Four-Dimension (STEP) Seismic Resilience Assessment Framework and Improvement of Urban Power System

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ABSTRACT: Power systems, the core of urban critical infrastructures, suffered heavy losses due to earthquakes. With the development of seismic resilience, seismic research of power systems have been extended to the overall concern of seismic performance, restoration and reconstruction. It is necessary to assess the response of power systems under earthquakes. In order to quantify and improve the seismic resilience of urban power systems, we combine physical element, abstract network and external influence, and assess the power system seismic resilience. Four-dimension seismic resilience assessment framework is proposed by comprehensively considering four dimensions (STEP), including social indicators (affected infrastructures and public services), technical indicators (power function calculated by DC power flow analysis), economic indicators (community GDP), and population indicators (affected population). Moreover, we determine static importance of power systems based on four-dimension framework. The research results show that single dimension resilience assessment may underestimate the actual disaster consequences of the power network. The multi-dimensional performance recovery curve is greatly affected by repair order and resource allocation. Four-dimension (STEP) can better reflect the actual situation of power system technology damage and recovery under earthquake. STEP resilience assessment framework integrates the impacts of society, technology, economy and population on the seismic resilience of power system, and has good practical significance and promotion significance.

Stable power systems are particularly important in the face of earthquakes, as the power system is the core of critical infrastructure systems. In the 2011 earthquake in Japan, 67 substations were severely damaged and 95% of the power system was restored to normal only 10 days after the earthquake. A large number of studies have been carried out on the seismic performance of power systems. Although these studies can reflect the seismic capability of various types of equipment from a probabilistic perspective, reflecting the level of seismic resistance of electrical equipment and even the system level, in reality, the occurrence of various disasters such as earthquakes is not instantaneous, there are various factors such as the duration of the earthquake, post-earthquake repair time, post-earthquake material deployment and economic losses. Therefore, a comprehensive analysis of the seismic capability of the power system from the occurrence of an earthquake to its complete repair is a hot issue that needs to be addressed.

A reasonable assessment of the seismic resilience of power systems is required. The definition of resilience is used to measure the ability of power systems to withstand, absorb and rapidly recover from extreme natural hazards(Carayon, Hancock et al. 2015, Patriarca, Bergstr M et al. 2018). In order to study the response of power systems under disasters and extreme events, and to achieve a reasonable assessment of the extent and breadth of disaster impacts, prevention and system enhancement, a resilience analysis of power systems is necessary.

Methods for resilience assessment of power systems can be divided into complex network analysis and flow analysis. Complex network analysis is divided into pure models (based on topology) such as degree (Dorogovtsev and Mendes 2013) and meshing (A, A et al. 2016), extended models (based on component models), which add the physical and electrical characteristics of electronic components to the CNA(Hossain, Alam et al. 2013). Flow models investigate the resilience of the grid by using models that combine tidal analysis in power engineering with complex network theory. The flow-based approach essentially considers physical characteristics. In power or flow studies where the steady-state solution of the power system is usually computed, the alternating current (AC) flow equation is non-linear(Larocca, Johansson et al. 2015) and solving the AC power flow equation can lead to a large computational burden. The direct current (DC) method limits this problem by linearizing the equations(Nedic, Dobson et al. 2006) and is suitable for large-scale simulations or multiple fault scenario analysis. It considers active power but ignores reactive power and transmission losses; its efficiency approximates AC power flow without iteration and is more accurate in high-voltage, low-load grids.

Bruneau et al. (2003) argue that resilience can be conceptualized in terms of four interrelated dimensions: technical, organization, social and economic (TOSE). Previous approaches to power system resilience assessment have focused mainly on technical dimensions, with relatively little multidimensional, holistic assessment, whereas social, economic and demographic factors are precisely what cannot be ignored in the aftermath of an earthquake, so we propose a framework that is able to integrate the four social, technical, economic and demographic dimensions and use them in arithmetic examples. The remainder of the paper is organized as follows: Section 1 explains the STEP four-dimensional resilience index, the power system vulnerability model, the restoration model under earthquakes and the calculation principle of DC currents, Section 2 illustrates the application of the framework through a 30-node arithmetic example, and Section 3 presents the main conclusions.

1. RESILIENCE INDICATOR

1.1 System Performance Indicator

This paper defines the system performance indicator, SPI, the physical meaning of which expresses how well the power system supply actually meets the overall network, i.e. the actual performance of the entire power system. The methods of using different study subjects as performance indicators are defined uniformly in this study, distinguishing them in the following way.

(1) Social indicators, the percentage of facilities with a high impact on social factors, such as hospitals, schools, railway stations and airports, that cannot be supplied with electricity due to the impact of disasters.

(2) Technique indicator, the number of nodes affected at the topology level that cannot be supplied with power.

(3) Economics indicator, the percentage of facilities with a high economic impact factor, such as shopping areas, pedestrian streets, factories and large servers, that are not supplied with electricity due to the impact of disasters.

(4) Popularity indicator, the percentage of the population affected by a disaster that does not have access to electricity.

Each of the four performance indicators has its own focus, each reflecting the impact of different objects on the disaster, and their respective formulas can be expressed in the following formula (1).

$$SPI\left(t\right)=\frac{n\left(t\right)}{N} \tag{1}$$

where: t denotes time, SPI denotes the system performance indicator, $n\left(t\right)$ denotes functioning number under each indicator (STEP) at time *t*, i.e. number of buildings with normal electricity(S), number of operating electricity nodes(T), economic areas with normal electricity(E) and population with normal electricity consumption(P), N denotes total number (buildings, electricity nodes, economy and population) of the city system.

1.2 STEP Resilience Indicator

All four indicators, social, technological, economic and population can be used as criteria for judging system performance indicators. In this study, these four indicators will be considered together, and the four indicators will be integrated to evaluate the final performance of the power system with the Comprehensive Performance Indicator (STEP).

The integrated performance indicators take into account the four aspects of social, technological, economic and population are proportioned according to different weights, considering the following formula (2).

$$SPI\left(t\right)=STEP\left(t\right)=\frac{s\cdot\sum S_t+t\cdot\sum T_t+e\cdot\sum E_t+p\cdot\sum P_t}{s\cdot S_0+t\cdot T_0+e\cdot E_0+p\cdot P_0} \tag{2}$$

where s 、 t 、 e 、 p denote the weights attributed to each indicator respectively, $STEP(t)$ denotes the composite performance indicator at moment t, S_t 、 T_t 、 E_t 、 P_t denote t number of buildings with normal electricity(S), number of operating electricity nodes(T), economic areas with normal electricity(E) and population with normal electricity consumption(P) at time t, respectively, S_0 、 T_0 、 E_0 、 P_0 denote the sum of the buildings, electricity nodes, economy and population, respectively. The specific weights can be flexible according to the actual needs, but $s+t+e+p=1$ should be ensured, we chose 0.25, 0.25, 0.25 and 0.25.

2. RESILIENCE ANALYSIS FRAMEWORK

2.1 Vulnerability model of power systems under earthquake

When analyzing the probability of damage to power system components, the components of the power system are considered in two aspects: substation components and overhead lines.

(1) Building and Substation

We believe that the seismic reliability of substation systems depends on the substation building facilities and the electrical system of the substation.

The seismic damage index of a building for a given seismic intensity $D\left(I\right)$ can be calculated according to the following formula (3).

$$D\left(I\right)=\sum_{j=1}^{5}p\left(d_j|I\right)d_j \tag{3}$$

where $p(d_j\,|\,I)$ denotes the proportion of d_j level damage occurring at column degree I for a particular type of structure, and d_j denotes the damage factor of the structure.

The probability of damage to electrical equipment can be obtained from the seismic susceptibility curve of electrical equipment, so that the probability of damage to a node under the action of an earthquake P_i can be calculated by the following formula (4).

$$P_i=1-[1-D(I)](1-P_{di}) \tag{4}$$

where $D\left(I\right)$ denotes the seismic damage factor for the building to which element i, P_{di} denotes the probability of damage to the electrical equipment of element i.

According to the statistics from the Wenchuan earthquake, the probability of failure of a transformer P_i in an earthquake of intensity 8 degrees is 0.1825, as shown in Table 1.

Table1 Seismic damage probability of components

Component	Seismic damage probability/10^{-4}		
	PGA0.2g	PGA0.15g	PGA0.1g
220kV Transfomer	1825	702.6	254.6

Assuming that the probabilities of damage are independent of each other and that each substation contains a transformer, the probability of damage to n_{tr} nodes in an earthquake is equation (5).

$$P_{di}\left(n_{tr}\right)=C_{N_{tr}}^{n_{tr}}P_{str}{}^{n_{tr}}(1-P_{str})^{N_{tr}-n_{tr}} \tag{5}$$

where N_{tr} is total number of transformer substations, P_{str} is probability of damage to a single transformer.

(2) Pole

In terms of the probability of damage to overhead lines, the original line structure of the power system has two types of overhead lines and cable lines, and since overhead lines are predominantly distributed, the probability of damage to overhead lines is mainly considered. Considering that overhead lines are suspended in the air and are less affected by seismic energy, their seismic performance is mainly determined by the towers that support them, if each tower on the line is considered a node, then a line can be seen as a tandem system consisting of multiple towers. For a line, its probability of damage under earthquake action F_S can be calculated by the following equation (6) and (7).

$$F_S=1-P_n(n_{ep}) \tag{6}$$

$$P_n(n_{ep})=\prod_{i=1}^{n}(1-P_{sep}) \tag{7}$$

where: P_{sep} denotes the probability of damage to the pole and tower element. According to the vulnerability model, we obtained the damage single electric probability of line towers under the action of different intensity I earthquakes $P_{sep}(I)$, as equation (8).

$$P_{sep}(I)=\begin{cases}25.7\times10^{-4} & I=8\\ 5.04\times10^{-4} & I=7\\ 0.645\times10^{-4} & I=6\end{cases} \tag{8}$$

Assuming that the damage to the electrical components is independent, the relationship between the number of tower damages n_{ep} and the probability of occurrence for the line under an earthquake of intensity I is given by equation (9).

$$P_n(n_{ep})=C_{N_{ep}}^{n_{ep}}[P_{sep}(I)]^{n_{ep}}[1-P_{sep}(I)]^{N_{ep}-n_{ep}} \tag{9}$$

where N_{ep} is total number of poles.

2.2 Model for power system restoration under earthquake

The repair of damaged components requires both specialist technicians to operate and adequate spare parts and materials to replace them, which are often not considered separately in existing studies of repair strategies for resilience analysis. In the aftermath of a disaster, there are often traffic closures, manpower shortages and lack of materials that hinder the progress of restoration works. It is therefore of practical interest to model restoration materials and restoration personnel separately.

(1) Repair supplies. Each damage requires one unit of material for restoration. After a disaster has occurred and the power system has failed on a large scale, the prepared components may not be able to meet the restoration requirements. It is therefore also necessary to distinguish between the two situations of sufficient and insufficient supplies in terms of the time required for restoration.

(2) Restoration personnel. In this study, the restoration staff required for one damaged component was considered as a unit of restoration staff.

(3) Restoration time. We take the statistics from the HAZUS model, for conservativeness and ease of calculation, assuming 0.5 days for pole repair, 2 days for substation (node) repair.

2.3 Restoration order

For the repair of a single damaged line, a non-preemptive repair method will be used in this study. This means that when a line is identified as the line to be repaired, all damaged components on that line must be repaired before moving to the next repaired line for repair work. We adopted three repair strategies: a random repair strategy, a repair strategy based on network metrics (degree) and a repair strategy based on STEP indicator. The degree of a node is the number of edges connected to it. See below for details of STEP indicators.

2.4 DC current analysis of power systems

Since the reactance X is much greater than the resistance R in a high-voltage grid and the conductance to ground can be neglected, scholars assume that $G_{ij}=0$. Since the voltage at each node of the grid differs little from the nominal voltage, the voltage can then be calculated as the per unit, considering $U_i=U_j=1$ .Also the phase difference between the two ends of each line is small, so that the scholar considers $sin\theta_{ij}=\sin\left(\theta_i-\theta_j\right)=\theta_i-\theta_j$. Considering that reactive power is not the object of our study in practical applications, the effect of reactive power on the line is ignored.

Based on the above assumptions, the power calculation is simplified as shown in Equation (10) below.

$$P_i=B_i\left(\theta_i-\theta_j\right)=\frac{\theta_i-\theta_j}{X_i} \tag{10}$$

Where X is (electrical) impedance.

If the physical quantities in Equation are expressed as a matrix, the listing can be rewritten as Equation (8).

$$\left[P\right]=\left[B\right]\left[\theta\right] \tag{11}$$

Where [P] is power matrix, [B] is nodal conductivity matrix, $\left[\theta\right]$ is voltage phase angle matrix.

It can be seen that this is a linear equation, which avoids the tedious calculation of iterations and allows the results to be derived quickly by a computer program. Using this method it is possible to obtain the voltage at each node, the phase angle at each node and the power distribution at each branch and use this as a basis for determining the state of the nodes and lines.

2.5 STEP Resilience analysis framework

We obtained damage results for the urban grid by deterministic analysis based on the power system vulnerability model. We imported the damage results into the DC current analysis to obtain the final affected results of the grid and the remaining functionality of the urban grid through the four STEP indicators. The final resilience curves were obtained through three different repair strategies. As shown in Figure 1.

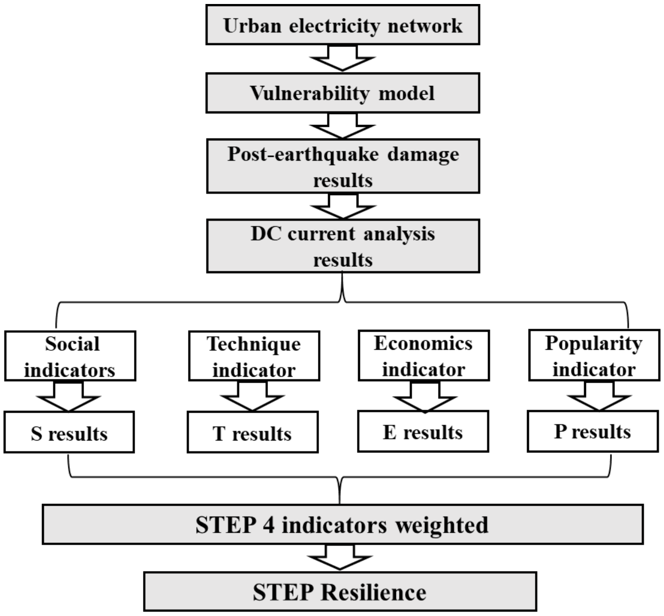

Figure 1: STEP Framework resilience assessment

3. CASE STUDY

3.1 Power system damage results

We applied the STEP seismic assessment framework to a 30-node virtual grid with the topology and node information as shown in the Table 2.

In summary, the damage of 30 nodes under an 8 degree intensity earthquake is shown in the Figure 2.

Table2 Node STEP Indicators

Node	S	T	E	P	STEP
1	Power Plant				
2	Power Plant				
3	1	2	1	2.2	1.51
4	3	4	2	4.2	3.28
5	0	2	1	0.5	0.87

6	5	7	3	6	5.28
7	0	2	2	1.5	1.3
8	0	2	3	2	1.63
9	5	3	1	5.5	3.64
10	2	6	2	4.7	3.62
11	4	1	1	8.6	3.42
12	5	4	1	3.6	3.53
13	Power Plant				
14	3	2	1	3.2	2.31
15	2	4	0	2.3	2.14
16	2	2	2	5.7	2.74
17	5	2	0	6.2	3.28
18	2	2	2	6.2	2.84
19	2	2	1	6.7	2.71
20	2	2	1	5.1	2.39
21	2	2	0	2.3	1.6
22	Power Plant				
23	Power Plant				
24	2	3	1	4.2	2.48
25	2	3	1	2.2	2.08
26	2	1	1	1.3	1.36
27	3	4	2	4	3.24
28	1	3	1	3	1.94
29	2	2	1	3	1.97
30	3	2	2	5	2.9

(Note: Indicator S is based on the number of social buildings, T is based on the number of network degrees, E is based on the number of consumer buildings, and P is based on the number of people, in 10,000 units, and STEP is the weighted average of four indicators.)

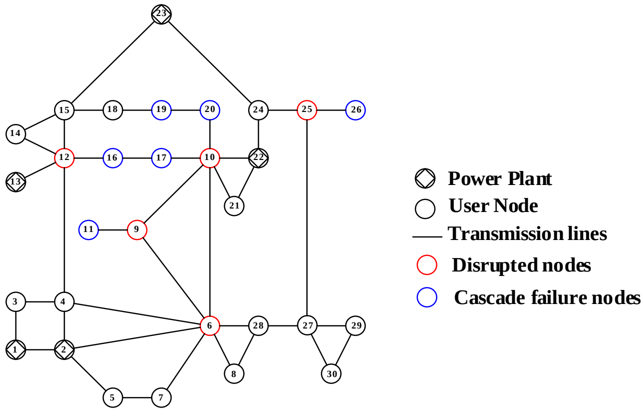

Figure 2: Virtual grid topology and disruption processes

3.2 STEP Resilience analysis framework

The following damage results were obtained using deterministic analysis based on an earthquake vulnerability model and DC current analysis of the power system, as shown in Figure 3. The results show that under earthquake effects, all four dimensions of the indicator experience 20 days of repair completion and return to function, with resilience values of 0.76, 0.88, 0.89 and 0.77 for the social, technical, economic and demographic dimensions respectively, and 0.81 for the combined indicator. the results surface that the use of a single technical dimension for DC current analysis overestimates the seismic resilience of the power system, and that the four dimensions of resilience assessment is more reliable.

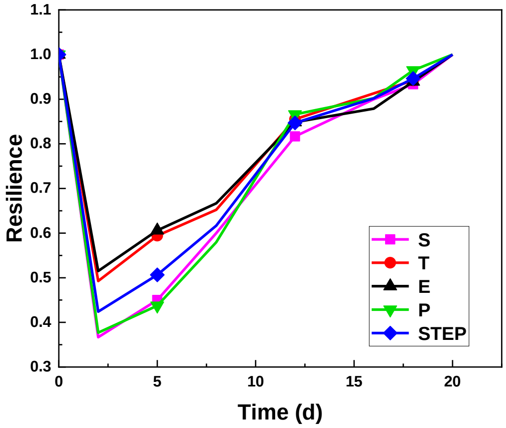

Figure 3: STEP Framework resilience assessment results.

In addition, two additional restoration sequences were selected, according to the STEP static index, and according to the topological index betweenness restoration, with the following results in Figure 4.

The results show that the city grid has the highest seismic resilience under restoration according to the STEP index. The resilience values obtained according to the betweenness, STEP and random order are 0.88, 0.90 and 0.81 respectively.

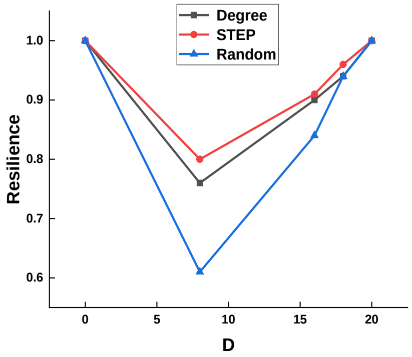

Figure 4: Comparison of Restoration Strategy Results

4. CONCLUSIONS

In order to quantify and improve the seismic resilience of urban power system, we combine physical element, abstract network and external influence, and assess the power system seismic resilience. Four-dimension (STEP) seismic resilience assessment framework is proposed by comprehensively considering four dimensions, which include social indicators (affected infrastructures and public services), technical indicators (power function calculated by DC power flow analysis), economic indicators (community GDP), and population indicators (affected population). Moreover, we determine the components STEP static importance of power system based on four-dimension framework. The following conclusions were formed.

(1) The research results show that single dimension resilience assessment may underestimate the actual disaster consequences of the power network. The multi-dimensional performance recovery curve is greatly affected by repair order and resource allocation.

(2) Four-dimension (STEP) can better reflect the actual situation of power system technology damage and recovery under earthquake. STEP resilience assessment framework integrates the impacts of society, technology, economy and population on the seismic resilience of power system, and has good practical significance and promotion significance.

(3) The order of repair decided on the basis of STEP static indicators has the greatest improvement in resilience than betweenness and random.

(4) The framework is currently only applied to small virtual grids and future work, we will see the STEP framework used for large cities and further research into the repair sequence.

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