EARTHQUAKE MONITORING, EARLY WARNING AND DAMAGE ASSESSMENT SYSTEM FOR ELECTRICAL SUBSTATIONS

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Abstract

Electrical substations are complexes of electrical equipment, steel tower structures and buildings, which form major nodes in electrical power grid. Modern electrical substations operate in high voltage level, using much larger and heavier equipment. Many kinds of equipment are slender in shape and contain lots of porcelain insulators, making them vulnerable in earthquake shakings. Earthquake monitoring and early warning system have achieved success in many countries and industry fields, but its application in electrical substation has not been carried out before. This study discusses deploying earthquake monitoring network in electrical substations. There are several advantages for choosing electrical substations as positions of monitoring sites. The distribution of electrical substations covers vast land and a typical distance between two nearby substations is smaller than 30 km in cities. More developed areas have more electrical substations, which also have higher demand for earthquake monitoring. On the other hand, electrical substations are well maintained, providing reliable power supply and communication network to support earthquake monitoring. This paper presents method of setting up earthquake monitoring station in electrical substation with an example. Monitoring data were collected in real time and sent to remote server via communication network. When monitoring stations reach a considerable number and form a network, earthquake early warning algorithm can be adopted to produce warning signals for substations, power plants or energy users in the area, which can be an important supplement for a country's earthquake early warning network. Damage assessment of electrical substation is important for power supply recovery after earthquake. This study raises a method for automatic damage assessment of electrical substations. The monitoring data can be integrated with seismic performance database of substation equipment, and after a pattern matching analysis, a quick damage assessment of substations will be reported. The assessment result is expected to be generated in a short time and also be more reliable than report from first responders considering the chaos in post-earthquake hours.

Keywords: Electrical substation, Earthquake, Monitoring, Damage assessment

1. Introduction

Electrical power is indispensable for disaster relief in post-earthquake period. Electrical substations are nodes of electrical power grid with important functionality. Equipment in substations is prone to be damaged in earthquakes. Both cylindrical electrical equipment and transformers were fragile in past earthquakes, as seen in Fig.1 and Fig. 2. The vulnerability is partly caused by structural element made of brittle porcelain material or irrational structural shape designed for electrical functionality. The M8.0 Wenchuan Earthquake in 2008 damaged 21 substations in 110kV or higher voltage level [1]. The Loma Prieta Earthquake in 1989 destructed 2 substations in 230kV and 500kV, interrupting the power supply to 1.4 million users [2]. In the M9.0 earthquake off the coast of Japan in 2011, hydrogen explosion happened at Fukushima Nuclear Power Plant due to failure of external power supply and emergency power, though the nuclear power unit was shut down during the earthquake [3]. The UHV grid substation in China [4] have not yet been affected by major earthquake due to relatively short service history. It will be disastrous once they were damaged and lost large power transmission capacity.

Fig. 1 Demolition of electrical substation in Wenchuan Earthquake

Fig. 2 Damage of cylindrical electrical equipment and transformer in 2008 Wenchuan Earthquake in China

Researchers in seismic engineering society have invested numerous effort to build earthquake resistant substations, including setting up seismic testing standard for equipment [5][6], developing seismic isolators for various kinds of equipment [7][8] and understanding dynamic interaction effect among connected pieces of equipment [9,10]. These efforts are mostly taken when substations are built, however, it is also important to develop a better strategy for seismic risk management during their operation period.

Other than enhancing seismic performance of structure, earthquake monitoring and early warning technique reduce casualty and mitigate damage by providing emergency response time. P-wave of earthquake travels faster than S-wave, and warning signal broadcasted in modern information system can transmit faster than earthquake wave. These are key points for earthquake early warning (EEW). Study by

Xia et al. [11] showed that 10s early warning time was enough for part of personnel indoors to run out of buildings and find shelters and for personnel outdoors to find safe places, thus reducing casualty by more than 39%. EEW system has already been built in Japan [12], United States [13], Turkey [14], mainland China [15] and Taiwan region of China [16], and the systems provided information that saved lives in several earthquakes. EEW system has been widely applied in industry too. Automatic control triggered by early warning signals can reduce loss in a few seconds. For example, the EEW system for railway in Germany could generate a visual early warning map based on P-wave information and quickly estimate the damage to railway infrastructure in the region [17]. Nuclear power plants are equipped with earthquake monitoring instruments too. International Atomic Energy Agency (IAEA) recommended nuclear power plants to be equipped with an earthquake monitoring network around its site and execute emergency shutdown during earthquake [18,19]. EEW for oil and gas pipelines has also been adopted in seismically active areas. Gas valves could cut off automatically when the speed of local earthquake spectrum reached a certain level, avoiding fire emergency after earthquake [20]. However, there has not been reports on application of earthquake monitoring and early warning system for power grids yet.

This paper discusses the application of earthquake monitoring and early warning in electrical grid, and uses monitoring data for damage assessment of substations, which will provide important information for post-earthquake decision making on operation mode of power grid and planning of recovery, so that further enhancing seismic resistance of power grid.

2. System framework

The system is designed for managing seismic risk of electrical substations during operation stage. When real time earthquake waves are collected, early warning signal can be generated and broadcasted for personnel in substation to find shield and turn on emergency operation mode, such as halting switching operation. The system will be integrated with fragility database of the electrical facility in substation, so that monitoring data triggers a pattern matching process to evaluate damage level of the substations in the region. Although personnel in substation could report damage manually, this kind of report can be incomplete and of low confidence, given the chaos in post-earthquake hours. And some substation equipment may look undamaged but be easily broken in aftershock. The automatic evaluation function of the system will provide more timely and reliable information.

The framework of the system is designed as seen in Fig. 3. It consists of four parts, including Sensing & Identification, Mapping & Early Warning, Damage Assessment and Reporting. Data from monitoring station in substations and other source such as national earthquake monitoring center will be used in earthquake identification, which produces map of influencing area and attenuation. In the same time, early warning signal can be broadcasted to substations. The damage assessment part is based on monitoring data, for instance, magnitude estimation and acceleration waves recorded inside of substations, and a quick damage assessment result can be reported to control center of power grid.

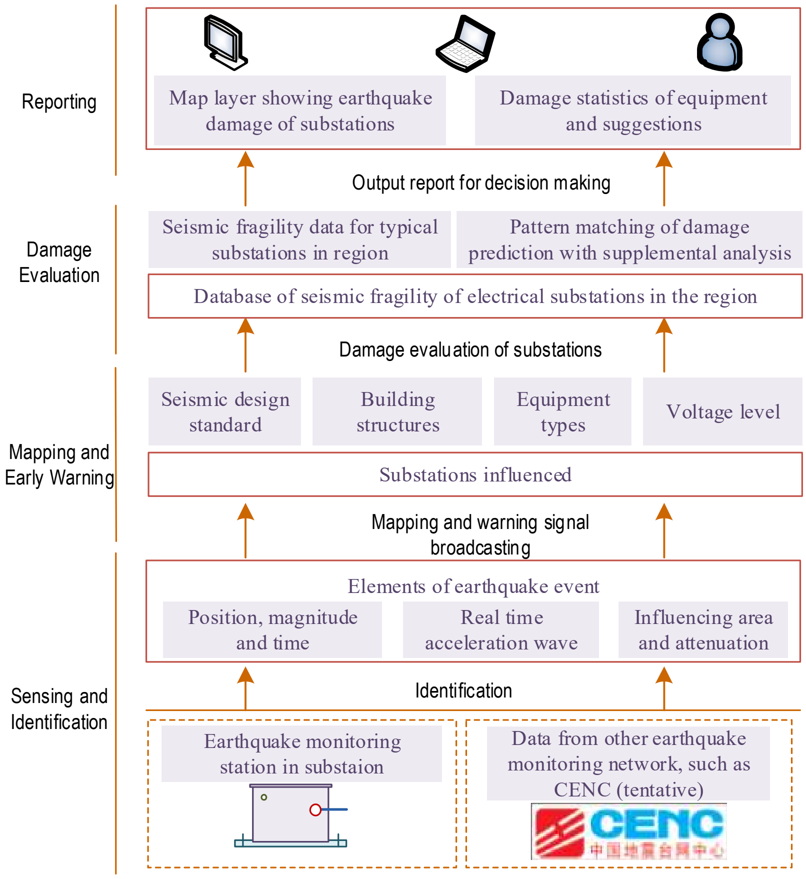

Fig. 3 Framework of earthquake monitoring and damage assessment system for electrical substations

3. Earthquake monitoring station in electrical substation

Electrical substations are ideal positions for earthquake monitoring. The EEW system generally requires a strong ground motion monitoring network with mesh density of 20~50 km, while the distribution of electrical substation of 110kV or higher voltage level in cities or industrial zones can meet this requirement well. In this way, setting earthquake monitoring station in electrical substations can built up a monitoring network for EEW system. The distribution of electrical grids reflects power demand in a region, and reflects the density of population or industry. A region with more electrical substations is the place where EEW can have its best outcome in terms of protecting lives and economics. Furthermore, EEW system heavily relies on reliable sensing data and real time communication system. Usually, it costs a lot in building and operating such monitoring network. When monitoring stations are built inside of substations, the cost can be largely reduced, due to the well maintained environment, reliable power supply and communication network.

China Electric Power Research Institute has started to set up earthquake monitoring stations in electrical substations in seismically active areas. Fig.4 shows a monitoring station in Sichuan province in China. It contains 5 earthquake sensors installed at ground surface, main transformer, switch equipment and surge arrester, as seen in Fig. 5. These sensors arranged for monitoring ground motion and seismic response of electrical equipment. In a more simplified station, only sensor at ground surface is required.

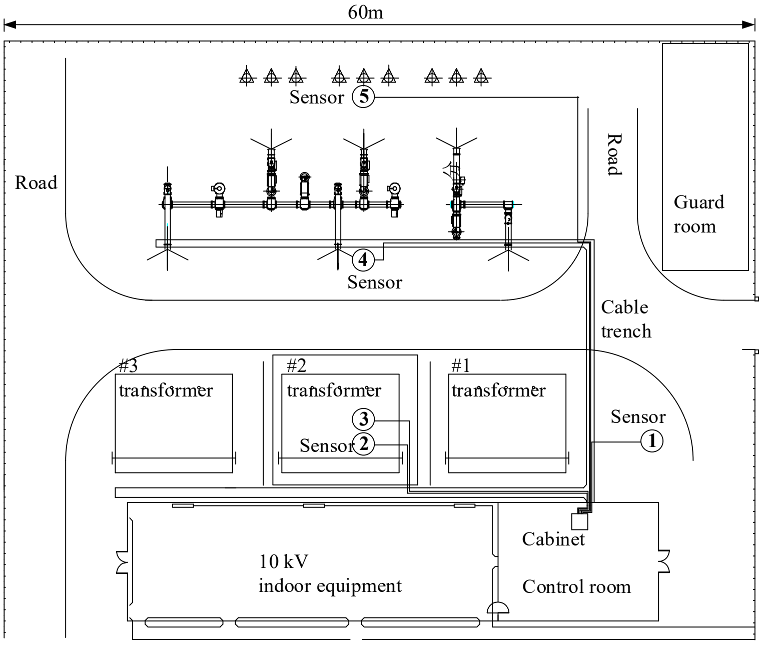

Fig. 4 Sensor arrangement in a 110 kV electrical substation

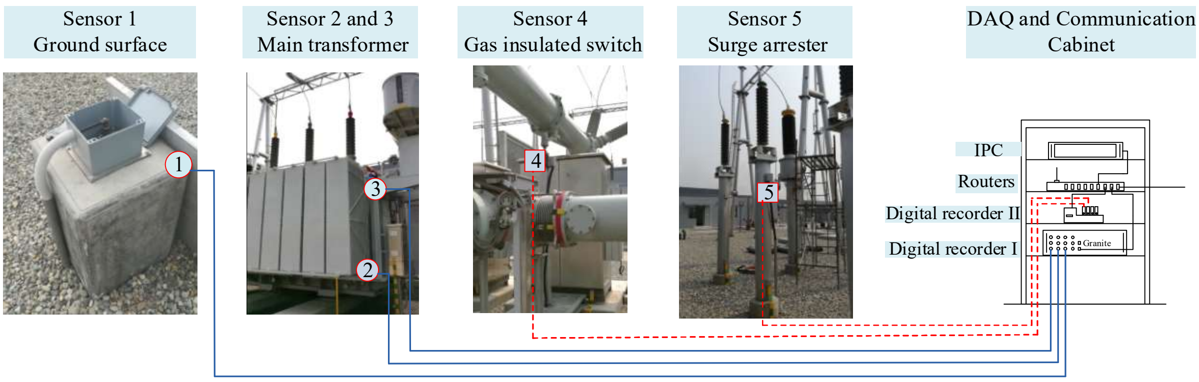

Fig. 5 Installation of earthquake monitoring station in electrical substation

4. Network and data center

The network is designed as demonstrated in Fig. 6. Monitoring stations send data to the center in real time. When earthquake sensors near the epicenter detect a possible event, the data center will send the first warning signal to substations in the region. And when more sensors are receiving earthquake waves, the data center will broadcasted again with a high certainty label. The warning signal is sent for substations in the region at present, and it can also be send to power plant or power users in the region. Meanwhile, damage assessment starts after the earthquake event. For substation installed with sensors, the recorded wave will be transferred to acceleration response spectrum for damage analysis. For other substation in the region without monitoring sensor, the damage assessment is based on magnitude estimation of the earthquake at its site.

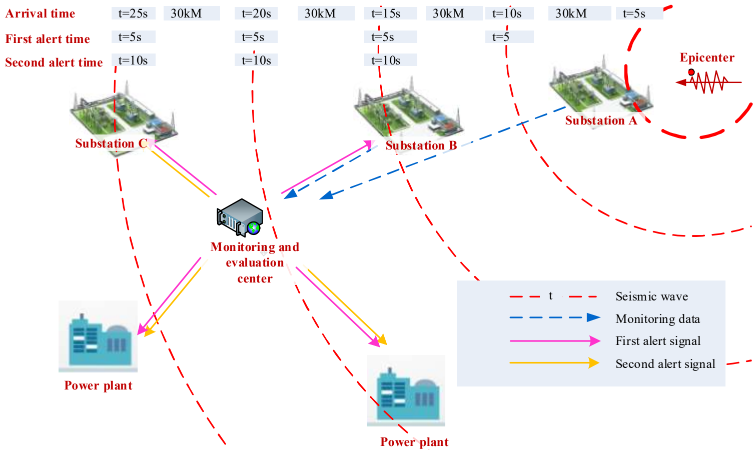

Fig. 6 Network of earthquake monitoring and damage assessment

There are technical challenges behind this network in two aspects. One is high real-time and reliability requirement of communication, and the other is quick damage assessment of substation. Data communication and processing chart is designed as shown in Fig. 7. The earthquake monitoring data are transferred to data center by local network build for electrical grid. MQTT protocol is adopted to transfer data in various types. MQTT is an Internet of Things (IoT) connectivity protocol designed as an extremely lightweight publish/subscribe messaging transport [21]. This protocol is chosen in order to enhancing reliability of communication and compatibility with other new sensing system in the power grid. Data acquired in the server by MQTT service is then pushed to database, which consist of a relational database and a time series database. The time series database is used for real time processing, which is significant for producing early warning signal. The commonly used relational database records earthquake event data from each station. This data is used for magnitude identification and determination of influencing area and attenuation. Then, the damage of substations in relevant area will be evaluated.

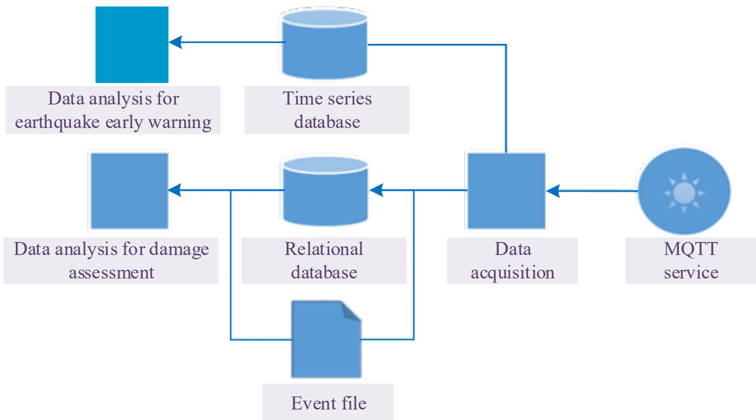

Fig. 7 Data communication and processing flowchart

5. Damage assessment method for electrical substation

Assessing the damage of substation in a short time, i.e. minutes after earthquake, is meaningful for disaster mitigation as thoroughly field investigation is impossible to conduct in a short time. Common damage assessment by Finite Element (FE) modeling will also take days or hours, even when the FE model has been built already. In this study, a pattern matching approach is adopted to produce assessment results in a short time. This approach builds assessment model of electrical substation and inputs a set of discrete input motions to get assessment results as outputs. The inputs and outputs of each substation will be store in database. After an earthquake event, the monitoring data is used to match one or several inputs, and then evaluation results can be produced by a combination or interpolation of seismic response data which has been already stored in the database.

An electrical substation is a complicate connection of various types of equipment and structures. Damage assessment of substation is rather different to common building structures. For building structures, key response items such as displacement, internal forces and plastic rotation can be chosen for damage assessment based on a structural engineering approach. It is different when comes to an electrical substation. For example, main transformer is thought to be the most important facility among different types of equipment, not only because of its crucial functionality in power transformation, but also the long period it will take to replace a new one. Main control building takes only a small part of a substation, but it is the place where most of personnel are located and have many control facility inside. The seismic assessment of electrical substation cannot only be handled by a structural engineering approach, but a more comprehensive viewpoint of personnel safety, electrical functionality and recovery effort is required.

In this study, Experts grading method is adopted to build a model to separate the substation into several subparts with different weight factors, and structural analysis is employed to evaluate the possible damage of each part. The experts in the panel are invited among different disciplines in the planning, construction and operation of power grid. Table 1 lists the expert panel anonymously with their affiliations and roles in industry.

Table 1 Expert panel in consulting of seismic damage model of electrical substation

No.	Affiliation	Role in industry of power grid
Expert 1	Headquarter of the State Grid Corporation of China	Owner
Expert 2	State Grid Economic and Technological Research Institute	Engineering economics study
Expert 3	China Power Engineering Consulting Group	Designer of substation, structural
Expert 4	China Power Engineering Consulting Group	Designer of substation, electrical
Expert 5	State Nuclear Electrical Power Planning Design & Research Institute	Designer of power grid, electrical
Expert 6	State Nuclear Electrical Power Planning Design & Research Institute	Designer of power grid, planning
Expert 7	China Academy of Building Research	Seismic testing of structures
Expert 8	China Academy of Building Research	Earthquake resistant design of structures
Expert 9	China Institute of Water Resources and Hydropower Research	Seismic testing of electrical facility
Expert 10	North China University of Technology	Seismology and structural engineering
Expert 11	Beijing University of Technology	Seismic isolation of structures

The consulting meeting was held in Beijing in 2019, as shown in Fig. 8. A presentation was provided at the beginning to explain the task and background, so that opinions from experts could be expressed based on a common target. Then intensive discussions were made among the consulting experts. The discussions yielded the first outcome on the separation of substation into 9 subparts, as shown in Fig. 9 and listed in Table 2. Then, anonymous grading was made by the experts to give a weight factor for each part.

Fig. 8 Photo of consulting meeting on damage assessment model of electrical substation

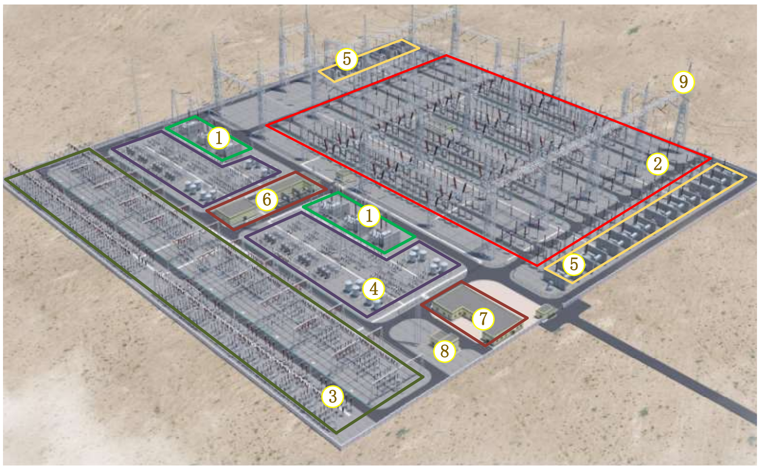

Fig. 9 The subparts of electricla substaion

Table 2 Subparts of electrical substation in seismic damage assessment

No	Category	Item	Weight factor
1	Electrical equipment	Main transformers	0.19
2		High voltage electricity distribution equipment	0.15
3		Medium voltage electricity distribution equipment	0.09
4		Low voltage electricity distribution equipment and reactive power compensation device	0.08
5		Shunt reactors	0.10
6		Indoor electricity distribution equipment	0.08
7	Buildings and structures	Main control building and facilities inside	0.19
8		Auxiliary facilities for fire extinguishing, water supply and emergency electricity generation	0.07
9		Tower and frame for suspension lines	0.05

The damage level is caculated as the weighted sum of damage percentage of each part, which can be expressed as

$$R=\Sigma(F_i \cdot C_i) \quad (i=1,2,\ldots,9) \tag{1}$$

in which R is the damge level of whole substation in percentage and C_i is the damge level of part i in percentage. The assessment of each subpart is based on finite element modeling and seismic response analysis as illustrated in Fig. 10. The damage percentage of each subpart can be graded according to the standard recommended in Table. 3.

Table 3 Seismic damage grading for each subpart of electrical substation

Level	Performance level	Damage percentage
1	The main structure is in good condition and functions well. Minor damage is found at unimportant parts. It can continue to serve without repairs.	0
2	The main structure is in good condition and functions well. Local damage can be repaired within 7 days.	20
3	The main structure is slightly damaged, and some unimportant part is obviously damaged. It can be repaired within 30 days.	40
4	The main structure is damaged but still has load bearing capacity. Some unimportant parts need replacement. Rebuild can be done in 60 days.	60
5	The main structure is damaged and unable to function. Rebuild can be done within 90 days with large part of replacement.	80
6	The main structure is damaged and cannot be repaired. It needs to be reconstructed almost totally.	100

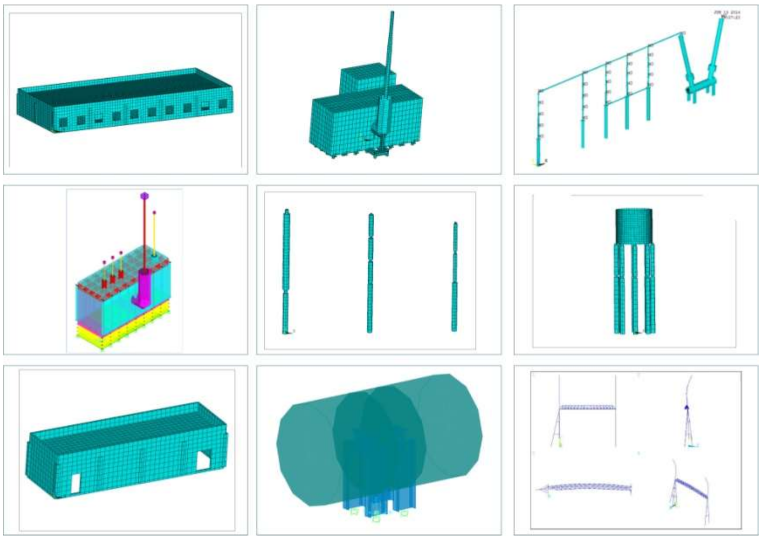

Fig. 10 An example of FE model of each subpart in substation

The first version program of earthquake monitoring and damage assessment system discussed in this study has been developed. Fig. 11 is a screenshot showing the damage of substations in a region affected by a simulated earthquake event. The monitoring data was used in damage assessment of each substation in the region, which is shown in Fig. 12.

Fig. 11 Seismic assessment of substations in a region

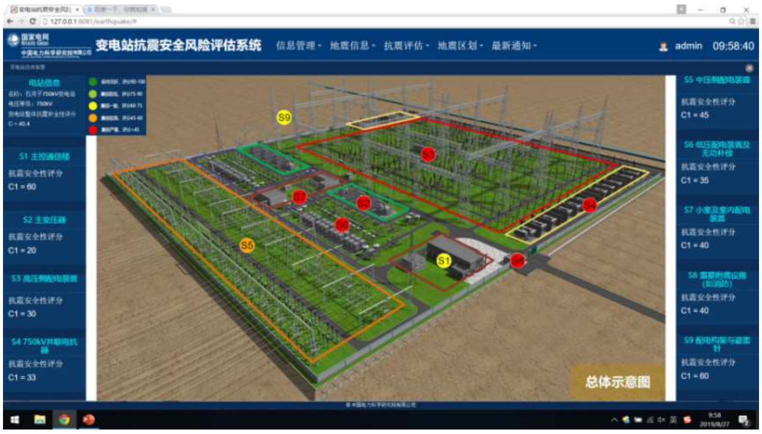

Fig. 12 Damage evalaution of subparts in a substation

6. Summary

This study provides a framework, methodology and example for seismic monitoring, early warning and damage assessment of substations in power grid. The system gets monitoring data from sensors in substations, and also integrates monitoring data from other sources. It is a meaningful initiative to set up monitoring stations inside electrical substations, as the network of substations has a vast coverage in populated or industrialized area, and can provide good maintenance for sensors and recorders. The early warning signal generated in this system can be used for substations to take emergency response, and potentially can be sent to power users. In damage assessment of substations, this study raises a quick assessment method based on pattern matching, in which fragility of substations is analyzed before an earthquake so that assessment results can be produced by matching the monitoring data to seismic inputs stored in the database. Seismic assessment model of substation is further developed for the quick assessment purpose. The system is in its trial deployment stage and further improvement will be made according to suggestions from experts in industry.

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8. Copyrights

9. References

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