Vulnerability Study of Electric Power Grid in Different Intensity Area in Wenchuan Earthquake

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SUMMARY:
The overall damage and losses of Sichuan electric power system caused by Wenchuan earthquake are introduced. The damages of substations at 110kv and above are listed， which are located in areas with earthquake intensity Ⅸ and above and managed by the state grid company in Sichuan province. The major damage phenomena of indoor and outdoor high-voltage electrical equipments, transmission towers, distribution poles and lines are summarized. The statistics of the damage frequency, interruption situation and recovery time of substations in different intensity area are given. On these grounds, the Wenchuan earthquake damage characteristics of electric facilities in areas with intensity Ⅵ to Ⅺ, and the failure mode of electric systems are summarized. The main factors for this earthquake damage to the systems are analyzed. Several new measures and suggestions to strengthen the system's weakness have been put forward. The results can provide the reference for rapid evaluating the substations damage and improving the electric facilities seismic reliability.

Keywords: Wenchuan Earthquake; electric power grid; vulnerability Monte Carlo method

1. GENERAL INSTRUCTIONS

The electric power system, one of the critical components of lifeline systems, is playing vital functions in the national economic and people's daily activities. Previous earthquake disasters show that once the system is damaged or disrupted due to the quake, not only huge direct/indirect economic losses are caused, but also people's normal life and social production are significantly affected. More important, it would put the post-earthquake actions, such as the emergency rescue, into great difficulties. Therefore, it is of great significance for improving the system performance to sum up the system damages, to analyze its causes, and to explore its failure characteristics.

The Sichuan power grid experienced severe damages during the Wenchuan earthquake occurred on May 12, 2008. After the earthquake, China Earthquake Administration organized a scientific investigation team on engineering disasters. One of its groups had specific investigations on the state power grid in the area covering Deyang, Mianyang, Guangyuan, Aba, and part area of Chengdu which suffered most severely in the earthquake. Based on the information acquired, this paper introduces the seismic damage of the Sichuan power system, and summarizes the damage phenomena and characteristics of some facilities including substation buildings, indoor and outdoor high-voltage electrical equipments, transmission towers, distribution poles and associated lines, all of which distribute in different intensity zones. In addition, the system failure mode has been analyzed. Finally, some specific measures and suggestions are given. Based on the knowledge mentioned above, this paper would be helpful for the rapid evaluation of the facility damage and the system performance.

2. GROUND MOTION INTENSITY OF WENCHUAN EARTHQUAKE AND ITS DAMAGE TO SICHUAN POWER GRID

The Wenchuan earthquake has high ground motion intensity and widespread effect. Its earthquake intensity in meizoseismal area has reached degree Ⅺ according to the Chinese seismic intensity scale.

Figure1 provides the isoseismal line map of high-intensity zones while Table2.1 contains the information of peak ground acceleration(PGA) recorded in each intensity zones.

There are 60 counties and cities in Sichuan province have been affected by the quake, and a total of 4.0507 million electricity customers experienced outages. The power grid of 10 counties suffered significant damage, which are Pengzhou, Dujiangyan, Mianzhu, Shifang, Zhongjiang, Mianyang, Beichuan, Jiangyou, Anxian, Qingchuan, and Jiange. The direct economic loss caused by the quake is 7.1 billion RMB, and the net loss of property is about 5.64 billion RMB, of which 5.43 billion RMB from Sichuan power companies(China Earthquake Administration Wenchuan Earthquake Emergency Headquarters, 2008).

Table 2.1. Record of PGA in Each Intensity Zones

Intensity	Number of Strong motion Observation Station Recorded Three Components of Acceleration	PGA in East-West Direction ($cm{\cdot}s^{-2}$)		PGA in North-South Direction ($cm{\cdot}s^{-2}$)		PGA in Up-Down Direction ($cm{\cdot}s^{-2}$)		Mean PGA in Horizontal Direction ($cm{\cdot}s^{-2}$)
		MAX	MIN	MAX	MIN	MAX	MIN	
Ⅺ	0	---	---	---	---	---	---	---
Ⅹ	1	824.1	824.1	802.7	802.7	622.9	622.9	813.4
Ⅸ	5	957.7	289.5	652.9	203.5	948.1	179.9	435.2
Ⅷ	5	511.3	273.7	458.7	279.0	379.6	177.4	339.4
Ⅶ	18	424.5	91.7	410.5	100.0	211.1	55.1	179.9
Ⅵ	55	195.8	7.8	299.5	9.5	127.1	6.2	83.6

According to the statistics of the power companies in Sichuan Province(Sichuan Electric Power Experiment Research Institute, 2008; Sichuan Province Power Company, 2008), the number of damaged substations and lines are shown in Table 2.2.
The load loss of Sichuan power grid is 4.3 million kilowatts. The detail loss of Chengdu, Mianyang, Deyang, Guangyuan and Aba are shown in Table 2.3.
According to the survey in Sichuan province, the earthquake had plunged some counties into total electric blackout, as shown in Figure2.1 where the blackout regions of Shanxi, Gansu and parts of Sichuan are not marked.

Table 2.2. Number of Damaged Substations and Lines in Wenchuan Earthquake

Voltage (kv)	Number of Damaged Substation	Number of Reconstruction Substation	Damaged Line
500	1		4
220-330	14	3	64
110	75	5	136
35	156	7	187
10			1252
Total	246	15	1643

Table 2.3. Power Grid Load Loss in the Major Stricken Areas

Area	Pre-earthquake Load (million kilowatts)	Post-earthquake Load (million kilowatts)	Electric Load Loss (percentage)
Chengdu	3.06	1.07	65
Deyang	1.07	0.11	90
Mianyang	0.56	0.01	98
Guangyuan	0.39	0.08	79
Aba	0.09	0.00	100

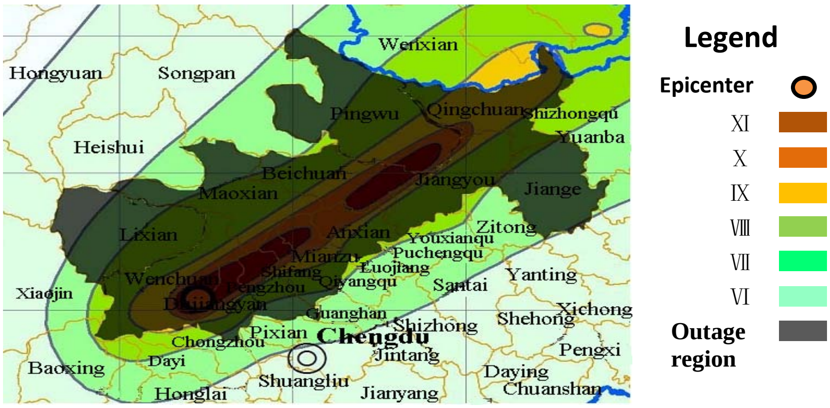


Figure 2.1. Outage situation of county or county-level city

3. TYPICAL DAMAGE PHENOMENA OF ELECTRIC POWER FACILITIES

A large number of substations suffered damage in the earthquake. The outlines of the damage information of substations of 110kv and above are shown in Table 3.1.

Table 3.1. Damage of Substation of 110kv and above in High-Intensity Area

Substation Name	Intensity	Voltage (kv)	Description of Facility Damages	Restoration Time
Aba Yinxing Substation	XI	220	Most of the equipments were damaged; the buildings were seriously damaged; some buildings were buried by landslides.	Reconstruction
Mianyang Leigu Substation	XI	110	I #, II # main transformers were seriously displaced; oil leaked, and bushing was ruptured; PT, CT, disconnect switch, knife, lightning arrester, communication equipments and other equipments were damaged; buildings were severely damaged.	Reconstruction
Aba Ertaishan Substation	X	220	Extensive damage occurred to various types of equipments; transformers were overturned; buildings were severely damaged.	Reconstruction
Mianyang Xiaoba Substation	X	110	I # main transformer was in a serious oil leakage and shift; 14 circuit breakers and 24 disconnect switches were smashed due to collapsed buildings; arrester / CT / PT were destructed; buildings were severely damaged.	Reconstruction
Deyang Hanwang Substation	X	110	I #, II # main transformer ejected fuel and 10kV bushing got ruptured; 3 disconnect switches and 1 lightning arrester were destroyed; the number of destroyed PT / CT were unknown; buildings were severely damaged, and some nearly collapsed.	Reconstruction
Aba Maoxian Substation	IX	500	I # main transformer bushing was severely damaged and caused on fire; II # main transformer bushing got burst; leakage occurred on the highly resistant bushing; and other high-voltage electrical equipments were damaged; GIS was intact.	Reconstruction
Mianyang Anxian Substation	IX	220	I #, II # main transformers were tilted, and oil blew out; bushing was fractured; 6 circuit breakers were damaged; 17 switch pillars were broken; 9 CT, 4 PT and 13 lightning arresters were fractured; communication equipment / capacitor / reactor / Power were impaired; 2 bus insulators were broken; main control room collapsed.	Reconstruction

Mianyang Yuanmenba Substation	Ⅸ	110	Oil blew out and bushing fracture occurred on 1 main transformer; 11 circuit breakers was destroyed or ruptured; 19 disconnect switches and 4 CT were fractured; 6 permeability, 4 PT and 3 lightning arresters got ruptured; communication equipment / DC power supply were damaged; a bus bar insulator became tilt; main control room was severely damaged	Reconstruction
Deyang Chuanxindi an Substation	Ⅹ	110	1 main transformer was displaced, oil blowout and bushing fracture were observed; 1 circuit breaker got failed; 2 switches, CT, PT were damaged, one part of bus insulator became tilt; the foundation of the main control room foundation sank seriously and could not be used any more.	Reconstruction
Deyang Xiangshan Substation	Ⅸ	110	1 main transformer was displaced, oil spilled and bushing was ruptured; 2 CT were fractured; 2 lightning arresters leaked.	2008/5/15
Mianyang Yongan Substation	Ⅸ	110	2 circuit breakers failed and were overturned; DC system and communication system was damaged.	2008/5/14
Mianyang Jushui Substation	Ⅸ	110	Bus was destroyed; pillar insulator became tilt; communication equipment / DC power supply were damaged.	2008/5/15
Guangyuan Qiaozhuang Substation	Ⅸ	110	I#, II# main transformer were displaced; I# main transformer bushing A, B phase operating at 110KV were displaced and oil spilled; B, C phase operating at 10KV spilled oil; some batteries were damaged, communication equipments were damaged.	2008/5/14 Partial recovery
Guangyuan Muyu Substation	Ⅸ	110	I # main transformer was displaced, severe oil spilling and bushing displacement occurred; 3 circuit breakers failed; 5 current transformers failed and oil spilled; 11 disconnect switches were damaged; 2 lightning arresters cracked.	Taking temporary phase and wiring，for the main transformer was destroyed

Wenchuan earthquake featured with a huge magnitude, large suffered area with various intensities. Therefore, the facility damage phenomena are different as well. Figure3.1 through Figure3.8 show the typical damage images.

Among the high-voltage electrical equipments, the major damage phenomena of transformers include gas protection tripping, body displacement, overturning and oil spills, bushing broken and oil spills, the failure of bottom bolts. As for circuit breakers, disconnect switches, current transformers(CT), voltage transformers(PT), lightning arresters and other tall pieces of porcelain, the damage phenomena primarily appear as the oil leakage, burst, bottom or the middle break, dumping and so on. Bus was often disconnected due to the insulator damage. Some high-rise equipment pulled down the adjacent associated devices due to their own collapse. Some devices had short circuit, or burnt down because of the loosen wires.

The damage of transmission lines mainly resulted from geological disasters such as landslides, rolling stones, etc., which led to the damage of the fort ridge of transmission towers, as well as the tower smashing, deformation, tilt and dumping. As for the distributed lines, the damage was often observed as a result of the nearby buildings' collapse which caused poles broken, overturning, lines disconnection, and so on. For the indoor equipments, the equipment boxes were often inclined and the equipments were destroyed by collapsed houses.

Most severe damage phenomenon was the collapse of the main control room, such as 110kv Hanwang substation, 220kv Anxian substation, and Yinxing substation where part of the house and outdoor equipments were buried in landslides.

Figure 3.1. Transformer toppling down in 220kv Ertaishan substation

Figure 3.2. Most of transformers and circuit breakers are damaged in Beichuan 110kv Qimingxing substation

Figure3.3. 10kv capacitor three-way reactor burnout and porcelain insulator burst in Guanghan Sanxingzhui substation

Figure 3.4. Main control room collapsed, transformer displaced and oil leaked

Figure 3.5. High voltage transmission tower toppled down and transmission line broken due to mountain landslide Yingxiu

Figure 3.6. Electrical wire destroyed by nearby collapsed buildings

Figure 3.7. 6kv reserve high voltage switchgear smashed in Yuanmenba

Figure 3.8. All equipments and buildings destroyed in Xiaogangjian substation

4. STATISTICS FOR SUBSTATION OUTAGE AND RECOVERY TIME

According to the collections of earthquake damage investigation, some statistics for substation outage status was conducted. The related area included Chengdu, Deyang, Mianyang, Guangyuan and Aba. Figure4.1 illustrates the distribution of sample substations operating from 35kv to 500kv and located in intensity Ⅶ and above areas. The composition of the power supply system in Sichuan province includes the state grid and some local power companies. Nevertheless, only the state grid and the host part of the local power grid are studied here and taken as statistical samples. Since the seismogenic fault of the Wenchuan earthquake is located at the brim of the Sichuan basin, the southeast to the fault is the bottom of the basin that is a plain area with a dense population, many industries and well-developed power grids. Therefore，the samples were concentrated in this area.

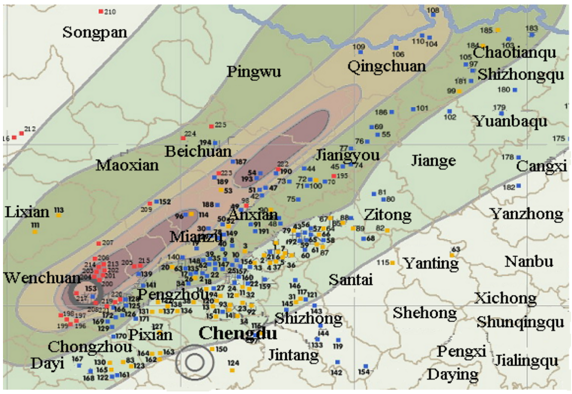


Figure 4.1. Distribution map of substation
Note: the red is the hosted substation of state grid corporation, the blue is the outage substation and the yellow is the non outage substation

4.1. Substation Outage Statistics

Figure4.2 shows the ratio of substations out of service. These substations are located in various intensity zones and belong to the state grid and the host part of the local power grids. As can be seen from the figure, in the intensity Ⅶ area, the outage ratio of electricity substations closes to 50%; in the intensity Ⅷ area it is 85%, while almost 100% goes off in the intensity Ⅸ and higher-intensity area. In the lower intensity area such as intensity Ⅶ areas, those factors such as the power failure of the upper substation, the transformer protection and so on, dominate, while with the intensity increasing to Ⅹand above, the structures of substations were severely damaged and all outages were caused by the structure failure. This result agrees well with Figure 1 which shows the situation of many whole-county blackouts.

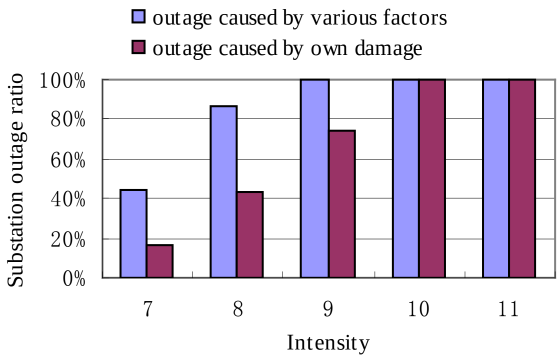


Figure 4.2. Distribution map of substation outage ratio in different intensity zones

4.2. Substation Equipment Ddamage Statistics

In the areas with various intensities, the damage ratios of all kinds of high-voltage electrical equipments of damaged stations are shown in Figure 4.3. It is observed that, 1) the outdoor high-rise porcelain equipments such as transformers, circuit breakers, disconnect switches, current transformers, voltage transformers, lightning arresters etc. are vulnerable to damage, especially transformers; 2) indoor equipments such as batteries, monitors and so on, are less damaged unless they encountered house collapse; and 3) the bus is less damaged, which was often caused by the insulator support failure.

The equipments are categorized into 8 groups: 1) transformers, 2) circuit breakers, 3) buses, 4) disconnect switches, 5) current transformers, 6) voltage transformers, 7) lightning arresters, 8) communication equipments, capacitors and power sources. The average numbers of damaged equipment groups at outage substations are as follows: 1-2 in the intensity Ⅵ, Ⅶ area; 3-4 in the intensity Ⅷ, Ⅸ area; 6-7 in the intensity Ⅹ area; and all in the intensity Ⅺ area as shown in Figure 4.4.

Two primary damage phenomena of transformers are displacement and leakage. According to the site survey, the bushing leakage possesses more than 85%, while the bulk oil spills is less. Following an inside probe, the internal of transformers are not damaged. At a lower intensity, the main damage is oil spills, but the body displacement phenomenon will increase with the intensity increase (see Table 4.1).

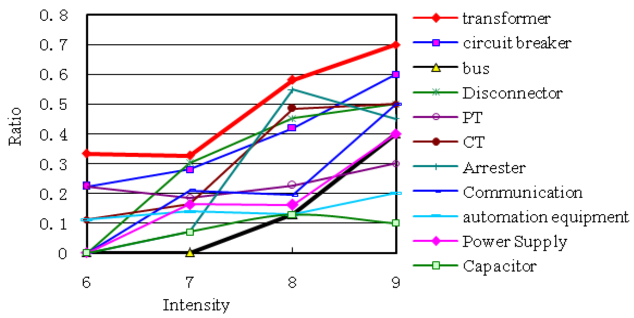


Figure 4.3. Damage frequencies of various equipments in damaged substations

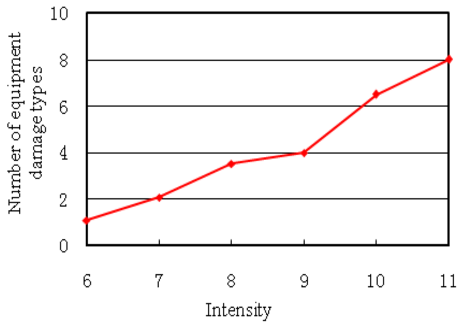


Figure 4.4. Relation between intensity and the average number of the Equipment damage type

Table 4.1. Damage Type Percentage of Transformer

Intensity	Displacement and Bushing Failure Simultaneously Occur	Simple Displacement	Simple Bushing Failure
Ⅵ	0.0%	0.0%	100.0%
Ⅶ	25.0%	18.7%	56.3%
Ⅷ	35.3%	11.8%	52.9%
Ⅸ	42.9%	14.2%	42.9%

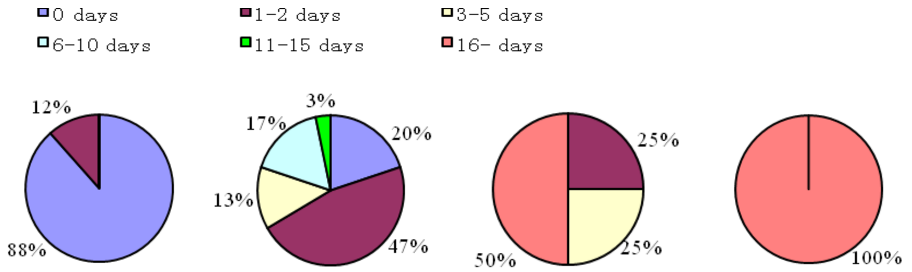
The damage types of outdoor high-voltage electrical equipments are shown in Table 4.2. These damage types include the high-rise procelain devices' broken, overturn, cracks, and some gasket leaks.

Table 4.2. Equipment Damage Type Percentage of 110kv and above Substation

Equipment	Main Damage Type and Its Percentage			
	Broken, Overturn, Crack and Burst	Spill or Leakage	Deformation	Other
Circuit Breaker	73.5%	17.6%		8.8%
Disconnect Switch	83.3%		13.7%	3.0%
Voltage Transformer	45.8%	20.8%		33.4%
Current Transformer	26.4%	28.8%	6.7%	38.1%
Lightning Arrester	95.7%			4.3%

4.3. Statistics of Substation Recovery Time

The recovery times of those out-of-service substations are shown in Figure 4.5. These substations are located in the areas with intensities from Ⅶ to Ⅺ. From the figure, in the area of intensity Ⅶ, nearly 90% damaged substations can be resumed in the same day; in the intensityⅧ area most damaged substations can be resumed in the next day. For intensity Ⅸ area, the average time is more than 5 days, while the intensity Ⅹand above area, it will take even longer period because of the reconstruction. Further, in high-intensity areas, in addition to the time for the damaged equipments to be repaired and replaced, it will take longer time to wait for the repair of the lines.



(a) Intensity 7 (b) Intensity 8 (c) Intensity 9 (d) Intensity 10, 11

Figure 4.5. Recovery time of outage substation

5. FAILURE CHARACTERISTICS OF POWER GRIDS IN DIFFERENT INTENSITY ZONES

Function loss of power systems can be classified into the following categories: 1) loss of power supply leading to blackouts; 2) indoor equipment's smashing or inoperablility resulted from the building destruction; 3) power failure caused by the damage of high-voltage electrical equipments of substations; 4) transformer protection action and tripping; 5) burning up of components introduced by voltage instability; 6) damage of power transmission lines; 7) initiative power cut to avoid loss expansion or maintenance interruption.

According to the analysis above, the 2008 Wenchuan earthquake demonstrates that the damage level, failure modes and the recovery time are various in different intensity zones, as shown in Table 5.1.

Table 5.1. Damage, Failure and Recovery Time of Power Systems in Different Intensity Zones

Intensity	Mean PGA in Horizontal Direction (cm • s-2)	Damage Status	Functional Status	Recovery Time
Ⅴ	---	Buildings and equipments were intact. No poles, transmission towers were damaged.	No power outage, but loss of voltage occasionally occurred.	
Ⅵ	83.6	Buildings and equipments largely were intact, only individual high-voltage equipment was slightly damaged. No poles, transmission towers were damaged.	Almost no outage, once it occurred, one main reason is its upper substation outage, the other occasional reason is the tripping or some damaged equipment .	It can be recovered within several hours.
Ⅶ	179.9	Buildings were largely intact, while individual component might be damaged. A small number of poles, transmission towers and lines were damaged.	Outage probability caused by its own loss-of-function is below 20%. Reasons for disruption include upper outage, transformer tripping and equipment maintenance.	Failure can be removed within several hours.
Ⅷ	339.4	Slightly damage was observed on most of the buildings. Some were moderately damaged. A small number of indoor equipments were damaged. There were also some outdoor equipments damaged such as transformer bushing prone to	Outage probability increases. Failure probability caused by own loss-of-function is about 40%. Reasons for disruption include upper	General repair time is not more than 2 days.

		leakage, transformers, circuit breakers, lightning arresters and other porcelain devices having connection failure.	outage, transformer tripping and equipment damage.	
Ⅸ	435.2	Most of the buildings were moderately damaged. A small number of them were severely damaged, A few buildings collapsed. Part of indoor equipments was vandalized. Outdoor equipments performed transformer displacement, bushing fracture, and oil spills. Transformers, circuit breakers, lightning arresters and other porcelain devices were fractured.	One major reason for outage is equipment failure. Other reasons such as tripping, miss-operation, upstream voltage loss and lines disconnection may also result in power outages.	Usually failure can be removed within a week. A small number of substations need reconstruction.
Ⅹ and Ⅺ	Ⅹ：813.4 Ⅺ：No Data	Buildings such as the main control room experienced serious damage or collapse. As a result of this the indoor equipments suffered serious damage. Outdoor equipment damages such as transformer overturning, derailment, displacement, bushing leakage and fault occurred. Poles, transmission towers might be damaged due to geological disasters. Distribution lines were often broken by the building collapse.	Service disruption results from indoor and outdoor equipment severe damage and transmission line disconnection. The overall substation loses voltage.	Recovery time will be substantially delayed, for a number of substations need to be rebuilt.

6. SUGGESTIONS FOR IMPROVING POWER SYSTEM SEISMIC PERFORMANCE

(1) Epicentral intensity of Wenchuan earthquake reached Ⅺ, while structures located within this area were designed to resist much lower seismic fortification levels: Ⅶ or undefended, which led to serious damage to the power grid. It is recommended that the regional seismic risk analysis be strengthened, the electric power facilities seismic fortification standards be revised, and be followed strictly.
(2) According to the investigation of past earthquakes such as Tangshan earthquake, Chi-Chi earthquake, Kobe earthquake etc., and other research results(Liu Huixian，1986； Yin Ronghua，Li Dongliang,Liu Gelin,2005), the seismic performance of transmission towers and poles is acceptable under normal circumstances, and light damage occurs when sustained strong ground motion. However，there were many destroyed reports in the Wenchuan earthquake, primarily as the result of geological hazards (landslides, avalanches and the Rolling Stones). Therefore, when the towers and poles are constructed in the bad geological areas, it should take full account of the possibility of geological damage by choosing the site seriously and taking anti-seismic measures for the foundation.
(3) The most vulnerable components in power system include circuit breakers, disconnect switches, lightning arresters, transformer bushings, column insulators and so on. These components are highly-brittle porcelain, and have a high gravity center. In addition，transformer displacement, overturning and rotation are also associated with the improper anchorage. To improve the seismic performance of the components, the suggestions are as follows:
1) Lower the gravity center, and employ the top-light structure. Moreover, it’s better to make use of GIS equipment which has a good seismic performance.
2) For rail type transformers, the anchorage shall be strengthened. The tilt bushing, if employed, shall be replaced by the vertical one; the vertical circuit breaker shall be adopted in place of the X-type one. The connections between high-rise structures and their supports shall be strengthened.
3) Since the porcelain material is brittle, alternative insulation material is preferable.
4) Hard connection shall be changed to soft connection. The connection length between facilities shall be long enough.
5) Vibration mitigation and isolation technology shall be considered for high-voltage electrical equipments.

7. CONCLUSION

The grief consequence of the Wenchuan earthquake brings us a profound lesson in terms of the losses of human lives and economic activities. It also provides a lot of valuable seismic disaster information, which would be undoubtedly helpful for the preparedness and the disaster reduction in potential earthquakes. Due to the time limitation, the electric power investigation is limited to the regions with severe earthquake damages, which are Deyang, Mianyang, Chengdu, Guangyuan, Aba and so on. There, a more detailed and extensive survey and statistics should be carried out in the future.

The electrical power system is a complex network. Network reliability analysis and tidal current analysis should be intensively conducted for the function failure during earthquake. The earthquake response of the weak portions such as high-voltage electrical equipment should be analyzed in detail by means of numerical simulation. Only understand the failure mechanism comprehensively, can effective measures for improving the seismic performance of electric power facilities be proposed.

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