

MONTE CARLO SIMULATION FOR THE SEISMIC RESPONSE ANALYSIS OF ELECTRIC POWER SYSTEM IN TAIWAN

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Abstract

In this study, a probabilistic approach to simulate the seismic performance of electric power networks is proposed and employed in the case study of power network in Taiwan. Transmission systems at 345 and 161kV levels are selected as the analysis subject. Only transformers in these systems are considered vulnerable, and the seismic performance analysis is carried out based on the damage status of these transformers determined through Monte Carlo simulation. Under various and very rough assumptions made to the range and chance of transformer damages, the probability to be out of electricity is observed to be 10% or less in each area approximately, and the worst situation – a blackout event on the whole island – is possible under the given seismic conditions.

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. Since they function in the way as a complex network, the ruggedness at not only the component level but also the system level should be of major concerns. It would be very beneficial if their seismic performance could be understood from the system's point of view. Such understanding will shed insights into the work on planning of electric facilities, rehabilitation of critical components, and seismic risk management of power grids, etc. As a result, direct and indirect losses due to power interruption caused by earthquake attacks could be reduced in the future.

Recently, researchers have independently taken into practice case studies of various power systems in the world with different aspects of research efforts (Ang et al., 1992; Shinozuka et al., 1999; Giannini et al., 2000). It should be noted that these analyses were carried out through integration of knowledge in electrical engineering, engineering seismology, geographical information system, and so forth. Particularly, a mature technology for such work is usually analysis-platform dependent, and the strategies employed might be constrained by the inventory data available to the researchers.

The purpose of this study is to present the current work by the authors on the development of a probabilistic approach for the seismic performance analysis of electric power networks. Theoretically, there are four key issues to be concerned:

1. The seismic fragility analysis of critical equipment in the power grid, such that strong ground motion conditions could be introduced to yield the corresponding damage status;
2. The GIS-supported inventory data of the power grid, through which the given seismic conditions could be incorporated to generate the corresponding damage status of power grid on a statistical basis;
3. The power-flow analysis of the power grid at both intact and damaged status, and then to interpret the result from the viewpoint of electrical engineering; and finally
4. The introduction of practical scenario earthquakes to the power grid, and the modeling of its seismic response under various damaged status specified by Monte Carlo simulation.

Details of these issues will be discussed in the following sections.

ELECTRIC POWER SYSTEM IN TAIWAN

Electricity in Taiwan 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.

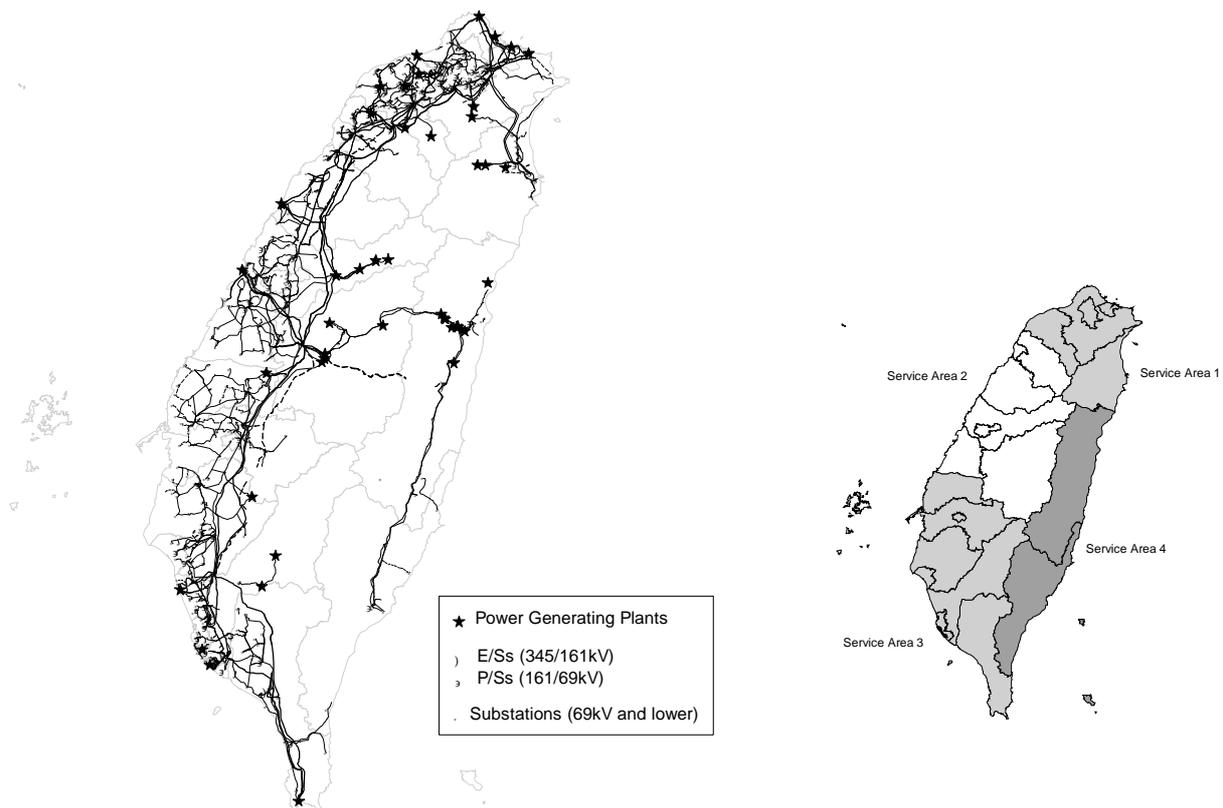


Fig. 1: The electric power system in Taiwan (1998, Taiwan Power Company)

This system, operated by the Taiwan Power Company (Taipower), can be fully described by two categories of inventory data. One is the GIS database of the whole system, and the other the input data for power-flow analysis. The input data available to the authors is a prediction of the peak load in 2002 summer. Fig. 1 depicts the entire electric power system in Taiwan. Locations of power generating plants, major substations, transmission lines above 69kV, and the Service Areas 1 to 4 (according to Taipower's classification) are all denoted on the map of Taiwan, too.

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.

POWER-FLOW ANALYSIS

The aim of power-flow analysis 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 (Bergen et al., 2000). Five categories of power system data are essential for performing such analysis. They are:

The buses in an electric power grid can be regarded as nodes with prescribed voltages. Among these buses, 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 buses. The network topology of the system is defined in the branch data, which consists of both transmission lines and transformers connecting these buses. In addition, transformers also appear in the transformer adjustment data to give the corresponding specification of transformation.

Power-flow analysis involves sophisticated numerical techniques, and well-developed commercial software has to be employed as a reliable platform for performing such analysis. In this study, PSS/E (Power System Simulator for Engineering, Version 26; Power Technologies, Inc.) was used for such analysis.

SEISMIC PERFORMANCE ANALYSIS OF POWER SYSTEM

Scenario earthquake and strong ground motion

After the active fault and an earthquake magnitude being specified, a scenario earthquake is defined. The distribution of earthquake-induced ground motion, in terms of PGA value at each interested site, could then be generated by using the following attenuation law:

$$\text{PGA} = 0.02938 \cdot e^{1.19950 \cdot M} \cdot [R + 0.14667 \cdot e^{0.69689 \cdot M}]^{-1.73413} \quad (1)$$

where M and R are the magnitude of the earthquake and the distance from the site to the fault line (unit in Km), respectively. This formula is of Campbell Functional Form, but with coefficients modified by Dr. W.-Y. Chien, NCREE, according to the data of 15 past earthquakes and local geological characteristics in Taiwan (Chien, 2002). The PGA value (unit in g) obtained by Eqn. (1) is for rock sites. The final value at ground surface could further be calculated based on the site class map in

Taiwan and the soil amplification factors suggested by the 1994 NEHRP Provisions (FEMA, 1995).

Damage status of transformers – Monte Carlo simulation

Given the populations of vulnerable transformers and a scenario earthquake, a damage status of transformers could be attained through the following steps:

1. Identify the location of each transformer, and find the PGA value of this location;
2. Find the probability of failure of each transformer according to the PGA value it will experience and seismic fragility curves for the interested populations of vulnerable transformers;
3. Execute a random number generator with uniform distribution between 0 and 1. A transformer is designated as “damaged” or “undamaged” depending on whether the returned number is greater or less than the attained probability of failure in Step 2;
4. Repeat Steps 1 to 3 to all vulnerable transformers to generate one set of damage status.

In this study, fragility curves for transformers developed by a group of experts from several California utilities (Utilities Working Group, UWG) will be adopted. Details about the UWG-proposed fragility curves can be found in Anagnos (1999). Specifically, it is assumed that the two curves in Fig. 2, which were 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), could be applied to the 161/69 and 345/161 kV transformers, respectively.

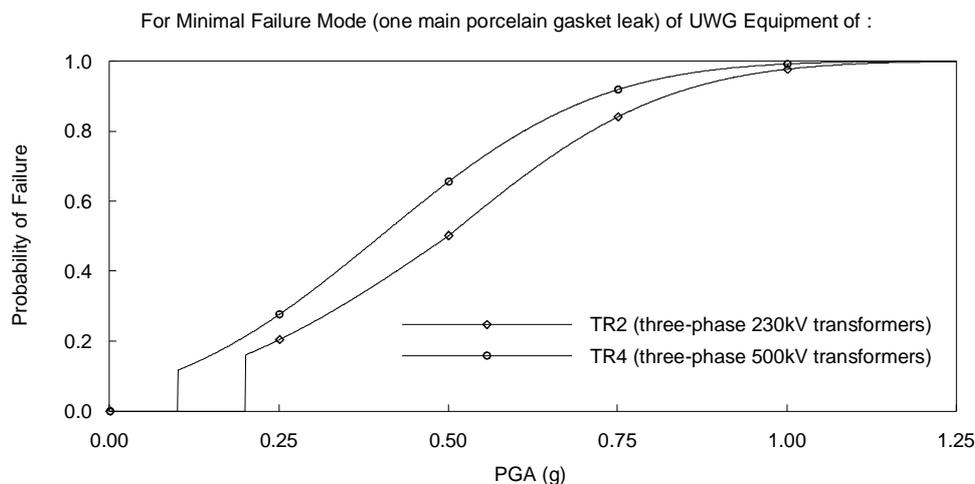


Fig. 2: The seismic fragility curves for transformers developed by UWG

To establish the linkage between the GIS information of components in power grid and the input file for performing power-flow analysis is very essential. Based on this linkage, modification in the input file for PSS/E analysis to represent such damage status could be made accordingly. Details about manipulating the data in this file will be described in the following subsection.

After these, the seismic performance of electric power network could be statistically determined if many sets of damage status have been included in analysis, and important performance/damage indices have been averaged and interpreted. This technique is called the Monte Carlo simulation.

Performance analysis of electric power system

The seismic performance analysis of electric power system could be attained through the following steps:

1. Identify the damaged transformers and designate them as “out-of-service” in the corresponding branch data;
2. Remove from the load data the loads which will lose their connectivity to the system due to the “out-of-service” branches. Remove too the intermediate branches and buses if the rest “survived” loads are not connecting to them;
3. Perform power-flow analysis after Steps 1 and 2 are done. Redispatch the power generation (up to $\pm 20\%$ of original values, and excess of generator capacity not allowed) to attain converged solution if necessary;
4. Identify all buses with abnormal voltage (beyond $\pm 20\%$ of rated voltage) after Step 3 is done. These buses are to be switched off in practice usually;
5. Identify and remove those loads who will lose their connectivity to the system as the buses classified as with abnormal voltage in Step 4 should be switched off from the system somehow;
6. Check all branches for exceeding their current rating (thermal capacity) by 20% or more after Step 3 is done. Initiate warning if there is any;
7. Determine the power supply in each service area based on the removal of loads in Steps 2 and 5.

The 20%-20% criterion appearing in Steps 3 and 4 basically follows the one recommended by Shinozuka et al. (1999), which is very reasonable from the viewpoint of electrical engineering. A blackout event will occur if the allowed range of tuning in power generation in Step 3 yields no solution. This situation refers to the shutdown of system due to power imbalance. Furthermore, the check in Step 6 is very important because such 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 seismic performance of the system could be judged by the percentage of power supply in each service area in Taiwan, which is the ratio between the average power supply from Monte Carlo simulation and the one from intact system. The average numbers of damaged transformers, buses with abnormal voltage, branches exceeding their current rating, etc., should also be of interest.

SIMULATION RESULTS

Two scenario earthquakes were chosen arbitrarily for introducing seismic conditions to the electric power grid in Taiwan. One was assumed to be triggered by the Shih-tang Fault, with a magnitude of M7.0, and the other the Tsu-kuo Fault, with a magnitude of M7.5. They will be denoted by Scenario I and Scenario II.

Fig. 3 and Fig. 4 depict for Scenario I and II, respectively, the distribution of earthquake-induced ground motions, in terms of PGA, and the locations of 53 E/S and P/S substations, of which a total number of 147 transformers are of either 345/161 or 161/69 kV transformation and thus are assumed vulnerable. Twenty sets of transformer damage status, which were generated according to the fragility curves given in Fig. 3, were used in each scenario for Monte Carlo simulation to yield the average seismic performance of the system.

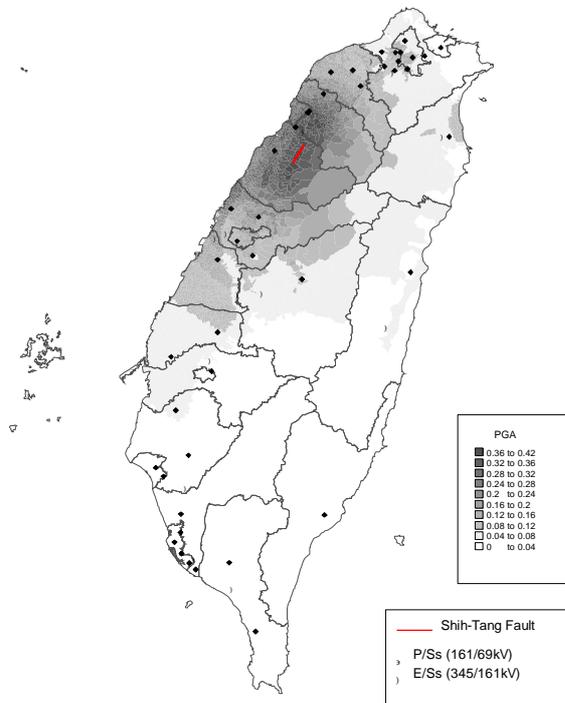


Fig. 3: The PGA map (PGA in g) for Scenario I (Shih-tang Fault, M7) and the locations of E/S and P/S substations (with vulnerable transformers)

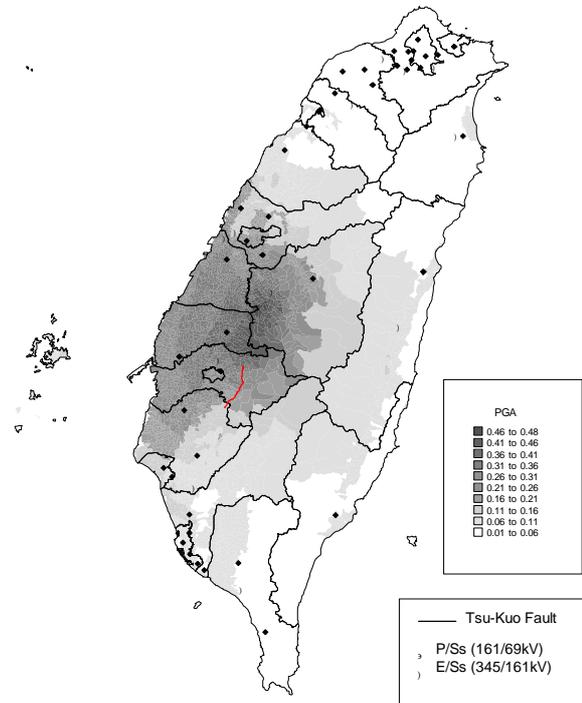


Fig. 4: The PGA map (PGA in g) for Scenario II (Tsu-kuo Fault, M7.5) and the locations of E/S and P/S substations (with vulnerable transformers)

The simulated damage status and corresponding seismic performance of the system, for each case in Monte Carlo simulation under Scenarios I and II, are summarized in Fig. 5 to Fig. 8. According to which, the average losses in power supply for Service Areas 1 to 4 are found to be (0.00, 10.61, 8.52, 0.00)% and (5.66, 7.52, 5.00, 5.00)% for Scenario I and II, respectively. Generally speaking, the probability to be out of electricity is 10% or less in each service area, and Service Areas 1 (northern Taiwan) and 4 (eastern Taiwan) seem unlikely to be affected under the given seismic conditions. However, it is observed that the damage status of Case 19 under Scenario II triggers the worst situation – a blackout event on the whole island.

It should be kept in mind that the above analysis results, which illustrate relatively low losses in power supply under the given seismic conditions, are obtained based upon the following facts: (1) The vulnerability of distribution transformers in substations at lower voltage levels had been excluded from the current analysis. The damage of these transformers, which outnumber those at 345 and 161kV levels, would greatly affect the power supply. (2) The improved redundancy in both the 345 and 161kV transmission systems, of which many circuits have been constructed and added to the power grid in the past few years, now allows electricity to bypass the damaged intermediate transformers, if the overall damage level is not too high.

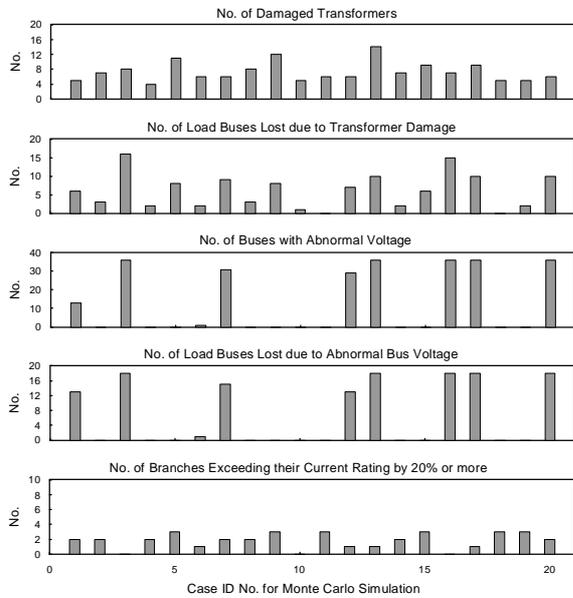


Fig. 5: Statistics of damages in the electric power system in Scenario I

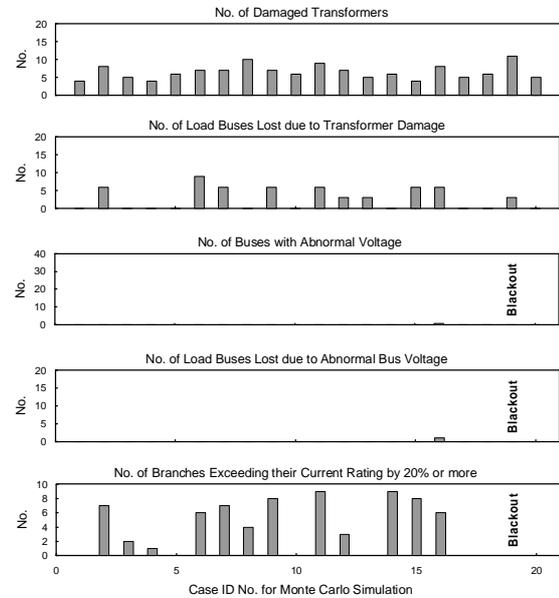


Fig. 7: Statistics of damages in the electric power system in Scenario II

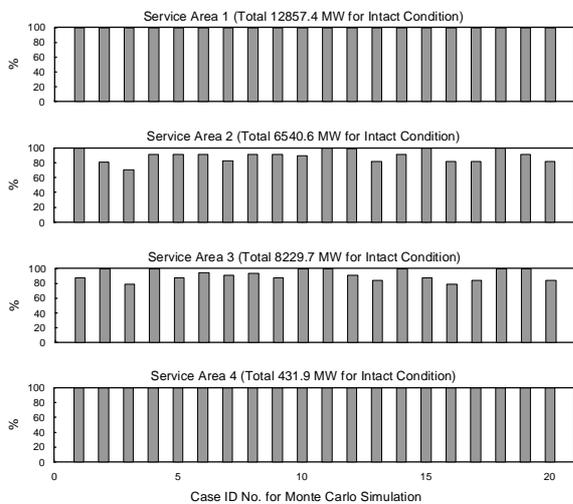


Fig. 6: Percentage of power supply in each service area in Scenario I

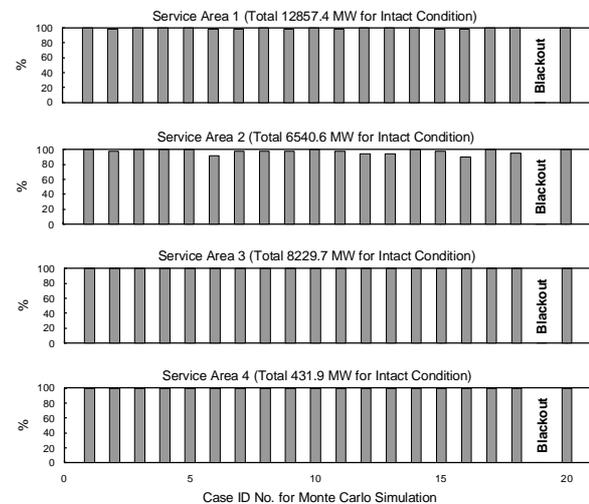


Fig. 8: Percentage of power supply in each service area in Scenario II

CONCLUDING REMARKS

A probabilistic approach for seismic performance analysis of electric power system in Taiwan has been developed in this paper, and preliminary analyses have been carried out successfully. Under various and very rough assumptions made to the range and chance of transformer damages, the probability to be out of electricity is observed to be 10% or less in each area approximately, and the worst situation – a blackout event on the whole island – is possible under the given seismic conditions.

Further studies to cover all transformers in the systems are highly recommended by the authors. The effects of other seismic failure modes, i.e. the damages in generating plants, bus connectivities, circuit breakers, transmission lines and towers (due to earthquake-induced landslides and slope failures) etc., should also be included in the analyses. Scenario earthquake, which may be randomly generated according to the state-of-the-art seismic hazard potential in Taiwan, should be treated along as an important independent variable for Monte Carlo simulation.

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