Research on evaluation algorithm and index of resilience power system under energy transformation

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Abstract. In order to solve the problem of increasing vulnerability and decreasing stability of power system under energy transformation, the resilience indexes that should be considered are summarized and an evaluation algorithm of elastic power system is proposed. Firstly, the overall idea and framework of elastic power system evaluation under energy transformation are given; secondly, the evaluation indexes of elastic power system are studied from three aspects: power supply side, transmission network side and distribution side; finally, based on proposed elastic indexes and PSD-BPA power flow and transient program, the algorithm of resilience power system evaluation is proposed. Effectiveness of the proposed method is verified by IEEE RTS39 system, reasonable suggestions for resilience grid are also given.

1. Introduction
In 2050, the proportion of non-fossil energy in the primary energy will be more than 50% in China’s energy production; in the energy consumption, the proportion of electric energy in the end energy consumption will be more than 50%. In order to achieve this goal, power system needs lots of new energy which resulting in great changes in the energy structure and forming a high proportion of new energy system which will bring a series of problems. Because the start-up mode of high proportion of new energy system is inconsistent with the stability requirements, resulting in increased vulnerability; second, lack of frequency and voltage regulation capacity of new energy leads to a significant decline in system stability. In addition to the risk of blackout similar to that in the UK, there is a serious risk of voltage security and stability due to large-scale DC transmission, and ability to resist faults is greatly reduced.

In order to solve the problem of increasing vulnerability and decreasing stability of power system under the energy transformation, many scholars have made active research, among which the research on building resilience power system has attracted wide attention. For example, literature [1-3] studied the concept, influence mechanism of resilience grid. Literature [4-6] studied the strategies to improve the power grid resilience in extreme scenarios. Literature [7-10] studied the role of microgrid, distributed power and reconfiguration strategies in maintaining system performance in the face of extreme events, and points out that these measures can effectively improve the recovery speed of system performance after disasters. Literature [11] described the classification of indicators. The above research mainly focuses on the study of resilience after the occurrence of small probability extreme events in the field of distribution network. From the previous research on power grid security, the risk of power grid mainly exists in the transmission network [12-13]. It is necessary to study the
resilience characteristics of the transmission network under the energy transformation to avoid the occurrence of extreme faults. The research scope of grid resilience should include generation side, transmission network and distribution side, and cover the whole process of recovery before, during and after the fault. Firstly, this paper studies the evaluation of resilience power system under the transformation of energy, then analyses the indicators that need to be studied in the power system, and finally puts forward research opinions of the resilience power system.

2. Overall thinking and framework of resilience power system evaluation under energy transformation

First, build a high proportion of non-fossil energy power development scenario; then based on the high proportion of non-fossil energy power development scenario, carry out production simulation calculation, according to the calculation results, build a high proportion of new energy actual access scenario, and finally high proportion of new energy is actually connected to the scene, and the power grid resilience is evaluated. According to the fault process, the assessment of power grid resilience can be divided into three stages: pre fault, fault and post fault recovery. Therefore, this paper proposes the main block diagram of resilience power system evaluation under energy transformation as shown in figure 1.

![Figure 1. Overall framework of evaluation and evaluation of resilience power system](image)

3. Evaluation index of resilience power system

3.1. Main indexes before fault of Power side

the main indicators before the power side fault are as follows:

3.1.1. Regional indexes. 1) Partition reserve capacity ratio \( P_{eb} \)

\[
P_{eb} = \frac{P_{ebi}}{P_{ei}}
\]  
(1)

Where, \( P_{ebi} \) is the capacity of standby power supply in the zone; \( P_{ei} \) is the total capacity of power supply in the zone.

2) Cross partition backup support rate \( P_{ebs} \)

\[
P_{ebs} = \frac{P_{ebi}}{P_{ebi}}
\]  
(2)

Where, \( P_{ebi} \) is the capacity of standby power supply for the zone to receive support from other zones.

3) Support rate of cross regional peak load regulation \( P_{plr} \)

\[
P_{plr} = \frac{P_{plri}}{P_{plrb}}
\]  
(3)

Where, \( P_{plri} \) is the peak load regulation capacity for the partition to accept the support of other partitions; \( P_{plrb} \) is the total peak load regulation capacity for the partition.

4) Electricity surplus rate \( P_{splus} \)
\[ P_{\text{plus}} = \frac{(P_{\text{epi}} - P_{\text{eli}})}{P_{\text{eli}}} \]  

(4)

Where, \( P_{\text{epi}} \) is the power supply capacity in the zone; \( P_{\text{eli}} \) is the load capacity in the zone.

5) Emergency reserve rate \( P_{\text{er}} \):

\[ P_{\text{er}} = \frac{P_{\text{eri}}}{P_{\text{eli}}} \]  

(5)

Where, \( P_{\text{eri}} \) is emergency reserve capacity in the zone.

6) Blocked capacity ratio \( P_{\text{block}} \):

\[ P_{\text{block}} = \frac{P_{\text{eblock}}}{P_{\text{eli}}} \]  

(6)

Where, \( P_{\text{eblock}} \) is the blocking capacity in the partition.

### 3.1.2. Power supply characteristic indexes

1) Energy connectivity. The proportion of new energy access is:

\[ P_{\text{new}} = \frac{Q_{\text{new}}}{Q_{\text{e}}} \]  

(7)

Where, \( Q_{\text{new}} \) - new energy power; \( Q_{\text{e}} \) total power of the whole society.

2) Installed ratio of distributed power supply \( P_{\text{new}G} \) is:

\[ P_{\text{new}G} = \frac{P_{\text{new}}}{P_{\text{e}}} \]  

(8)

Where, \( P_{\text{new}} \) distributed power capacity; \( P_{\text{e}} \) total installed capacity of the system in China.

### 3.2. Main indexes in faults of power transmission network

As the ability of power system stability in fault or disasters are affected by structure, static and transient stability, the elastic evaluation indexes before transmission network faults are mainly divided into the following two categories:

#### 3.2.1. Relevant indexes of power grid structure

1) Hub degree index of substation

The degree of complexity theory can better describe the importance of a node in the system, but in the actual system, the importance is closely related to the system power flow. Therefore, combining the complexity theory and the system power flow, this paper proposes the hub degree index of the substation \( T_{h} \) as shown in formula (9).

\[ T_{h} = \begin{cases} \omega_{i}C_{i} = \omega_{i} \times \frac{2E_{i}}{k_{i}(k_{i}-1)} & C_{i} \neq 0 \\ \omega_{i} \times k_{i} \div N - 1 & C_{i} = 0 \end{cases} \]  

(9)

Where, \( P_{i} \) indicates the incoming power flow of the \( i \) substation; \( P_{e} \) is the total load in the area. \( \omega_{i} = \frac{P_{i}}{P_{e}} \), \( k_{i} \) - the degree and \( C_{i} \) - clustering coefficient of the substation, \( E_{i} \) represents the actual number of sides between nodes. The higher the \( T_{h} \) value, the higher the degree of substation hub.

2) The transmission section margin index is shown in formula (10).

\[ H_{o} = \frac{P_{\text{Max}} - \sum_{j}P_{j}}{P_{\text{Max}}} \]  

(10)
Where, $P_{max}$ is the maximum transmission capacity of the transmission section, $p_j$ is the transmission capacity of the line in the transmission section.  

3) Intensity index of transmission channel
In case of extreme disaster, dense transmission lines may encounter disasters at the same time, so it is necessary to study the intensity index of transmission lines.

$$L_C = \sum_{i=1}^{K} \frac{P_i}{P_L}$$  \hspace{1cm} (11)

Where, $P_i$ is the power of the first circuit in the $k$ th transmission channel.

3.2.2. Related indexes of system stability
1) Change of short circuit current level
The change of short-circuit current level in substations with different proportion of new energy.

$$\Delta S_{scp} = \frac{S_{scp}'}{S_{scp}}$$  \hspace{1cm} (12)

Where, $S_{scp}$ is the initial short circuit ratio of the substation; $S_{scp}'$ is the short circuit ratio of the substation after the change of new energy ratio.

2) Change of short circuit ratio level
The DC short-circuit ratio and the effective short-circuit ratio of the system under different proportion of new energy.

$$EMISCR = \frac{S_i - Q_{i0}}{p_{i0} + \sum_{j=k} Z_{ij} P_j}$$  \hspace{1cm} (13)

3) AGC frequency modulation capacity caused by new energy grid connection $p_{nh}$

$$p_{nh} = wp_{r,i0} - wp_i$$  \hspace{1cm} (14)

Where, $wp_{r,i0}$ and $wp_i$ are respectively the frequency modulation capacity before and after grid connection; the larger $p_{nh}$, the worse the flexibility of the system.

4) System can keep stability when adopt control measures, such as load cut-off in low frequency and low voltage. Then the transient load cut index of the system is:

$$L_j = \sum_{i=1}^{L} w_i l_i$$  \hspace{1cm} (15)

Where, $w_i$ is the type weight of the load cut of the node, and $l_i$ is the load cut of the node.

The load elasticity index of power grid $R$ is:

$$R = \frac{\sum_{j=1}^{L_j} L_j}{JL}$$  \hspace{1cm} (16)

Where, $J$ is the total number of faults, $L$ is the system load considering the node load type weight.

3.3. Main indexes of power distribution fault recovery
The distribution network is directly related to users. In the process of recovery after grid collapse, most of them adopt the "bottom-up" strategy [14]. Therefore, the main indicators to be considered in the recovery stage are as follows:

1) Proportion of important user's own power supply.

2) Response time of load recovery. The response time from the end of the disaster to the implementation of load recovery measures indicates the emergency response ability of the system.

3) Recovery time of system. The time taken for the system function trapezoid curve to recover from the lowest point to the normal level represents the recovery speed of the system.

4) Important recovery time of load. Time of important loads return to normal level.

5) Recovery time of grid structure. Time of system network frame returns to normal state.
6) Repair speed and time of equipment. The repair quantity per unit time of a certain equipment and the time taken to complete the repair of all such equipment, indicating the repair speed.
7) Black start capability. The urban distribution network should have black start capability.
8) Power balance index. The composition of power supply in the system will affect the recovery speed of the system. Therefore, combined with the recovery speed, recovery time and whether it can be used as black start power supply of various power types in the system, such as: pumped storage, hydropower, gas power, conventional power, distributed power, etc. Power balance index is proposed as shown in formula (17).

\[
B_k = \sum_{i} w_i G_i - w_j L_j
\]  

(17)

Where, \(G\) is the power supply in the area, \(w_i\) - weight of the class power supply, \(L_j\) - capacity of the class load in the system, and \(w_j\) - weight of the load.

4. Resilience evaluation algorithm of power grid
The indexes before and after the fault can be calculated by combining the network structure and parameters, while the evaluation of restoring power grid in the fault must be carried out by combining the transient stability analysis program of power grid. The algorithm steps of resilience evaluation are as follows:
1) Calculate the energy proportion of the system;
2) Carry out production simulation calculation and determine the basic scheme;
3) Based on the basic scheme, forming the final partition with Floyd-warshall algorithm.
4) Power flow analysis is carried out by time-domain simulation power flow program PSD-BPA, and power flow weight index of the substation is calculated based on the power flow of each branch, and the power flow weight index of the substation is calculated according to formula (9).
5) On the basis of power grid partition, the cut set of power grid is searched quickly and the direction of power flow is tested, so as to obtain the section, and the section margin index is calculated according to formula (10).
6) In the interior of the division, according to the administrative region, combined with the geographical boundary, the grid is preliminarily determined. According to the conclusion of grid power demand and spatial load forecasting, the power supply capacity of multiple adjacent grids is comprehensively compared, and the grid boundary is adjusted to form the final grid. According to equation (11), the intensity index of transmission channel in grid is calculated.
7) Determine the set of simple faults and extreme faults. The main fault types considered are as follows: cascade hydropower or power base with large capacity is stopped at the same time; full stop of important hub substation, loss of centralized transmission channel at the same time, loss of both power transmission and receiving DC, and other faults that may cause chain reaction.
8) Calculate system transient stability under every fault by BPA transient stability program.
9) Judge whether the system is unstable.
10) In view of the failure of system instability, start the control measures of the system, such as load cut-off and load reduction measures of low-frequency and low-voltage. After the measures, the system can recover stability, and calculate the load cut according to formula (15). It is impossible to maintain the stable fault of the system through the operation control measures, start the splitting device, and judge that the isolated island area collapse and blackout. The load cut of the system is the overall load in the island area.
11) For the region of system collapse, the system recovery analysis is carried out, and the corresponding index is calculated according to formulas (16-17).

5. Example analysis
Because there are too many indexes involved in this paper, we can decide which indexes to adopt according to the actual needs. This paper briefly describes how to evaluate the most important transmission network resilience in the resilience grid evaluation with IEEE RTS39 node system.
Keep the IEEE-39 node network topology unchanged, and combine the network topology with GIS, as shown in figure 2. The system is reconstructed. Because the generators bus34 and bus33 are located close to each other, they are all transformed into hydropower stations with a capacity of 1.28GW. It is assumed that there are three wind farms connected to bus 36, bus 37 and bus 38 respectively, with a capacity of 1GW. The wind farm output model adopts an interval uncertainty model. In this system, the proportion of non-fossil energy access is 57.4%, and the proportion of new energy access is 31%.

![Figure 2. IEEE RTS39 system power flow diagram combined with GIS](image)

Combined with the system power flow, according to the formula (9), the pivotal degree index of the substation is calculated as shown in Table 1.

| Node name | Degree value | Node name | Degree value | Node name | Degree value | Node name | Degree value |
|-----------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|
| BUS-29    | 0.04365      | BUS-26    | 0.00995      | BUS-10    | 0.008        | BUS-23    | 0.00776      |
| BUS-16    | 0.02108      | BUS-39    | 0.00914      | BUS-22    | 0.008        | BUS-25    | 0.00761      |
| BUS-6     | 0.01619      | BUS-2     | 0.00801      | BUS-19    | 0.00798      | BUS-8     | 0.00756      |

It can be seen from table 1 that the top five hub substations are 29, 16, 6, 26 and 39. The Floyd-warshall algorithm is used to search all the shortest paths in the grid, find the side with the highest number of network mediations, and gradually remove the side with the highest number of mediations to form the final partition, as shown in figure 2. See Table 2 for the system section and the section margin index calculated according to formula 5.

| Cross section | 3 separate zones | Section margin index |
|---------------|------------------|----------------------|
| Section 1     | BUS-1 ~ BUS-39, BUS-5 ~ BUS-6, BUS-5 ~ BUS-8, BUS-6 ~ BUS-11, |
|               |                  | 0.3695               |
| Section 2     | BUS-2 ~ BUS-25, BUS-3 ~ BUS-18, BUS-15 ~ BUS-16         |
|               |                  | 0.416                |
The grid of the system is divided according to the distance of 10km * 10km. The main dense transmission channels are as follows:

BPA transient stability program is used to evaluate the anti-disturbance capability of the resilience power system under simple faults and extreme faults. The fault types and some calculation results considered are shown in Table 3.

| Fault type                                      | Specific fault            | System stability results | measure          |
|------------------------------------------------|---------------------------|--------------------------|------------------|
| Loss of cascade hydropower stations at the same time | hydropower station BUS-33 and BUS-34 fault | Stability after measures | Cut load 464MW   |
| large capacity power supply fault               | BUS-39 generator fault    | Stability after measures | Cut load 750MW   |
| stop after failure of important hub substation  | BUS-29 fault              | Stability after measures | Cut load 638MW   |
|                                                 | BUS-16 fault              | Stability after measures | Cut load 640MW   |
|                                                 | BUS-6 fault               | Stability after measures |                  |
|                                                 | BUS-26 fault              | Stability after measures | Cut load 55MW    |
| Simultaneous loss of transmission lines          | BUS29-BUS26 and BUS28-BUS26 fault | Stability after measures | Cut load 54MW    |
| Section fault                                   | BUS16-BUS19 and BUS24-BUS16 fault | Stability after measures | Cut load430MW   |
|                                                 | Section 1 fault           | Stability after measures |                  |
|                                                 | Section 2 fault           | Unstable                 |                  |

According to the results of table 3, combining formula (16) and formula (17), the elasticity index of power grid is calculated as 0.8946. In the case of section fault 2, the system is unstable. According to table 2, the system is divided into three areas, as shown in figure 2, green area is zone 1, blue area is zone 2, and yellow area is zone 3. According to the power balance index in the area, the recovery capacity indexes of the three areas are 1084, -236 and -643, respectively. Therefore, zone 1 is selected to start the system and record the system recovery speed.

6. Conclusion and suggestions of power system resilience demand
At present, China's power system plays an important role in promoting new energy consumption, reducing air pollution, coping with extreme disasters, and ensuring power supply. In future, on the basis of the existing power system, we should fully consider and undertake the intermittence and fluctuation of new energy power generation, improve the ability to resist and quickly recover from extreme disasters, study and build a new generation of power grid with the characteristics of resilience, comprehensively guarantee the transmission, distribution and consumption of high proportion of new energy generation, and ensure the safe and stable operation of the power system. The main conclusions and suggestions are as follows:

1) It is helpful to evaluate the resilience of power grid before and during the fault, so as to understand the resilience performance of power grid and correct it in time in the planning stage.

2) The higher the self-sufficiency rate of power supply, the fewer the hub substations, the fewer the dense transmission corridors, and the better the disaster tolerance ability of the system.

3) The resilience assessment should include the whole process of generation side and transmission side. According to the research results, the weak links of the system should be found to improve the active resilience of large power grid.

4) The disaster resistance ability of large power grid mainly depends on the generation and transmission grid, and the main research focus of distribution network is the recovery ability.

7. References
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