A dynamic vulnerability evaluation model to smart grid for the emergency response

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Abstract. Smart grid shows more significant vulnerability to natural disasters and external destroy. According to the influence characteristics of important facilities suffered from typical kinds of natural disaster and external destroy, this paper built a vulnerability evaluation index system of important facilities in smart grid based on eight typical natural disasters, including three levels of static and dynamic indicators, totally forty indicators. Then a smart grid vulnerability evaluation method was proposed based on the index system, including determining the value range of each index, classifying the evaluation grade standard and giving the evaluation process and integrated index calculation rules. Using the proposed evaluation model, it can identify the most vulnerable parts of smart grid, and then help adopting targeted emergency response measures, developing emergency plans and increasing its capacity of disaster prevention and mitigation, which guarantee its safe and stable operation.

1. Introduction

With the development of economy, the electric power system in China has entered into a new era of larger-scale power network, large unit and higher voltage. The large-scale interconnection of power grid achieves the optimal allocation of resources within a larger scope, but reduces the security and stability degree of the system at the same time. Physical parts of power grid—important facilities including substation, convertor station and transmission line/pole/tower, play a key role on the stable operation of power grid. However, facing the typical kinds of natural disasters, the damage or malfunction on power grid will cause the decrease of part or all function of power grid, then resulting in too much loss. This paper defines the probability, the degree of such loss, and its corresponding resilience as the vulnerability of power grid.

According to the historical statistics of power grid emergencies, natural disasters influencing the China's power grid mainly includes geological disasters, such as earthquakes, collapse, landslide, debris flow, etc.; meteorological disasters, such as typhoon, torrential rain, low temperature, frozen, etc.; flood disasters, such as storm floods, rain and snow mixed floods, dam bursting floods and flash flood disasters, etc.. The following Table 1 shows the power grid damage and the corresponding characteristics caused by some typical natural disasters.

Table 1. The damage characteristics of the China's power grid caused by the typical natural disasters.

Disaster type	Damage characteristics caused by natural disasters
Earthquake	It can damage almost all facilities of power grid, causing power outage for several days or even several months; the damage degree rapidly decreases with the increase of the distance from the epicentre; with the improvement of transmission voltage, the number of large transformer substations increases, and its anti-seismic capacity reduces.
Frozen	Snow and ice disaster has high-impact on power grid, more likely to result in the freezing crack of the support insulator; aggravating the drip of oil-filled electrical equipment such as transformer and switch. And the framework, wires and equipment may be covered by ice widely, leading to severe external insulation discharge. The wire icing increases the load of the wire and expands the wind age area of wire. The wind leads to line slipping and breaking and porcelain crashing. The ice flashover can lead to tripping, and part of transmission towers will fall or tilt, etc.
Typhoon	It leads to tower tilting or collapse, cross arm fracture or falling off, wire snapping or grounding or inter-phase short circuit which causes the line to break off, etc. It also levels trees, resulting in the short trouble of transmission and distribution lines. With typhoon, the heavy rain will wash tower foundation, causing tower collapse.

In 2011, the system fault of 220 KV and above in the State Grid region is 1400 times, and natural disasters are the main reasons, accounting for about 65%. The line tripping of 110 KV and above in the Southern Power Grid region is 2862 times, and lightning tripping accounted for 59%, icing and typhoon accounted for 14%, mountain fires accounted for 3% and external destroy accounted for 17%.

For natural disasters vulnerability and risk, Yan-rui Shang [2] introduced the concept of natural disasters vulnerability, and analyzed the typical model of natural disasters vulnerability by contrastive analysis detailed; Liu Yi et al. [3] established application data enveloping analysis model of regional natural disasters system from three aspects that are hazard dangerousness, hazard-affected bodies exposure and disaster loss degree ; El - Kadyn et al. [4] introduced the concept of vulnerability into power grid system, and analyzed and evaluated the dynamic security of power grid system. Jun-mei Wang [5] took traffic for example, putting forward road traffic emergency management framework model from the system point of view, revealing the mechanism of road traffic emergency each elements, and designing the three-dimensional structure of road traffic emergency management system model with the combination of hall structure model. The analysis of the structure model showed the composition and the relationship between the elements of road traffic emergency management system from different sides and perspectives; From the Angle of the vulnerability, he conducted thorough research on the road traffic incident, deepening and expanding emergency management theory and its related theories. Xiang Gao has carried on the comprehensive analysis on the possible influencing factors of coal mine emergency management vulnerability by using the method of identification of vulnerability factors according to the corresponding vulnerability identification process. He summarized four categories of factors that influenced the coal mine emergency management vulnerability, determining the relevant principles and methods of evaluation index ,dividing the first evaluation index of vulnerability evaluation into personnel vulnerability, supplying vulnerability and environmental vulnerability, among which are a total of nine 2nd-level evaluation indicators and a total of 24 3rd-level evaluation indicators. Then he determined evaluation indicators weights by the fuzzy analytic hierarchy process (F-AHP) and constructed hierarchy grey comprehensive evaluation model of coal mine emergency management vulnerability evaluation. Liu Chenching et al. [7] analyzed the factors affecting the vulnerability of power grid system, and divided them into two aspects of external vulnerability and internal vulnerability.

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Zheng gang Cheng [8] analyzed the key technology factors and existing problems in the power grid system emergency according to the current situation of the construction of electric power emergency management system of China, and established the vulnerability assessment method of power emergency system covering monitoring, warning and so on four aspects. He gave the preliminary evaluation calculation model based on the vulnerability of disaster losses of the power grid emergency system combining with the research principles of vulnerability risk assessment.

Based on the analysis, the current researches on vulnerability assessment of natural disasters mainly focus on a certain natural disaster vulnerability assessment of a specific area, and the evaluation of power grid system are mainly concentrated in power grid operation vulnerability, however the researches on overall vulnerability assessment of smart grid infrastructure and operation are less. This paper studies natural disasters vulnerability evaluation for the smart grid infrastructures, including extracting key indicators, building vulnerability evaluation indicator system and putting forward indicator evaluation method. Through this study, it can not only implement vulnerable degree's contrast sorting in different important power grid infrastructures using for optimal allocation of resource, and it can take effective control measures for all kinds of natural disasters vulnerability caused by all kinds of power grid facilities accidents, to reduce the accident economic loss and bad effects, raising the level of safety management in power grid facilities, safeguarding the safe and stable operation of the power grid.

2. The concept of power grid vulnerability

Power grid vulnerability is a certain loss possibility, degree and resilience when the damage or malfunction of facilities' ontology result in the loss of all or part of the system function under the external destroy of natural disaster and human damage to power grid system facilities. This concept involves three aspects, namely: hazard - emergencies such as natural disasters and human damage, etc., are the cause of damage and loss; hazard-affected body-important power grid facility's ontology, is the object suffered emergency impact and damage; Emergency response -hazard-affected body have resistance and resilience to hazard in the face of hazard damage at the same time.

3. Vulnerability assessment triangle model

According to the power grid vulnerability definition, it builds the power grid network vulnerability assessment model, namely, D-G-E model, this model mainly includes:

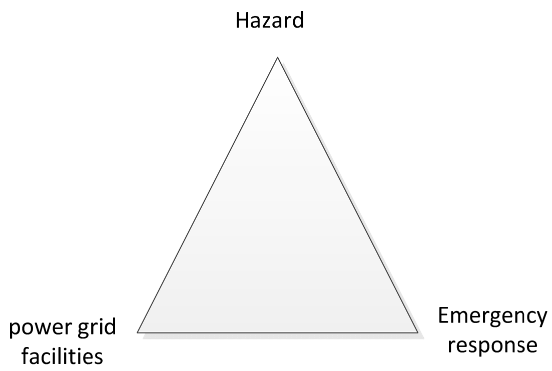

Figure 1. Vulnerability assessment triangle model.

(I) Hazard

Hazard is the pressure from the outside world to important power grid facilities, correspondingly the "hazard" in the defination of power grid vulnerability, to make specific characterization with natural disasters and human factors. Disasters include natural disasters and the external destroy .Natural disasters are mainly earthquake, wind, frozen, floods, landslides, mud-rock flow, lightning, etc.; Human damage mainly include external destroy, malicious theft, etc.

(II) Power grid facilities

The running state of important power grid facilities themselves, correspondingly the “hazard-affected body” in the definition of grid vulnerability, reflects by some factors used to represent ontology characteristics of important power grid facilities, such as the basic physical properties, technical status, running parameters and tripping rate of the infrastructures.

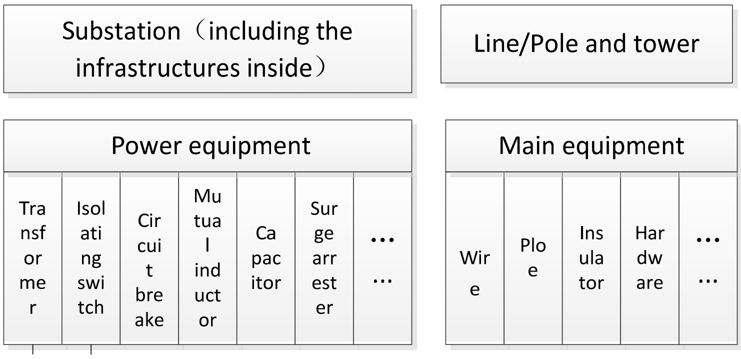

Figure 2. Power grid facilities.

(III) Emergency response

They are some remedial measures according to some of the problems (facility failure, failure, etc.) in facilities running. Correspondingly the "emergency response" in the definition of grid vulnerability, it is expressed with protection system and emergency response capacity, reflecting by the protection system that refers to self-protection function of the power system secondary device (relay protection and safety automatic devices, direct current system unit, prevent false lock device, integrated automation system and RTU unit) and the power grid system emergency rescue capability. Power grid emergency rescue capabilities include accident slowing down, emergency protection, command and coordination and aftermath recovery.

4. Building the evaluation index system of power grid vulnerability

It determines the earthquake, wind, frozen, floods, landslides/mud-rock flow, forest fires and flashing 8 hazard types as the typical research objects of natural disasters combined with accident case analysis of the damage from natural disasters to important power grid facilities. And according to the principle of "combination of peacetime and hazard", it sets up static index and dynamic index for each kind of natural disasters, static index (peacetime) used for vulnerability assessment before hazard and dynamic index for hazard vulnerability assessment. As shown in Table 2, it builds the power grid vulnerability evaluation index system based on multiple hazard types considering the easily availability of index raw data and the maneuverability in the specific implementation process, reducing artificial subjective factors.

Table 2. The evaluation index system of power grid vulnerability.

1st-level index	2nd-level index	3rd-level index	1st-level index	2nd-level index	3rd-level index
A Earthquake	A1 static index	A11 geographic location	E landslides/mud-rock flow	E1 static index	E11 geographic location
		A12 seismic grade (fortification intensity)			E12 geological conditions complexity
	A2 dynamic index	A21 earthquake magnitude		E2 dynamic index	E21 hazard grade
		A22 earthquake intensity			E22 the terrain slope
		A23 duration of strong shaking			E23 surface coverage
B Wind	B1 static index	B11 geographic location	F lightning stroke	F1 static index	F11 geographic location
		B12 the grade of wind resistance			F12 thunder and lightning days throughout the year
	B2 dynamic index	B21 the grade of wind damage		F2 dynamic index	F21 the thunder disaster level
		B22 maximum wind speed			F22 lightning type
		B23 duration			F23 lightning frequency
C Frozen	C1 static index	C11 geographic location	G forest fires	G1 static index	G11 geographic location
		C12 Ability to resist ice			G12 the annual average temperature
	C2 dynamic index	C21 the grade of frozen		G2 dynamic index	G21 fire grade
		C22 the thickness of the ice			G22 the distance to the place fire occurs
		C23The duration of low temperature frozen			G23 combustion duration
D Floods	D1 static index	D11 geographic location	H pollution flashover	H1 static index	H11 pollution grade
		D12 flood control standard			H12 overcast and rainy high humidity and fog wet rainy weather throughout the year
	D2 dynamic index	D21 flood level		H2 dynamic index	H21 filthy layer thickness
		D22 the distance to the source of flood disasters			H22 pollution flashover frequency
		D23 submerged depth			H23 pollution flashover accident grade

5. The index evaluation method of smart grid disaster vulnerability

This study adopts the index evaluation method based on the construction of power grid vulnerability evaluation index system for more scientific and objective vulnerability assessment, and it need to determine the scope of the indexes and grade standard to give the evaluation process and algorithms.

5.1. The values range and assignment basis of natural disasters vulnerability evaluation index

To get a comprehensive natural disasters vulnerability index value, it must assign to each 3rd-level index, combined with other industry index assignment standards and the characteristics of this research object to determine the static value range of 0-10. As in the following, it takes earthquake disaster for example to specify 3rd-level index value range and assignment basis (Table 3).

Table 3. The values range and assignment basis of natural disaster vulnerability evaluation index.

1st-level index	2n-level index	3rd-level index	index level	value range	assignment basis
A Earthquake	A1 static index	A11 geographic location	V degree	0≤A11<2	According to China's seismic intensity zoning map; earthquake magnitude distribution map; determining basic intensity grade in the area of the object to be evaluated, and then correspondingly valuing.
			VI degree	2≤A11<4	
			VII degree	4≤A11<6	
			VIII degree	6≤A11<8	
			IX degree	8≤A11≤10	
		A12 seismic grade (fortification intensity)	1st-level (9 degree)	0≤A12<3	According to electric power facilities seismic design code (GB50260-96)", the seismic grade is divided into four classes, determining basic intensity grade in the area of the object to be evaluated, and then corresponding valuing.
			2nd-level (8 degree)	3≤A12<5	
			3rd-level (7 degree)	5≤A12<8	
			4th-level (6 degree)	8≤A12≤10	

The thoughts of index value range and assignment in other natural disasters type about three-level indexes are as the same as the earthquake disaster.

5.2. The evaluation process and hierarchy of natural disasters vulnerability

In order to evaluate the same type of important power grid infrastructures, it needs to determine the level of vulnerability. In the previous section we know that each 3rd-level index value ranges of 0-10, then each type of natural disasters vulnerability index multiplied by two indexes is a maximum of 100; To avoid the subjective factors in the evaluation process, it gets the comprehensive vulnerability evaluation index of important power grid infrastructures by adding each type of natural disasters vulnerability index. As shown in Figure 1, it is the evaluation process and calculation rules.

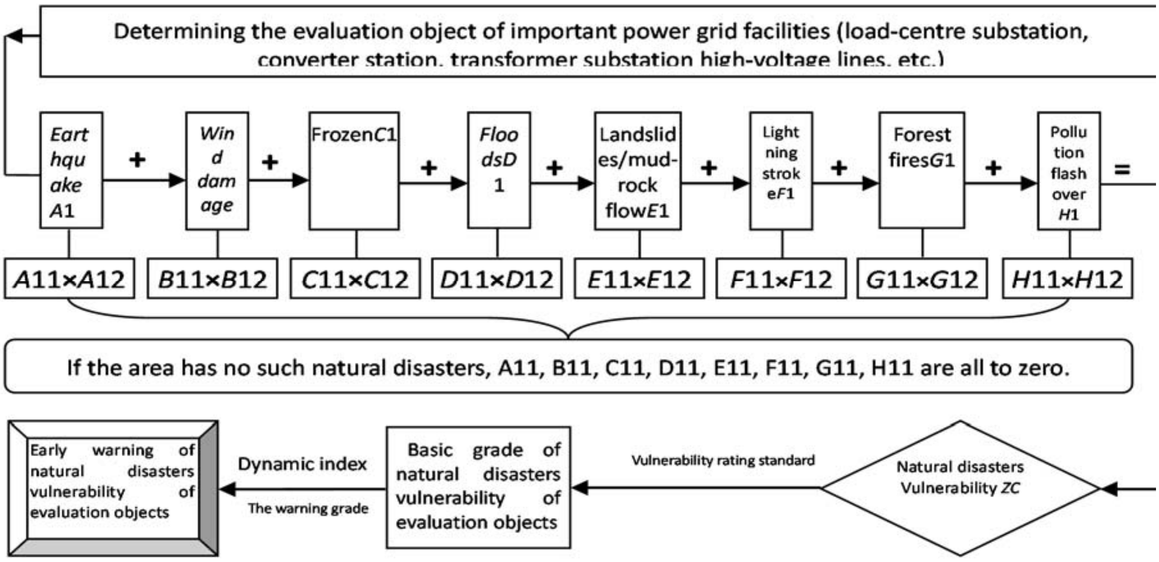

Figure 3. The evaluation process and calculation rules of power grid vulnerability evaluation.

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This study considered 8 kinds of natural disasters. So based on the multiple disasters types, the maximum of comprehensive natural disasters vulnerability index is 800. The degree of vulnerability could be divided into four grades, according to the vulnerability index to command emergency response. As shown in Table 4, it is the relationship between vulnerability and emergency response.

Table 4. The relationship between vulnerability and emergency response.

vulnerability index	Emergency response level
1～128	Lighter
129～288	Medium
289～512	Higher
513～800	Highest

6. Conclusion

The research on power grid vulnerability is complex system engineering, and the current research in this field is still in its infancy. This study has carried out some work in natural disasters vulnerability evaluation research, using the index evaluation method, facing to the needs of emergency response, constructing vulnerability evaluation index, and combining with the verification from actual case to the model method. The study gets the following conclusions:

(I)Previous power grid vulnerability research considers stability a lot from the angle of the system itself, mainly studying the system structure and operation mode. This study proposes a new evaluation method of power grid vulnerability index, and determines their assignment standard and evaluation grade, to understand the grid vulnerability and provide evaluation tools for contrasting the sorting.

(II)According to the judge before the hazard, it can get more influential factors to the natural disasters vulnerability of power grid infrastructures, to provide ways of reducing power grid vulnerability itself. In the practical application, it needs to determine the dynamic index in combination with monitoring all kinds of natural disasters index, then it need comprehensively judge the real-time power grid vulnerability degree with static indexes, to provide data support for the early warning of power grid disasters.

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