photovoltaic $\Delta W_S$ for convolution operation. In order to avoid the huge amount of calculation for complex convolution operations, the additivity of the semi-invariants is used to obtain the half-invariants of each order of injection power $\Delta W$:

$$\Delta W^{(i)} = \Delta W_G^{(i)} + \Delta W_L^{(i)} + \Delta W_S^{(i)}$$  \hspace{1cm} (9)

The semi-invariants of each order can be obtained by the moments of the origin of the random variables, and the semi-invariants of node voltage and line power can be expressed as:

$$\begin{align*}
\Delta X^{(i)} &= S^{(i)} \Delta W^{(i)} \\
\Delta Z^{(i)} &= T^{(i)} \Delta W^{(i)}
\end{align*}$$  \hspace{1cm} (10)

Where $S^{(i)}$ and $T^{(i)}$ are the i-th power formation of elements in $S$ and $T$ respectively.

For a random variable $\xi$ use its expected $\mu$ and standard deviation $\sigma$ to standardize: $\eta = (\xi - \mu)/\sigma$. Then the Gram-Charlier series expansion of $\eta$ is based on the Hermite polynomial, we can get:

$$\begin{align*}
f(\eta) &= \varphi(\eta) + \sum_{i=1}^{+\infty} c_i \varphi^i(\eta) \\
F(\eta) &= \phi(\eta) + \sum_{i=1}^{+\infty} c_i \phi^i(\eta)
\end{align*}$$  \hspace{1cm} (11)
Where: \( \phi(\eta) \) and \( \phi(\eta) \) respectively represent the probability density function and probability distribution function of the standard normal distribution, \( c_i \) represents the coefficient of each class number, which is calculated from the origin moments of the random variable, \( \phi^i(\eta) \) and \( \phi^i(\eta) \) respectively represent the derivative of the corresponding function.

3. Line overload rate and load shedding calculation

3.1. Line overload rate calculation

Based on random power flow, the probability density function \( f_i(P_i) \) of active power of the line can be calculated:

\[
f_i(P_i) = \phi(P_i)[1 + \frac{\partial}{\partial P_i}H_3(P_i) + \frac{\partial}{\partial P_i}H_4(P_i) + \frac{\partial}{\partial P_i}H_5(P_i) + \frac{\partial}{\partial P_i}H_6(P_i)]
\]

(12)

Where: \( P_i = (P_i - \mu) / \sigma \).

The line overload probability is:

\[
P_{out} = 1 - \int_{-t_{max}}^{t_{max}} f_i(P_i) dP_i
\]

(13)

Where: \( P_{out} \) is the line overload rate, \( T_{max} \) is the line rated capacity, \( P_i \) is the line active power.

3.2. Load shedding calculation

The optimization model is used to simulate emergency control measures taken after an accident. Based on the DC power flow model, the goal is to minimize the sum of the load shedding of each load node in the case of avoiding line overruns, control variables include generator active power and node load shedding, state variables include node voltage phase angle, equation constraint is DC Power flow equation, inequality constraints are system state variable constraints and stability levels. It is assumed that each line in the system can eliminate overload by adjusting load and generation power. Establish the following load shedding model:

Objective function:

\[
min \ Y = P_{out,\max} \sum_{i=1}^{n_l} r_i
\]

(14)

Where: \( n_l \) is the number of load nodes, \( r_i \) is the load shedding of each load node, \( P_{out,\max} \) is the line with the highest overload probability, and the line may be disconnected.

Constraints:

\[
\sum_{i=1}^{n_l} P_{G_i} + \sum_{i=1}^{n_w} P_{W_i} + \sum_{i=1}^{n_s} P_{S_i} = \sum_{i=1}^{n_l} P_{L_i}
\]

(15)

\[
P_S + P_G + r + P_W - P_L = B\theta
\]

(16)

\[
P_i = B_{ij}\theta
\]

(17)

\[
P_{G_i,\min} < P_{G_i} < P_{G_i,\max}
\]

(18)

\[
P_i < T_{max}
\]

(19)

\[
0 \leq r_i \leq P_i
\]

(20)

Where: \( n_G \) is the number of generators, \( P_{G_i} \) is the generator active power, \( n_W \) is the number of wind farms, \( P_{W_i} \) is the wind power, \( n_S \) is the number of photovoltaic power plants, \( P_{S_i} \) is the photovoltaic power, \( P_{L_i} \) is the load power, \( B \) is the node admittance matrix, \( \theta \) is the node voltage phase angle, \( P_i \) is the branch active power, \( B_f \) is the branch-node correlation matrix, \( P_{G_i,\min} \) and \( P_{G_i,\max} \) are the upper and lower limits of the active power of the unit.

The variables involved in the above equations are the expected values of the corresponding variables. When considering the dynamic changes of wind, solar and load fluctuations that cause the risk of line overload, combining equations (16) and (17) can be obtained:

\[
\Delta P_i = B_f \cdot B^{-1} \cdot \Delta(P_S + P_W - P_L)
\]

(21)

It can be seen that line fluctuations are caused by wind, solar and load fluctuations. When the model of each variable is determined, the line fluctuation value is a fixed value and uncontrollable. The fluctuation of the line power in a small range can be regarded as approximately normal distribution, and its standard deviation \( P_{L,\sigma} \) remains unchanged. Therefore, in the process of load
shedding optimization, the difference between the expected line active power and the line rated power needs to be adjusted according to the line active power flow standard deviation.

Then the capacity of the corresponding line in equation (19) is changed to:

$$P_t < T_{max} - A\sigma$$  \hspace{1cm} (22)

Where: A is a coefficient indicating the size of the line overload rate, and represents the line capacity that should be reserved.

The standard deviation of the active power distribution of the line is often small in practice, so the normal distribution curve is approximated by the "3\(\sigma\)" principle. When $T_{max,i} - P_{t,i} \approx 3\sigma_i$, that is, $A = 3$. It can be considered that uncertain factors will not cause the line to overload.

4. Case analysis

The test example uses the IEEE30 system, as shown in Figure 1. The system contains 30 buses and 41 branches. In the calculation process, the load follows a normal distribution, the load expectation is a given value, and the standard deviation is 0.3. A wind farm with a rated power of 150MW is connected to node 6. In the Weibull distribution parameters of wind speed, the scale parameter $c = 10$ and the shape parameter $k = 2.3$, the cut-in wind speed, rated wind speed and cut-out wind speed of the doubly-fed wind turbine are respectively set to: 3m/s, 15m/s, 25m/s. A photovoltaic power station with a rated capacity of 100KW is connected to node 20, and the photoelectric conversion efficiency $\eta$ is 0.14, the shape parameters $\alpha$ and $\beta$ are respectively 1.732 and 2.888, the maximum irradiance $r_{max}$ is 700W/m², the total photovoltaic area A is 10000 m². Lines 6-7 and 10-17 were out of service due to failures. The program is realized by matlab programming.
In order to verify the validity of the random power flow calculation based on the semi-invariant method, the Monte Carlo simulation method is used to calculate the power flow of the calculation example under the same conditions. The probability density and probability distribution of active power flow for some lines are shown in Figure 2. It can be seen that the difference in power distribution obtained by the two methods is very small. So the random power flow method used in this paper can better reflect the influence of power and load fluctuation on the system power flow.

Based on the semi-invariant method random power flow calculation, the power probability expectation, variance and overload rate of some lines are shown in Table 1.

Table 1 Part of the branch load flow.

| From Bus | To Bus | Expect value/pu | Variance /pu | Overload probability | Rated Capacity/pu |
|----------|--------|----------------|--------------|----------------------|------------------|
| 5        | 7      | 0.2316         | 0.0698       | 0                    | 0.7              |
| 6        | 8      | 0.2482         | 0.0784       | 0.1801               | 0.32             |
| 12       | 15     | 0.1151         | 0.0271       | 0                    | 0.32             |
| 15       | 18     | 0.1299         | 0.0313       | 0.1687               | 0.16             |
| 15       | 23     | 0.0957         | 0.0287       | 0.0126               | 0.16             |
| 18       | 19     | 0.1004         | 0.0168       | 0                    | 0.16             |

It can be seen from Table 1 that if the power uncertainty on the source and load side is not taken into consideration and only deterministic power flow calculation is used, the expected line active power flow does not exceed the rated capacity of each line. However, after using random power flow calculation, by calculating the active power probability density of each line, it can be found that some lines have the possibility of overload. Therefore, if the source-load side volatility is ignored, it will lead to a more optimistic evaluation result, which will lead to the risk of system cascading failure.

In order to prevent the cascading failure caused by the risk of line overload, the minimum load shedding method is used to handle it. The calculation process assumes that the line with the highest overload probability in the system is out of service and does not consider the constraints of economic factors, so as to obtain the corresponding load shedding amount of each load node and the power adjustment of the generator.

Table 2 Load shedding of load bus.

| Load bus | Load shedding/MW |
|----------|------------------|
| 8        | 0.3469           |
| 18       | 0.5764           |
| 19       | 0.5230           |

Table 3 Generator power adjustment.

| Generator bus | Power adjustment /MW |
|---------------|-----------------------|
| 1             | -4.1063               |
| 2             | -0.0289               |
| 22            | -1.3297               |
| 27            | 2.6340                |
| 23            | 0.8443                |
| 13            | 0.5403                |

After adjusting the load and generator active power as shown in Table 2 and 3, recalculate and find that the overload probability of the line in Table 4-1 is significantly reduced, and the overload probability of line 6-8, 15-18 and 18-19 Respectively: 0.053, 0 and 0.

When the line does not overload under the deterministic power flow calculation, the system will not take load shedding measures. This method can reduce the load loss risk of cascading failures caused by the line overload rate, and realizes a safer and more reliable minimum load shedding control in emergency situations.
5. Conclusions
The access of distributed power sources and load fluctuations lead to more uncertain factors in power grid dispatching. This paper uses the method of semi-invariant combined with Gram-Charlier series expansion to calculate the risk of line overload caused by source load fluctuations, combined with the load shedding method based on traditional DC power flow, to reduce cascading failures risk caused by line overload. Through the analysis of calculation examples, the following conclusions are obtained:

1) The stochastic power flow method can deal with uncertain factors such as wind, solar power, load fluctuations. It can more comprehensively discover and quantify the risk of line overload than deterministic power flow calculations, and increase the reliability of power grid dispatch.

2) Through the improved load shedding method, the potential cascading failure probability of the system can be reduced on the basis of a more comprehensive discovery of the line overload risk, thereby reducing the system's load loss risk.

The model used in this article does not consider the risk of over-limiting the system bus voltage and the economic cost of system load adjustment and power generation, which will be reflected in future research.

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References
[1] Li, X., Zhang, G.Q., Guo, Z.Z. (2004) Combined load shedding scheme based on static safe power flow constraint of transmission section N-1. Automation of Electric Power Systems, 22: 42-44.
[2] Yang, X.J., Qin, C., (2018) Power System Stochastic Power Flow Calculation Considering Wind Power Dispatching Strategy. Electric Power, 51:54-59.
[3] Zhu, X.Y., Liu, W.X., Zhang, J.H. (2013) Summary of Research on Stochastic Power Flow and Its Application in Safety Assessment of Power System. Transactions of China Electrotechnical Society, 28: 257-270.
[4] Dong, W., Yu, J.M., Yang, M.M. (2012) Stochastic power flow calculation and voltage safety analysis of distribution network containing wind farms. Electric Power, 45: 82-86.
[5] Gan, G.X. (2019) Power System Cascading Failure Analysis and Emergency Control Research. Zhejiang University.
[6] Ge, A.H., Zhao, H., Chen, Y., Ma, H.M. (2017) Research on Minimum Load Shedding Method Considering Load Difference. Shandong Industrial Technology, 19: 169-170.
[7] Ren, J.W., Li, S., Yan, M.M. (2013) Emergency control strategy for line overload based on power flow tracking algorithm. Power System Technology, 37: 392-397.
[8] Wu, P., Cheng, H.Z, Qu G. (2008) Calculation method of interval minimum load shedding in power grid planning. Proceedings of the Chinese Society of Electrical Engineering, 2: 41-46.