

# SEISMIC RISK ANALYSIS OF ELECTRIC POWER NETWORKS USING HAZARD-CONSISTENT SCENARIO EARTHQUAKES

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## SUMMARY

An approach for the seismic risk analysis of electric power networks is proposed in this research work. A technique has been developed for generating numerous earthquakes termed as hazard-consistent scenario earthquakes (HCSEs), whose locations of epicenters, magnitudes and annual recurrence rates as a whole can match the regional seismicity temporally and spatially. The power flow calculation could then be conducted for examining the performance of the network under seismic conditions, whose critical components could previously be decided as being either damaged or not probabilistically according to both their fragility curves and the ground motions induced by each of the HCSEs. According to the Monte Carlo simulation results, the risk the network is exposed to could be interpreted. The electric power system in Taiwan has been preliminarily investigated as a case study.

# INTRODUCTION

Seismically sustainable lifelines play as a key factor for minimizing the effects of a major earthquake. Essential as electricity is in post-disaster situation, electric power systems are extreme vulnerable since they contain a large number of vulnerable pieces of equipment usually not well designed seismically. A power network usually covers a large region and, as a result, the level of strong ground motions experienced by its facilities (e.g. power plants, substations, switch yards and transmission lines) may differ from each other during a major earthquake. With the essentiality of each component to the network's functionality being different from each other, the actual behavior of the network is somewhat complicated and almost impossible to be expressed in an easy way. For these reasons, the evaluation of a power network seems extremely difficult to be carried out except through Monte Carlo simulation (MCS),

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which works on the statistics attained from numerous damage statuses of the network simulated probabilistically under various imposed destructive conditions.

Regarding the seismic hazard of a region, there is usually no direct information about except the available catalog of seismicity and the derived information from the catalog. The catalog of seismicity itself is of tremendous volume, and the contents are not ready for use except after being appropriately processed. Usually, a set of scenario earthquakes may be used instead for risk-related analysis work. This set of scenario earthquakes may be called hazard-consistent if they as a whole represent seismically, which means that their locations of epicenter, magnitudes and annual recurrence rates temporally and spatially match the regional seismicity.

Accordingly, the seismic risk of a power network can be analyzed by using a set of hazard-consistent scenario earthquakes (HCSEs). Each of the HCSEs has to be employed alone first to attain the interested performance indices of the system (say the remained power supply capability, etc.). The seismic risk curves of the system can then be achieved with the annual probability of exceedance plotted against the performance indices of the corresponding scenario earthquake. Based on the past research work of Dr. Jean [1], a procedure for generating HCSEs has been developed at NCREE (National Center for Research on Earthquake Engineering, Taiwan). In this study, this procedure will be summarized and applied to the risk assessment of electric power system in Taiwan.

# INVENTORY DATA AND POWER FLOW CALCULATION OF A POWER SYSTEM

There are essentially five categories of inventory data needed in the performance analysis of a power system. They are: (i) node data (or bus data, in the terminology of electrical engineering), (ii) load data, (iii) generator data, (iv) linkage data (or branch data), and (v) transformer data. Each node is prescribed with an operating voltage. Among these nodes, some work as power supplying nodes and are further specified in the generator data (generator buses), while some work as power demanding nodes and are further specified in the load data (load buses); the rest are simply intermediate nodes. The topology of the grid is defined in the linkage data, which consists of both transformers and transmission lines interconnecting all nodes (buses). In addition, transformers also appear in the transformer data to give the corresponding specification of transformation.

Taking the power system in Taiwan for example, electricity is delivered mainly through the 345 and 161kV transmission systems. The extra-high-voltage substations (E/Ss) and primary substations (P/Ss) play the pivotal role of 345/161 and 161/69 kV transformations, respectively. Electricity below 69kV is further forwarded to either distribution substations (D/Ss) or secondary substations (S/Ss) for utility and household uses. This system, operated by the Taiwan Power Company (Taipower), can be represented by two sets of data. One is the GIS data of the whole system, and the other the above-mentioned inventory data for power flow calculation. Fig. 1 depicts the locations of major facilities like power plants, substations, transmission lines above 69kV in the electric power system in Taiwan. Service Areas 1 to 4 (north, middle, south and east of Taiwan, respectively; Taipower classification) are denoted in Fig. 2.

The aim of power flow calculation is to attain the operable solution, if exists, which indicates the details of how the electric power will be distributed and forwarded in a network [2]. It involves sophisticated numerical techniques, and well-developed commercial software has to be employed as a reliable platform for performing such calculation. In this study, PSS/E (Power System Simulator for Engineering, Version 26; Power Technologies, Inc.) was used.



Fig. 1 The electric power system in Taiwan



Fig. 2 The classification of power service areas in Taiwan

#### HAZARD-CONSISTENT SCENARIO EARTHQUAKES

The procedure to generate HCSEs, whose characteristics of recurrence are assumed a stationary Poisson process both spatially and temporally, could be summarized as follows:

### Seismic source zoning

The interested region can be adequately divided into several source zones according to its tectonic structure, geological profile, subduction model and, most important, the regional catalog of seismicity.

#### **Source parameters**

A well-accepted seismic recurrence model is the Gutenberg and Richter relationship, which reads:

$$\log_{10} \mathbf{N}(m) = a \cdot b \cdot m \tag{1}$$

where N is the average number of earthquakes per year of magnitude m and larger. The coefficients a and b are associate with a source zone and are determined by the regional catalog of seismicity. A lower bound  $m_0$  and an upper bound  $m_u$  have to be specified too to further rule out earthquakes of no significance and not realistic, respectively.

#### **Recurrence relationship**

With the source parameters  $(m_0, m_u, a, b)$  of a source zone being attained, the Gutenberg and Richter relationship can be used to derive the corresponding annual recurrence rate function. Firstly, the earthquake magnitudes between  $m_0$  and  $m_u$  can be descretized by an increment  $\Delta_m$ , and the annual recurrence rate for earthquakes with a magnitude between  $m_0 + (k-1) \cdot \Delta_m$  and  $m_0 + k \cdot \Delta_m$  (k = 1, 2, ...) can be found to be

$$\mathbf{Y}_{k} = \left[\mathbf{N}(m_{0}) - \mathbf{N}(m_{u})\right] \times \left[\mathbf{F}_{\mathbf{M}}(m_{0} + k \cdot \Delta_{m}) - \mathbf{F}_{\mathbf{M}}(m_{0} + (k-1) \cdot \Delta_{m})\right]$$
(2)

where  $F_{M}(m)$  is the distribution function of earthquake magnitude and has the following explicit form:

$$F_{M}(m) = \begin{cases} 0 & ; m \le m_{0} \\ 1 - \frac{N(m) - N(m_{u})}{N(m_{0}) - N(m_{u})} & ; m_{0} \le m \le m_{u} \\ 1.0 & ; m_{u} \le m \end{cases}$$
(3)

The attained annual recurrence rate  $v_k$  actually refers to the earthquakes with a magnitude of

$$\overline{m}_{k} = m_{0} + (k - 0.5) \cdot \Delta_{m} + \frac{1}{\beta} + \frac{\Delta_{m}}{1 - \exp(\beta \cdot \Delta_{m})}$$

$$\tag{4}$$

where  $\beta = b/\log_{10} e = 2.3026 \cdot b$ . The value  $\overline{m_k}$  refers to the expected value of magnitude between  $m_0 + (k-1) \cdot \Delta_m$  and  $m_0 + k \cdot \Delta_m$  weighted by the corresponding number of earthquakes given by Eq. (1).

## **Generation of HCSEs**

The HCSEs in a source zone could be represented as a sequence of  $(\overline{m_k}, v_k)$  (k = 1, 2, ...). Usually each source zone needs being divided further into sub-source zones of smaller size, so that the generated HCSEs could distribute more evenly in this source zone. For each sub-source zone, the HCSEs have a common epicenter located at its centroid; the total number and magnitude distribution of HCSEs are the same as that generated from this source zone alone, but now the value of each annual recurrence rate has to be adjusted proportionally to the size of its area.

Taking the region of Taiwan for example, the seismicity for major earthquakes (magnitude greater than or equal to 4.5) between 1900 and 2002 is depicted in Fig. 3. It has been divided into 13 seismic source zones shown as DS01 to DS13 in Fig. 4. With an increment  $\Delta_m = 0.5$  being employed, a total of 536 HCSEs can be generated. However, if those from DS01, DS04, DS07, DS09, DS12 and DS13 could be excluded, as these zones are either remote relatively or of low seismicity, then the total number can be reduced to 278, see Fig. 4. Their earthquake magnitudes range between 6.69 and 8.05. These remained HCSEs will be used in analysis later.

### SEISMIC PERFORMANCE ANALYSIS OF POWER SYSTEM

With the attenuation relationship for ground motion intensity (e.g. PGA, peak ground acceleration) and the fragility characteristics of critical components at hand, the damage state of a power system can be simulated. An analysis sequence could then be used for examining the remained capability of a damaged system in power supply. Finally, the seismic performance of the system is determined through MCS.



Fig. 3 The seismisity of Taiwan Region (earthquake data between 1900 and 2002; M≥4.5)



Fig. 4 Seismic source zones of Taiwan Region (DS01 to DS13) and the HCSEs used in the analysis (each dot may represent more than one scenario earthquake)

### Scenario earthquake and strong ground motion

The distribution of earthquake-induced ground motion intensity, i.e. PGA value, could be simulated by using any adequate attenuation law. For the case of Taiwan Region, the law may read [3]:

$$PGA = 0.02938 \cdot e^{1.19950M} \cdot [R + 0.14667 \cdot e^{0.69689 \cdot M}]^{-1.73413}$$
(5)

where M and R are the magnitude of the scenario earthquake and the distance from the site to the epicenter (unit in Km), respectively. This local attenuation relationship is of Campbell Functional Form, but the coefficients were decided according to the ground motion data of 15 past earthquakes in Taiwan. The PGA value (unit in g) given by Eq. (5) is for rock sites. The final value at ground surface could further be calculated based on the site class map in Taiwan and soil amplification factors suggested by the 1994 NEHRP Provisions [4].

### Damage status of the system

Given the distribution of ground motion intensity (say PGA) and the fragility characteristics of critical components, a damage statue of the power system could be attained. This is done by firstly identifying the location of each vulnerable component, then finding the probability of failure of the interested component according to the PGA value associated with this location. Through the execution of a random number generator with uniform distribution between 0 and 1, the component could be designated as damaged or undamaged depending on whether the returned number is greater or less than the attained probability of failure. At last, the damage statue of the whole system can be simulated if all vulnerable components have been designated as damaged or not in this way.

## Performance analysis of a damaged electric power system - Monte Carlo simulation

An analysis sequence, which not only makes the damaged system analyzable but most importantly also meets the rationale of system operation, is needed for examining the remained capability of a damaged system in power supply. The one proposed by Shinozuka and his co-workers [5~7] reads:

- (1) Identify the damaged components and designate them as "out-of-service" in the inventory data;
- (2) Remove from the load data the loads that will lose their connectivity to the system due to the "out-ofservice" linkages. Isolate too the intermediate nodes and linkages if the rest "survived" loads are not connecting to them;
- (3) Perform power flow calculation after the completion of (1) and (2). Re-dispatch, if necessary, the power generation (excess of generator capacity not allowed) for attaining converged solution;
- (4) Identify all buses with abnormal voltage (beyond  $\pm 20\%$  of rated voltage) after the completion of (3). In practice, these buses usually need to be switched off;
- (5) Identify and remove those loads who will lose their connectivity to the system as the buses classified as with abnormal voltage in (4) should be switched off from the system;
- (6) Determine the power supply in each service area based on the removal of loads in (2) and (5).

A blackout event might be attained from the calculation if the allowed range of re-dispatch in power generation in step (3) yields no solution. This situation refers to the shutdown of system due to power imbalance. Furthermore, after the completion of (3), all transmission lines will be examined to see if they exceed their current rating (thermal capacity) by 20% or more. Such examination is very important because the rate-exceeding situation will cause thermal expansion in transmission lines and might result in grounding fault. In practice, on-line inspectors will be warned and have to deal with such situation immediately if it happens. Finally, the performance of the power network can be judged by the attained performance indices (for example, the percentage of power supply remained in each service area, which is the ratio between the average power supply from MCS and the one from intact network).

## CASE STUDY – POWER SYSTEM IN TAIWAN UNDER SEISMIC CONDITIONS

The scope of this research work covers both the 345 and 161kV transmission systems, as they play as the backbone in the power grid in Taiwan. Consequently, only the 345/161 and 161/69 kV transformers in the systems will be assumed as vulnerable. The main interest here lies in understanding how the damages of these transformers due to earthquake attacks will affect the overall network performance. In this study, fragility curves for transformers developed by UWG (Utilities Working Group, a group of experts from several California utilities) will be adopted [8]. Specifically, the two curves proposed by UWG for the minimal failure mode (one main porcelain gasket leak) of equipment categorized as TR2 Class (three-phase 230kV transformers) and TR4 Class (three-phase 500kV transformers), see Fig. 5, were assumed applicable to the 161/69 and 345/161 kV transformers in Taiwan, respectively.

As mentioned above, the 278 HCSEs generated from 7 major source zones in the region of Taiwan were employed in analysis. (As for the propose of demonstration only, no MCS was actually performed for each HCSE here, so that the amount of computational work involved was significantly reduced, and as a result the attained seismic performance of the system for each HCSE may not be conclusive.) Each HCSE was used to simulate one state of transformer damage. It was found that 79 out of 278 HCSEs were destructive to the two grades of transformers. After the completion of power flow calculation, the seismic performances of the network under these HCSEs could be summarized as shown in Fig. 6. It was further found that, although not conclusively, 39 out of 79 HCSEs result in reduction in power supply in any of the four service areas. Finally, the risk curves for each service area in Taiwan are attained as the ones shown in Fig. 7. From the comparison of these curves, Service Area 4 seems more easily affected, especially by major offshore earthquakes occurred at the eastern coast of Taiwan.

Low-loss scenario simulation and risk assessment results were attained under yet severe seismic conditions. There are two other factors that mostly affect the results: (1) The redundancy of the system is a significantly improved one, especially due to the activation of the Third 345kV Circuit after the 1999 Chi-Chi Earthquake [9]; (2) Effects of the other failure modes, i.e. the damages in power plants, circuit breakers, transmission lines and towers (caused by earthquake-induced slope failures) etc., are excluded currently.



Fig. 5 The seismic fragility curves for transformers proposed by UWG



Fig. 6 Seismic performance analysis results



Fig. 7 Seismic risk curves in each service area

## CONCLUDING REMARKS

With the help of the introduced HCSEs, a methodology for the seismic risk analysis of electric power network has been proposed. The procedure for estimating the power supply capacity of a damaged electric power network was summarized in detail, and the sequence to generate HCSEs has been explained, which as a whole could reflect the seismic hazard in a region. With the damage in transformers of higher voltage grades taken into account, a case study of the power system in Taiwan has been preliminarily carried out.

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