Study on Early Warning of Cascading Failure for Power Grid Considering Wind Power Integration

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Abstract. With the rapid development of wind power and the increasing degree of grid interconnection, the structure of power grid is becoming more and more complicated, and the operation mode is also more diversified. Some small disturbances may lead to cascading failure, or even collapse of grid. So it is important to study on cascading failure of complex grid. In this paper, the power model of wind power is first established, and the brittleness is used to evaluate the risk of brittle chain of cascading failure from two aspects: probability and severity. The brittle chain with high risk is forecasted. Then a method of early warning for cascading failure with power grid integration is proposed. Finally, the feasibility and effectiveness of the early warning method are verified by IEEE 30-node example with wind farm. This method provides support for early warning of cascading failures.

1. Introduction

Large blackouts in power grid are usually caused by cascading failure. When a component in the grid fails, it will cause the nearby line overload or protection equipment tripping. With the spread of failure, the large-scale power outages will be caused [1]. Therefore, the cascade failure early warning can provide an important basis for mastering the safe operation state of the power grid, discovering the potential danger and judging the development of the accident [2]. And with the energy problem has become increasingly prominent, wind power has been widespread concern. In China, large-scale wind farms have joined the power grid. However, its grid-connected generation makes the grid structure and mode of operation become more complex and various, which will make effects on grid operation and control [3].

For the study of early warning of cascading failure, an intelligent early-warning system for on-line relay protection based on EMS/DTS is proposed in literature [4]. An online safety and stability analysis and early warning system are proposed. The static safety pre-warning of the grid is carried out by online scanning and N-1 scanning [5]. However, the studies above do not take the wind power connection into account, especially the influence of the centralized wind farm connection to complex grid on cascading failure early warning.

Therefore, this paper takes wind farm integration into consideration. Firstly, the model of wind power is built. Then, based on brittleness theory, the uncertainty of occurrence of cascading failure is fully considered, and the probability of occurrence of brittle chain is classified. The indexes are established from two aspects: stability and load loss, and the severity of different brittle chains are
classified. Finally, the risk assessment of the brittle chain is carried out by fuzzy evaluation, and the risk early warning of different brittle chains in grid is realized. The feasibility and effectiveness of the early warning method are verified by example analysis.

2. The model of wind power

2.1. The active power model

The active power of wind turbine is related to many factors, including wind speed and blade size [6]. The mechanical power of wind turbine is show as follows:

\[ P_m = 0.5 C_p(\lambda) \rho S V^3 \]  

(1)

Where \( S \) is the wind area of blades; \( \rho \) is the air density; \( V \) is the wind speed; \( C_p(\lambda) \) is the wind energy utilization coefficient, which is a function of tip speed ratio \( \lambda \). \( \lambda = \omega r / V \), \( \omega \) is the wind wheel angular velocity, \( r \) is the wind wheel radius.

It can be seen from Equation (1) that the mechanical power of wind turbine is proportional to the wind area and third power of wind speed. According to wind speed, the theoretical active power of the wind turbine can be calculated.

2.2. The reactive power model

Figure 1 is a simplified equivalent circuit of an asynchronous generator. In figure 1, \( U \) is the motor terminal voltage. \( I_s \) is the stator current. \( I_m \) is the excitation current. \( I_r \) is the rotor current. \( X_m \) is the excitation reactance. \( R/s \) is the mechanical load equivalent resistance. \( X_\sigma \) is the sum of stator leakage resistance and the rotor leakage resistance. \( s \) is the slip.

![Figure 1: Equivalent circuit model of asynchronous generator.](image)

It can be seen from Figure 1 that, the asynchronous generator output of electromagnetic active power \( P_e \) and power factor \( \tan \phi \) expressions are as follows:

\[
\begin{align*}
P_e &= \frac{sRU^2}{s^2X_\sigma^2 + R^2} \\
\tan \phi &= \frac{R^2 + X_m(X_s + X_\sigma)s^2}{sRX_m}
\end{align*}
\]

(2)

Among them, the asynchronous generator slip is as follows:

\[
s = \frac{R \left( U^2 - \sqrt{U^4 - 4X_\sigma^2P_e^2} \right)}{2P_eX_\sigma^2}
\]

(3)

Meanwhile, the output reactive power of asynchronous generator is as follows:

\[
Q = \frac{\left[ R^2 + X_m(X_s + X_\sigma)s^2 \right]P_e}{sRX_m}
\]

(4)

From Equation (3) and Equation (4), it can be seen that the reactive power of the asynchronous generator has been converted to a function of active power and voltage. From Equation (1), it can be seen that the active power (ignoring loss) is also a function of wind speed.

Therefore, as long as the wind speed is determined, the active power output by the wind generator can be obtained for Equation (1), and then the reactive power of wind generator can be obtained from Equation (3) and (4).

3. The brittle chain of cascading failure and its comprehensive evaluation
3.1. The brittle chain

The brittle chain consists of brittleness generator, brittleness receiver and brittleness transmission. The cascading failure in complex grid is the process of brittleness excitation and brittleness propagation. Because the process of cascading failure is one-way, the brittle chain form used in this paper is shown in Figure 2.

Figure 2. The form of brittle chain in cascading failure in grid.

The disturbance in complex grid is complex and various. Therefore, the brittle chain generated by brittleness of the grid is also diversified, and the consequences of different brittle chains are different. The definition of nth brittle chain is as follows:

$$C_n = K_{n1} \cap K_{n2} \cap \ldots \cap K_{nm}$$  \hspace{1cm} (5)

Where $K_{ni}$ ($i=1, 2, \ldots, n$) is the brittleness receiver of the nth brittle chain. If the brittleness process continues to propagate after pass through a brittleness receiver, the brittleness receiver will becomes the brittleness generator of the next brittleness receiver, that is, $K_{ni}$ is both the brittleness receiver for $K_{ni-1}$ and a brittleness generator for $K_{ni+1}$.

3.2. Occurrence probability of brittle chain

For the evaluation of the brittle chain, the occurrence probability of brittle chain should be calculated. In the calculation of the probability of the brittle chain $C_n$, the occurrence probability of its links should be determined first. The occurrence probability of brittle chain link $K_{ni}$ is only related to itself and the previous link $K_{ni-1}$. Therefore, the occurrence probability of $K_{ni}$ $P_{n, i}$ is as follows:

$$P_{n, i} = \alpha \sum_{j=1}^{i} \omega_{nij} y_{nij} + \beta P_{n, i-1} \sum_{j=1}^{i} \omega_{nij} y_{nij}$$  \hspace{1cm} (6)

Where $y_{nij}$ is the quantization value of the influence factor $S_{nij}$, which is described in literature [7]. $\omega_{nij}$ is the weighting factor of influencing factors; $\alpha$ and $\beta$ are link coefficients. In initial links, $\alpha=1$, $\beta=0$. In intermediate links, $\alpha=0$, $\beta=1$.

According to the occurrence probability of each link in the brittle chain, the probability of occurrence of the brittle chain $C_n$ is as follows:

$$P_n = \prod_{i=1}^{m} P_{n, i}$$  \hspace{1cm} (7)

Since the cascading failure is usually a small probability event, in order to make the occurrence probability of brittle chain distribute between $[0, 1]$, the logarithmic transformation is used.

$$d_n = \frac{5 + \log P_n}{5}$$  \hspace{1cm} (8)

The probability of occurrence of brittle chain is classified by fuzzy classification, which is divided into 5 grades: “Very likely (Grade 5)”, “Possible (Grade 4)”, “Sometimes (Grade 3)”, “Less likely (Grade 2)”, “Negligible (Grade 1)”. The corresponding $d_n$ values of each grade are $\{1, 0.8, 0.6, 0.4, 0.2\}$, and the triangle function is used as membership function [8].

3.3. The severity of brittle chain

In this paper, the severity of different brittle chains is evaluated from the aspects of grid stability and load loss. It mainly includes the following 4 indicators: voltage deviation, power angle deviation, load shedding value and generator tripping value.

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3.3.1. Voltage deviation. The voltage deviation $I_U$ is used to reflect the nodal bus voltage deviation caused by the brittle chain $C_n$.

$$I_U = \sum_i \left( \frac{U_i - \frac{U_i^{\text{max}} + U_i^{\text{min}}}{2} \cdot 2}{U_i^{\text{max}} - U_i^{\text{min}} \cdot 2} \right)^2$$

(9)

Where $\Omega$ is the set of all nodes’ buses. $U_i$ is the bus voltage amplitude of node $i$. $U_i^{\text{max}}$ and $U_i^{\text{min}}$ are the allowable maximum and minimum values of voltage respectively.

3.3.2. Power angle deviation. The power angle deviation $I_\delta$ reflects the degree of deviation of the generator power angle caused by the brittle chain $C_n$.

$$I_\delta = \frac{\delta_i - \delta_j}{\Delta \delta_{\text{max}}}$$

(10)

Where $\delta_i$ and $\delta_j$ are the power angles of any two generators in the transient process after fault removal. $\Delta \delta_{\text{max}}$ is the instability criterion angle.

3.3.3. Load shedding value. The load shedding value $I_L$ is used to describe the grid load loss rate caused by the brittle chain $C_n$.

$$I_L = \frac{P_L}{P_a}$$

(11)

Where $P_L$ is the total load shedding value. $P_a$ is the total capacity of the grid.

3.3.4. Generator tripping value. The generator tripping value $I_G$ reflects the rate of tripping generators caused by the brittle chain $C_n$.

$$I_G = \frac{P_G}{P_a}$$

(12)

Where $P_G$ is the total quantity of the generator tripping.

Based on the 4 indicators above, this paper uses the weighted average method ($\omega$ is the weight coefficient) to calculate the severity $W$.

$$W = \omega_U I_U + \omega_\delta I_\delta + \omega_L I_L + \omega_G I_G$$

(13)

The severity of the brittle chain is classified by fuzzy classification. In this paper, the severity is divided into 5 grades: “disaster (Grade 5)”, “very bad (Grade 4)”, “bad (Grade 3)”, “general (Grade 2)”, “negligible (Grade 1)”. The corresponding values of $N$ for each grade are $\{1, 0.8, 0.6, 0.4, 0.2\}$, and the membership function is triangular.

3.4. Risk assessment and early warning of brittle chain

The risk is divided into 5 levels: Grade 5, the consequence of the accident is catastrophic; Grade 4, the consequence of the accident is serious, and protection measures should be taken timely; Grade 3, the consequence of the accident is general, the loss of risk and the risk avoidance cost should be balanced; Grade 2, the accident can be ignored under certain conditions and the intensity of surveillance should be increased; Grade 1, the consequence can be ignored. Combining with the experience of operators, the risk level of brittle chain with different probability and severity can be obtained (Table 1).

| Severity Probability | Grade 5 | Grade 4 | Grade 3 | Grade 2 | Grade 1 |
|----------------------|---------|---------|---------|---------|---------|
| Grade 5              | 5       | 5       | 4       | 4       | 3       |
| Grade 4              | 5       | 4       | 4       | 3       | 3       |
| Grade 3              | 4       | 4       | 3       | 3       | 2       |
| Grade 2              | 4       | 3       | 3       | 2       | 1       |
| Grade 1              | 3       | 3       | 2       | 1       | 1       |

Table 1. Evaluation rules of risk level.
Combining with research above, the basic process of early warning in complex grid for cascading failure is as follows: the formation of brittle chain, the evaluation of brittle chain and the early warning of high risk brittle chain. This paper will pre-alarm the brittle chain with risk grade 3 or above.

4. Case study
The IEEE 30-node system with wind farm is used to analyse, as shown in Fig.3. The wind farm is connected to node 6.

The output power of the wind farm is shown in Table 2 [9]. This case study does not consider the effect of adverse weather.

Table 2. The output active and reactive power of wind farm.

|                     | without wind farm | wind speed 4m/s | wind speed 8m/s |
|---------------------|-------------------|-----------------|-----------------|
| Active power/MW     | 0                 | 17.44           | 42.84           |
| Reactive power/MVar | 0                 | -14.55          | -32.01          |

4.1. Without wind farm
The 3 lines with the largest brittleness of IEEE 30-node system are found when the wind farm is not involved. When using brittle source identification, only the components with largest degree of brittleness correlation are discontented. Thus, the brittle chains formed by the 3 lines with largest brittleness are shown in Table 3.

Table 3. The brittle chain of cascading failure without wind farm.

| Fault line | Britteness value | Brittle chain     |
|------------|------------------|-------------------|
| L11        | 1.633            | L11-L12-L18       |
| L27        | 1.052            | L27-L35           |
| L7         | 0.875            | L7-L26            |

The risk assessment of the brittle chains in Table 3 is shown in Table 4.

Table 4. Risk assessment and early warning of brittle chain without wind farm.

| Brittle chain     | Probability | Severity | Risk Level | Warning state |
|-------------------|-------------|----------|------------|---------------|
| L11-L12-L18       | 0.72        | 0.77     | 5          | Warning       |
| L27-L35           | 0.69        | 0.44     | 4          | Warning       |
| L7-L26            | 0.36        | 0.40     | 2          | No warning    |

From Table 4, it can be seen that the risk early-warning method can not only reflect the brittle chain process, but also show the weakness of the grid effectively. When wind farm is not connected, the lines L11 and L12 are the grid’s weak links, which is consistent with the actual situation: the total
load of node 10, 17, 19, 20, 21, 24 is 52.7MW, accounting for 18.6% of the total load. Node 6 delivers 43.5MW power to the load node above, which bears 82.5% of the power supply. If lines L11 and L12 are disconnected for some reason, a large area blackout will occur.

4.2. With wind farm

In this paper, the brittle chains of IEEE 30-node grid with wind farm are evaluated when wind speed is 4m/s or 8m/s. The evaluation process is the same as in (1) and the results are shown in Table 5 and 6.

Table 5. Risk assessment of brittle chains at wind speed of 4m/s.

| Brittle chain | Probability | Severity | Risk level | Warning state |
|---------------|-------------|----------|------------|---------------|
| L15-L26       | 0.64        | 0.77     | 5          | Warning       |
| L14-L28       | 0.71        | 0.80     | 5          | Warning       |
| L36-L18-L7    | 0.57        | 0.55     | 3          | Warning       |

Table 6. Risk assessment of brittle chains at wind speed of 8m/s.

| Brittle chain | Probability | Severity | Risk level | Warning state |
|---------------|-------------|----------|------------|---------------|
| L41-L36-L15   | 0.81        | 0.82     | 5          | Warning       |
| L11-L15       | 0.69        | 0.85     | 4          | Warning       |
| L27-L28       | 0.46        | 0.75     | 3          | Warning       |

From Table 5 and 6, it can be seen that when the wind farm is connected to the grid, it will produce brittle chains different from the non-integration. And when the wind speed changes, the weak link of the power grid will also change. The early-warning method of cascading failure can effectively identify the potential brittle chains in the grid with different wind speeds. The evaluation results reflect the level of risk from the quantitative point of view, and provide effective direct basis for the early warning of chain fault.

5. Conclusion

Early warning of cascading failure is very important for the stable and reliable operation of power grid. Based on the brittleness theory, this paper evaluates the brittle chain of cascading failure from two aspects: probability and severity and quantifies the risk level of brittle chain to make early warning by combining with wind power model. The feasibility and effectiveness of the early warning method are validated by a case study in a complex grid with wind farm. However, this method is mainly based on line disturbance, and the wind farm model is relatively simple. These aspects need to be further researched.

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