Research on power system risk assessment considering large-scale wind and solar access

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Abstract—The grid connection of new energy will bring some risks to the safe operation of power system. In this paper, the wind-output power model is established according to the wind-output characteristics, and the generator set, line and load probability models are established considering the uncertainty of other components of the system. From the perspective of power grid operation and new energy consumption, the traditional operation risk indexes such as voltage overrun and voltage collapse and the new wind and light abandoning indexes are selected, and the non-sequential Monte Carlo method is used to sample the operation state of the power system after wind and wind connecting to the grid, and the index is calculated. Finally, the influence of wind grid connection on system operation risk is analyzed to provide guidance for large-scale new energy grid operation risk assessment.

1. INTRODUCTION
As carbon neutral strategy is put forward, China will gradually build with new energy as the main body of the new type of power system, because the scenery and other new energy output is random, intermittent and uncertain problems, such as landscape of large-scale power grid tend to cause problems such as insufficient voltage crossing the line, electric power, power imbalances, serious impact on the smooth and safe operation of power system. Therefore, it is an urgent problem to be solved to carry out operation risk assessment research on the power system integrating wind and wind into the power grid and formulate targeted solutions according to the assessment results, so as to reduce the pressure of new energy grid connection on the system and ensure the safe and stable operation of the power grid.

At present, there is a certain research foundation for the system risk assessment after the grid connection of new energy such as scenery. From the perspective of system risk assessment after wind power integration, literature [1] designs progressive three-layer risk assessment indicators to assess system risk, and introduces value-at-risk theory calculation to represent the overall risk level of the power system in the future time interval. Literature [2] evaluated the system operation risk from the three aspects of failure state, economic loss and structural strength, and improved the Monte Carlo method to improve the accuracy of risk assessment. In reference [3], the time cycle characteristics of wind speed are taken into consideration in the system risk assessment after wind power is connected to the grid, so as to reflect the characteristics of the system risk changing with time. An example is made with the help of ieEE-RTS79 system and the actual wind speed data of a wind farm, proving the scientific nature of the algorithm. Literature [4] improved the traditional risk assessment method on the
basis of fully considering the error distribution of wind power, and proposed an improved risk assessment method, so as to measure the system operation risk more accurately.

From the perspective of system risk assessment after photovoltaic grid connection, literature [5] introduces third-order Fourier function and random variables subject to three-parameter Weibull distribution to perform fitting and superposition processing on the variation trend of sunshine intensity, which more accurately reflects the time variability of photovoltaic output and system operation risk. Literature [6], on the basis of considering traditional risks, introduces ALARP criterion to grade all risk indicators, and adopts non-sequential Monte Carlo method to carry out risk assessment. When analyzing the operational risk of photovoltaic grid connection, literature [7] introduces semi-invariant series to conduct random power flow research, so as to assist in assessing the risk factors brought by photovoltaic grid connection. In the risk assessment of literature [8], the influence of the combined output of weather and scenery on the line outage rate was considered, and the weight of each indicator was calculated by combining analytic hierarchy Process (AHP) and entropy weight method to make the assessment results more comprehensive and objective.

To sum up, previous studies on the risk of grid connection of new energy sources such as wind power or photovoltaic mostly focused on a single wind power or photovoltaic, while there were few studies on new energy sources including wind power, and the selection of indicators was not fully considered. Therefore, this paper considers the factors of wind power output, system operation state, load uncertainty and so on, and establishes the operation risk assessment model of power system including wind power grid connection. Taking IEEE-RTS79 system as an example, the non-sequential Monte Carlo sampling method is used to calculate the risk index and analyze the operation risk of power system caused by wind power grid connection. It provides reference for making measures to reduce the operation risk of grid connection.

2. OPERATION RISK ASSESSMENT MODEL OF WIND-GRID CONNECTED POWER SYSTEM

2.1 Theory of risk assessment

The risk research of the traditional coal-fired power system mainly focuses on the transient and static state of the generation and transmission system. With the continuous integration of wind farms and photovoltaic stations into the power grid, the idea of probability assessment needs to be introduced to comprehensively consider the uncertain factors of the new power system for risk assessment, which can be expressed as follows:

$$R(X_{i,s}) = \sum P_r(E_i)S_s(E_i).$$

(1)

Where: $R(X_{i,s})$ is the operation state of the power system at time $t$, $E_i$ is the system state caused by the disturbance of the $i$th uncertain risk, $P_r(E_i)$ is the probability of risk occurrence under the system state, and $S_s(E_i)$ is the severity of loss caused under the system state.

2.2 Probabilistic model of output of new solar energy

2.2.1 Wind power output probability model

The output power of wind turbine is related to wind speed, and the uncertainty of wind speed will affect the output of wind turbine. The output probability of wind power generation is as follows:

$$f_{\text{WT}}(P_{\text{WT}}) = \frac{k}{c} \left(\frac{P_{\text{WT}}}{c}\right)^{k-1} \exp\left[-\left(\frac{P_{\text{WT}}}{c}\right)^{k}\right]$$

(2)

Where; $P_{\text{WT}}$ is the active power output of wind; $c$ is the scale coefficient; $k$ is Weibull distribution shape coefficient, which is used to describe the shape of wind speed distribution density function. $k=1$ is the exponential distribution, $k=2$ is the Rayleigh distribution, generally 1.8 to 2.8.
2.2.2 Photovoltaic power generation output probability model
The output power of photovoltaic power station is mainly affected by solar radiation intensity, and Beta distribution is selected to describe its probability density:

\[
f_{PV}(P_{PV}) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \left( \frac{P_{PV}}{P_{PV,max}} \right)^{\alpha-1} \left( 1 - \frac{P_{PV}}{P_{PV,max}} \right)^{\beta-1} \tag{3}
\]

\[
\alpha = \mu \left( \frac{\mu(1-\mu)}{\sigma^2} - 1 \right)
\tag{4}
\]

\[
\beta = (1-\mu) \left( \frac{\mu(1-\mu)}{\sigma^2} - 1 \right)
\tag{5}
\]

Where: \( P_{PV} \) is the output power of photovoltaic panel; \( \alpha \) and \( \beta \) is the shape parameter of Beta distribution, which is calculated by the mean and standard deviation of photovoltaic panel output. \( P_{PV,max} \) is the maximum intensity of illumination.

2.2.3 State probability model of power system components
Wind-output characteristics will cause uncertain risks in the operation of power system, but other components in the power system will also have certain risks. The components in the system can be divided into four categories: fan, photovoltaic cell, generator and circuit. In the actual operation of the system, each category of components has probability of failure and shutdown and normal operation respectively. Therefore, Markov two-state model is selected to model various components, whose states can be expressed as:

\[
\begin{align*}
P(E_n) &= \prod_{c\in C_{off}(n)} P_{c,i}(E_n) \prod_{c\in C_{on}(n)} (1 - P_{c,i}(E_n)) .
\end{align*}
\tag{6}
\]

\[
P_{c,i,j} = 1 - e^{-\lambda_{i,j}}
\]

Where, \( C_{off}(E_n) \) and \( C_{off}(E_n) \) are the set of \( n \) components that are out of operation and running in the system respectively, and the number of elements in the set is the total number of components in the power system. \( P_{c,j,t} \) is the failure rate of component \( i \) at selected time period \( t \); \( \lambda_{c,j} \) is the failure rate of component \( i \).

Wind farms and photovoltaic power stations are often built in resource-rich regions, so it is necessary to consider the impact of bad weather on lines. When element is line \( P_{c,j,t} \), it should be modified as:

\[
P_{c,j,t} = 1 - e^{-\omega \alpha_{i,j}}
\tag{7}
\]

Where, \( \omega \) is the weather correction coefficient under extreme conditions. According to the results of literature [8], \( c_i \) is the \( i \)th system component, and \( \Omega \) is the set of circuit components.

2.2.4 Load probability model
For the load of power system, normal distribution is adopted to describe the uncertainty of system load, and its probability density function is:

\[
f_{load}(P_L) = \frac{1}{\sqrt{2\pi}\sigma_L} e^{-\frac{(P_L-\mu_L)^2}{2\sigma_L^2}} .
\tag{8}
\]

Where: \( P_L \) is the system load of the selected area; \( \mu_L \) and \( \sigma_L \) are mean and standard deviation of load respectively.
3. POWER SYSTEM OPERATION RISK INDEX SYSTEM
The selection of power system operation risk indicators should be systematic, representative and comprehensive, and fully measure the risks faced by the system operation.

3.1 Steady-state frequency off-limit index
The steady-state frequency characteristics of the system are considered in risk assessment, and the steady-state frequency off-limit index is introduced, and its severity function is as follows:

\[
S_1 = e^{\frac{\Delta f_{\text{max}}}{\Delta f_{\text{max}}} - 1}
\]

(9)

Where: \(|\Delta f|\) is the steady-state frequency deviation of the system; \(\Delta f_{\text{max}}\) is the maximum steady-state frequency deviation acceptable to the system.

\[
|\Delta f| = \frac{|\Delta P|}{K_1 + K_2}
\]

(10)

Where, \(|\Delta P|\) is the total change of system active power; \(K_1\) and \(K_2\) represent the frequency adjustment coefficient of load and generator respectively.

3.2 Line active power overlimit indicator
Considering that the active power on each line exceeds the maximum active power that can be carried, the line active power overlimit index is established based on this, and its severity function is as follows:

\[
S_2 = \sum_{n=1}^{N} e^{\max(P_n - P_{n,\text{max}})} - 1
\]

(11)

Where: \(N\) is the total number of system lines; \(P_n\) is the active power of line \(n\); \(P_{n,\text{max}}\) is the maximum active power that line \(n\) can carry.

3.3 Voltage beyond limit indicator
Consider the voltage amplitude at the node deviating from the normal operating range to set the voltage off-limit index, and its severity function is as follows:

\[
S_3 = \sum_{i=1}^{I} e^{\max(V_i - V_{i,\text{max}})} - 1
\]

(12)

Where: \(I\) is the total number of system nodes, \(V_i\) is the voltage amplitude of the node \(i\).

3.4 Voltage breakdown index
Existing studies usually attribute the consequences of voltage collapse to the loss caused by the loss of load in the system state [9]. The severity function of indicators is as follows:

\[
S_4 = kL_h
\]

(13)

Where: \(L_h\) is the total load under the system state \(h\); \(k\) is the conversion coefficient, which is 0.1 in this paper.

3.5 System load loss indicators
The system loss load index is measured by the value of the system loss load, and its index severity function is as follows:
\[ S_5 = \frac{\sum_{i=1}^{I} P_{i,j}}{\sum_{i=1}^{I} P_{i,j}}. \]  

(14)

Where: \( P_{i,j} \) is the active power loss of node \( i \); \( P_{i,i} \) is the active power load of node \( i \).

### 3.6 Abandoned new energy power index

When the output of new energy such as scenery exceeds the actual acceptable capacity of the power grid, wind and light abandonment risk will occur, and its severity function is as follows:

\[ S_6 = Q_h = \alpha P_{h1} + \beta P_{h2}. \]  

(15)

Where: \( Q_h \) is the total electric quantity of wind and light abandoning under system state \( h \); \( \alpha \) and \( \beta \) are wind abandoning rate and light abandoning rate respectively. \( P_{h1} \) and \( P_{h2} \) are respectively the wind and light outputs in system state \( h \).

### 3.7 Comprehensive risk indicators

Assign weights to the above 6 risk indicators to obtain comprehensive risk indicators, as follows:

\[ R = \sum_{i=1}^{6} \omega_i S_i. \]  

(16)

Where: \( \omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6 \) are the weights of the above indicators respectively.

This paper makes comprehensive use of subjective and objective combination assignment method to determine the weight of indicators, namely:

\[ \omega_i = \frac{\sqrt{\omega_{i1} \omega_{i2}}}{\sum_{i=1}^{6} \sqrt{\omega_{i1} \omega_{i2}}}. \]  

(17)

Where: \( \omega_{i1} \) and \( \omega_{i2} \) are the weights of the \( i \)th index determined by analytic hierarchy process and entropy weight method respectively.

### 4. POWER SYSTEM OPERATION RISK ASSESSMENT PROCESS

#### 4.1 Non-sequential Monte Carlo method

This paper defines that there are two states of each component in the power system. In order to evaluate the operation risk of the power system, sampling methods are needed to generate different system operating states. The non-sequential Monte Carlo simulation method is to sample the states. By taking a large number of samples, frequency is taken as the probability, which can be expressed by the following formula:

\[ R = \sum_{i=1}^{A} \omega_i S_i. \]  

(18)

Where: \( A \) is the sampling times; \( A \) is the total sampling times of period \( A \).

#### 4.2 AC optimal power flow model

##### 4.2.1 Objective function

The operation risk assessment of new energy grid connected power system is mainly to meet the load demand of users. In this paper, the ac optimal power flow model is selected to calculate the risk index, and the minimum active power loss of the system in one day is regarded as the optimal function, as follows:
\[ F = \min \left( \sum_{j=1}^{n} \sum_{i=1}^{l} P_{\text{cut}} \right). \] (19)

4.2.2 The constraint
Constraint conditions mainly include system power, system loss load, upper and lower limits of unit output, voltage amplitude, etc. System power is expressed as follows:

\[ U_i' \sum_{j=1}^{n} U_j' (G_y \cos \lambda_y + B_y \sin \lambda_y) + . \quad (20) \]

\[ P_{G_d}^t + P_{PV}^t + P_{WT}^t + P_{\text{cut}}^t - P_{d,l}^t = 0 \]

\[ U_i' \sum_{j=1}^{n} U_j' (G_y \sin \lambda_y - B_y \cos \lambda_y) + . \quad (21) \]

\[ Q_{G_d}^t + Q_{PV}^t + Q_{WT}^t + Q_{\text{cut}}^t - Q_{d,l}^t = 0 \]

Where: \( P_{G_d}^t, P_{PV}^t \) and \( P_{WT}^t \) respectively represent the active power output of generator, photovoltaic and wind power generation of node \( i \) in time period \( t \), and \( Q_{G_d}^t, Q_{PV}^t \) and \( Q_{WT}^t \) respectively represent the reactive power output of generator, photovoltaic and wind power generation of node \( i \) in time period \( t \). \( G_y, B_y \) and \( \lambda_y \) represent the mutual conductance, mutual susceptance and voltage phase Angle difference between nodes respectively. \( P_{\text{cut}}^t \) and \( P_{d,l}^t \) are the active power and reactive power loss loads of node \( i \) respectively. \( Q_{\text{cut}}^t \) and \( Q_{d,l}^t \) are the active and reactive load values of node \( i \) respectively.

For other constraints, refer to reference [4].

4.3 Risk assessment process
The calculation process of the risk assessment model constructed in this paper is shown in Figure 1, and the specific steps are as follows:

- Set sampling times and input system model parameters
- Start sampling to get different system states
- Calculate the real-time status of system components
- Solving power flow distribution using AC Optimal Power Flow Model
- Calculate the weight of evaluation index
- Output data

Figure 1. System risk assessment process

Step1: Set the sampling times of sampling method and input risk assessment model parameters, including wind speed, light intensity and system component parameters;
Step 2: Start sampling and calculate the real-time state probability of each component in the system under different states;
Step 3: Calculate the risk index based on the ac optimal power flow model;
Step 4: Calculate the index weight, and analyze the system operation risk according to the index value.

4.4 Component risk classification
After calculating the risk index results, it is necessary to evaluate the risk level of components. Therefore, ALARP (As Low As Reasonably Practical) criterion widely used in safety risk management is adopted to determine the risk level of power grid components. The criterion introduces unacceptable risk level line and negligible risk level line, and divides the whole component risk into unacceptable area, acceptable minimum area and negligible area.

Power enterprises can use ALARP criteria to classify the risk of power grid components according to their actual power grid line operation and demand. Using this criterion, the risk negligible level line can be defined as the product of the lowest component failure probability level and the lowest consequence level, and the unacceptable risk level line can be defined as the product of the component failure probability level and the unacceptable consequence level.

Taking the line active power as an example: the relevant risk evaluation criteria can be obtained by calculating the national overhead line data over the years; The lowest attention shall be paid to the level of component failure probability, and refer to the reliability index data issued by China Power Council. The reliability data of overhead lines over the years are shown in the table 1.

| Year | Forced outage rate (Times / Hundred kilometer year) | Non shutdown time (Hour / hundred kilometer year) |
|------|-----------------------------------------------|-------------------------------------------------|
| 2011 | 0.233                                         | 2.75                                            |
| 2012 | 0.085                                         | 3.14                                            |
| 2013 | 0.059                                         | 1.3                                             |
| 2014 | 0.081                                         | 0.556                                           |
| 2015 | 0.094                                         | 0.976                                           |
| 2016 | 0.067                                         | 1.055                                           |
| 2017 | 0.055                                         | 0.453                                           |
| 2018 | 0.062                                         | 2.439                                           |

For the data of the above years, the data deviation before 2014 and 2018 is large. Therefore, the data from 2014 to 2017 are taken to calculate the mean value. In recent years, the average forcing rate is 0.07425 times / hundred kilometer year, and the average non-stop time is 0.76 Hour / hundred kilometer year). Therefore, the lowest failure probability level of components that should be paid attention to is obtained:

\[
P_{\text{min}} = \frac{0.07425 \times 0.76}{8760} = 6.44 \times 10^{-6}.
\]  

(22)

According to the safety accident investigation regulations of State Grid Corporation of China, when the power supply load is reduced by 4% or less, it does not constitute a power grid event of level 4 or above, and more than 30% of the power supply load is a particularly serious power grid accident. Therefore, the minimum attention to the consequence level is defined as 4% of the power supply load reduction, and the unacceptable consequence level is 30% of the power supply load reduction.

Thus, it can be obtained that the negligible risk level line of component risk is:

\[
R_{\text{min}} = 6.44 \times 10^{-6} \times 4% = 2.58 \times 10^{-7}.
\]  

(23)

The unacceptable risk level of component risk is

\[
R_{\text{max}} = 6.44 \times 10^{-6} \times 30% = 1.93 \times 10^{-6}.
\]  

(24)
Thus, the classification standard of risk level of line active power out of limit is obtained, as shown in the table. The division methods of other indicators are shown in reference [10].

| Risk level | Index risk value |
|------------|------------------|
| Low        | $< 2.58 \times 10^{-7}$ |
| medium     | $1.93 \times 10^{-6} - 2.58 \times 10^{-7}$ |
| high       | $> 1.93 \times 10^{-6}$ |

5. EXAMPLE ANALYSIS

5.1 Example design
For the operation risk assessment model and indicators established in this paper, EIEE-RTS 79 system is selected to carry out risk calculation, and the calculation process of relevant indicators is carried out on the Matlab platform. In this paper, the line operation data of the system are referred to the literature [11]. The wind and light rejection rate is calculated based on the wind and light output data of a province in Northwest China. The output of 1MW wind and light unit is shown in the figure 3.
5.2 Risk index calculation
Scenario 1: 200MW wind farm and photovoltaic power station are connected at node 1 and node 2 respectively. The number of Non-Sequential Monte Carlo sampling is 10000, and the outage probability of components in the system is 5%. The calculation results of risk indicators are shown in Table 2.

| Risk indicators                      | Index weight | Numerical value | Evaluation level |
|--------------------------------------|--------------|-----------------|-----------------|
| Steady state frequency out of limit  | 0.21         | 1.57×10^{-7}    | low             |
| Line active power out of limit       | 0.04         | 8.64×10^{-7}    | medium          |
| Voltage beyond limit                 | 0.33         | 9.70×10^{-5}    | high            |
| Voltage collapse                     | 0.07         | 5.54×10^{-6}    | high            |
| System loss of load                  | 0.19         | 2.23×10^{-8}    | low             |
| Abandoned new energy power           | 0.16         | 2.58×10^{-4}    | high            |
| Comprehensive risk assessment        |              | 7.39×10^{-5}    | high            |

It can be seen from the results in Table 3 that the risk of Abandoned new energy power, Voltage beyond limit and Voltage collapse are all at a high level after the new energy is connected to the grid. The reason is that the uncertainty of the new energy being connected to the grid increases the operating burden of the power grid system, and the grid structure of some nodes of the system is weak, leading to a large voltage risk.

Scenario 1, the distance between the conventional unit and node 1 and node 2 is far, and the risk of system load loss is low, but the voltage stability of the system grid cannot be maintained. The grid connection distance between wind farm and photovoltaic power station is too close, which will increase the system operation risk due to the output characteristics of scenic resources. Therefore, the access system location of scenic new energy power generation can be changed to reduce the system operation risk.

5.3 The impact of new energy access location on operational risk
Scenario 2: Based on scenario 1, change the access position of the wind farm to 15, increase the distance from the photovoltaic power station, and keep other parameters unchanged.

Scenario 3: Based on scenario 2, change the access location of photovoltaic power station to 13, shorten the distance from generator node no. 23, and keep other parameters unchanged.

Scenario 4: Based on scenario 3, change the access position of the wind farm to 18, increase the distance from the photovoltaic power station, and keep other parameters unchanged.

The calculated results of risk indicators in each scenario are shown in Table 4.

| Risk indicators                      | Scenario 1   | Scenario 2   | Scenario 3   | Scenario 4   |
|--------------------------------------|--------------|--------------|--------------|--------------|
| Steady state frequency out of limit  | 1.46×10^{-6} | 1.40×10^{-6} | 1.43×10^{-6} | 1.37×10^{-6} |
| Line active power out of limit       | 8.01×10^{-6} | 7.59×10^{-5} | 8.11×10^{-5} | 6.13×10^{-5} |
| Voltage beyond limit                 | 9.00×10^{-4} | 6.15×10^{-4} | 5.67×10^{-4} | 5.00×10^{-4} |
| Voltage collapse                     | 5.14×10^{-5} | 5.34×10^{-5} | 5.14×10^{-5} | 5.14×10^{-5} |
| System loss of load                  | 2.07×10^{-8} | 1.64×10^{-4} | 8.07×10^{-5} | 1.46×10^{-5} |
| Abandoned new energy power           | 2.40×10^{-3} | 2.40×10^{-3} | 2.40×10^{-3} | 2.40×10^{-3} |

The main difference between the four scenarios lies in the location of the new energy connection system, including the distance between each other and the distance between the new energy power station and the traditional generator set. By analyzing the change of risk indicators in each scenario in Table 4, the impact of the change of new energy access location on different indicators can be obtained.

In the four scenarios, the two indexes of Abandoned new energy power and Voltage collapse did not change, which may be related to the consumption of new energy and wind-connected grid capacity. The change of access location of wind-connected power station has little influence on the consumption of...
new energy, so the influence of change of access capacity of wind-connected power station on the risk of system indicators can be further explored.

Steady-state frequency off-limit fluctuation is small, and the change of scenery grid-connected position will increase or decrease the distance from the conventional generator set, resulting in the change of active power output of the generator set and the change of power system frequency. Since voltage mainly depends on the capacity of the system to bear the load, the voltage breakdown index varies little.

The wind access position will have great influence on voltage overlimit, line active power and system load loss. From scenario 1 to scenario 4, the distance between wind farm and photovoltaic power station gradually increases, and the distance between wind farm and conventional unit gradually approaches. Increasing the distance of the scenic power station can avoid the voltage risk brought by the uncertain superposition of the scenery. Meanwhile, the conventional units can also exert the maintenance voltage to reduce the interference of new energy to the system stability. This means that in new energy planning, increasing the distance between solar power stations or close to conventional units can reduce the system voltage risk. In addition, the location change of the new energy access system will change the active power distribution of the original line and affect the off-limit index, and the location selection of the new energy connection in the weak part of the system grid can reduce the load loss event caused by the line.

6. CONCLUSION
This paper studies the operation risk of new energy grid-connected power system. Considering the uncertainty of wind power output fluctuation characteristics, system component state and load, the risk assessment model and index system of power system including wind renewable energy are established, and the following conclusions are drawn.

(1) The access of solar new energy to the power system will lead to the risk of abandoning wind and light, which will have a certain impact on the voltage of the power system. If there are more conventional generating units in the system, the active power fluctuation risk caused by the grid-connected new energy can be reduced. Therefore, large-scale grid connection of new energy requires sufficient unit resources to maintain system voltage and reduce the operation risk of power system.

(2) The grid connection location of solar new energy will affect grid security. The grid connection distance between wind farm and photovoltaic power station should not be too close, and the distance with conventional generator set should not be too far. Therefore, large-scale grid integration of solar new energy requires reasonable planning of grid connection nodes to avoid the superposition of solar uncertainty, which will lead to strong volatility of new energy generation and affect the safe operation of the power system.

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