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# Seismic PRA of electric power supply systems

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ABSTRACT: The object of this paper is to provide a method for seismic probabilistic reliability assessment (PRA) of electric power supply systems. Based on the connectivity analysis of a power network system, a relationship between power loss and associated probability of occurrence will be determined under a scenario earthquake by the proposed approach. The developed computer program is shown to be effective and useful for assessing the impact of earthquakes on customer service.

## 1 INTRODUCTION

This paper describes a method developed for seismic probabilistic reliability assessment (PRA) of electric power supply systems.

A complete electric power supply system will consist of the power generating stations, substations, energy control center, system control and data acquisition systems, high-voltage transmission lines, distribution systems and supporting structures. These may be above-ground and/or in-ground structures, and exposure to potential seismic hazards in a region.

In Japan, major electric equipment in the system is designed according to respective seismic standards; it is nevertheless important and useful for utility engineers to evaluate the reliability of a power system under a given scenario earthquake (Matsuda et al.1991). Although it is not economically possible to absolutely prevent damage to the system, pre-earthquake countermeasures and post-earthquake restoration can be more effectively performed through a seismic PRA on the system. Based on the probability of failure of each of the major electric equipment in a system, the corresponding probability of loss of electric service to a given demanding area can be determined.

The main components of the developed PRA method consist of the following:

-- network modelling for a connectivity analysis of a power system which consists of generation, substation, and transmission facilities.

-- determination of the disconnected demanding substations and associated power loss in a network given the probability of failure at each node.

-- establishing a relationship between the power loss and its probability of occurrence.

## 2 ANALYSIS METHOD

### 2.1 Network modelling

The various stations and substations are interconnected by the transmission lines. These interconnections can be represented by a graphical network model of nodes and branches (Ang et al.1992). In this study, substations and transmission lines are modeled as nodes in a network. The electric functional connectivity between these nodes are the network branches. Since the functional behavior of a substation is, however, not simple as it is a

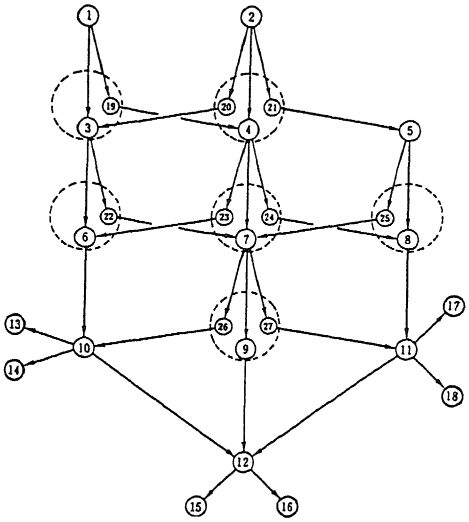

Figure 1. A graphical network model

Table 1. Conditions given to the network nodes

| NODE NO. | DEMAND (MW) | PROBABILITY OF FAILURE |
|---|---|---|
| 1 | 0 | 0.002 |
| 2 | 0 | 0.002 |
| 3 | 100 | 0.004 |
| 4 | 200 | 0.005 |
| 5 | 150 | 0.007 |
| 6 | 250 | 0.004 |
| 7 | 300 | 0.005 |
| 8 | 140 | 0.004 |
| 9 | 130 | 0.008 |
| 10 | 0 | 0.005 |
| 11 | 0 | 0.007 |
| 12 | 0 | 0.006 |
| 13 | 150 | 0.008 |
| 14 | 500 | 0.008 |
| 15 | 350 | 0.008 |
| 16 | 110 | 0.008 |
| 17 | 230 | 0.008 |
| 18 | 230 | 0.008 |
| 19 | 0 | 0.004 |
| 20 | 0 | 0.004 |
| 21 | 0 | 0.004 |
| 22 | 0 | 0.005 |
| 23 | 0 | 0.005 |
| 24 | 0 | 0.005 |
| 25 | 0 | 0.005 |
| 26 | 0 | 0.008 |
| 27 | 0 | 0.008 |

single node, we have divided a substation node into a subnetwork in accordance with its functionality. A subnetwork consists of supply node(s) to a lower voltage substation and bypass node(s) to other substations. A dual branch between two nodes is modeled by a set of parallel branches directed inversely with each other.

Power failure due to disconnectivity at a demand node is defined as the condition for which the demand node is disconnected from all supply nodes.

## 2.2 Determination of the disconnected nodes

Disconnected node(s) is determined by enumerating the elements of a cut set in a network. A cut set is a set of branches which divide the connected graph into separated graphs so that a demanding node is not supplied from any other nodes. The probability of occurrence of a cut set is calculated as the product of probability of failure of minimum node(s) which forms the corresponding cut set. The failure of probability of each node is assumed as independent.

Given the initial (i.e., normal) electric load flow in a network, power loss is then calculated in accordance with generation of each cut set. The amount of power loss is determined as the sum of the initial electric load of the demanding nodes which are affected by the occurrence of cut set. A shortest path algorithm (Dijkstra 1969) is used to search non-supplied node giving a large number as a distance of the affected branch. Non-supplied node(s) is thus determined comparing the path distance from the supply node to the demanding node with an arbitrary small threshold distance value.

## 3. ILLUSTRATIVE EXAMPLE

### 3.1 Network model

Fig.1 shows the configuration of an idealized power system. Nodes ① and ② are set to be supply nodes. Nodes ③ ~ ⑨ and ⑬ ~ ⑱ are set to be demanding nodes. We evaluate connectivity between these supply nodes and demanding nodes, and calculate associated power loss. Nodes within a dash circle form a high voltage substation with bypass and supply functions to other substations. For example, node ⑦ can receive power supply directly from upper node ④, and also receive bypassed power from ㉒ and/or ㉕ . Node ⑦ supplies the power down to

Table 2. Output of the analysis for the network model

| CUT SET NO. | NODES CONSISTS OF THE CUT SET | PROBABILITY OF FAILURE | CUMULATIVE PROBABILITY | POWER LOSS ( MW ) | DISCONNECTED NODES |
|---|---|---|---|---|---|
| 1) | 1- 4- 20- 21- 0- 0- 0- 0 | 1.600E-10 | 1.600E-10 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 2) | 1- 4- 5- 20- 0- 0- 0- 0 | 2.800E-10 | 4.389E-10 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 3) | 2- 3- 4- 0- 0- 0- 0- 0 | 4.000E-08 | 4.044E-08 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 4) | 3- 4- 21- 0- 0- 0- 0- 0 | 8.000E-08 | 1.203E-07 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 5) | 3- 4- 5- 0- 0- 0- 0- 0 | 1.400E-07 | 2.594E-07 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 6) | 2- 3- 19- 0- 0- 0- 0- 0 | 3.200E-08 | 2.913E-07 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 7) | 1- 2- 0- 0- 0- 0- 0- 0 | 4.000E-06 | 4.291E-06 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 8) | 2- 6- 7- 19- 0- 0- 0- 0 | 1.600E-10 | 4.291E-06 | 2840 | 3 4 5 6 7 8 9 13 14 15 16 17 18 |
| 9) | 2- 4- 6- 7- 0- 0- 0- 0 | 2.000E-10 | 4.291E-06 | 2740 | 3 4 5 6 13 14 15 16 17 18 |
| 10) | 4- 6- 7- 21- 0- 0- 0- 0 | 4.000E-10 | 4.292E-06 | 2740 | 4 5 6 7 8 9 13 14 15 16 17 18 |
| 11) | 4- 5- 6- 7- 0- 0- 0- 0 | 7.000E-10 | 4.293E-06 | 2740 | 4 5 6 7 8 9 13 14 15 16 17 18 |
| . . . . . . . . . . . . . . . . . . . . omitted . . . . . . . . . . . . . . . . . . . . . . . . . . . . | | | | | |
| 149) | 1- 20- 0- 0- 0- 0- 0- 0 | 8.000E-06 | 9.990E-02 | 100 | 3 |
| 150) | 3- 0- 0- 0- 0- 0- 0- 0 | 4.000E-03 | 1.035E-01 | 100 | 3 |

lower nodes ⑨, ㉖ ,and ㉗ . Moreover, node ⑦ has also its own regional demand(300MW) as indicated in Table 1.

Table 1 shows the list of given values of electric load(MW) for the assumed demanding nodes and of failure probability of each node. It is noted that a total power demand is set at 2840MW in this model. The power loss from this total demand due to the system failure will be discussed later.

## 3.2 Numerical Results

A computer code "NETWORK" was developed and used to enumerate the elements of all cut sets, associated probability, disconnected nodes and amount of power loss (Tohma et al.1991). A list of the calculated results is shown in Table 2. A total of 150 cut sets are determined.

For example, cut set No.1 consists of nodes ①, ④, ⑳ and ㉑ . In other words, the simultaneous failure of these nodes generates cut set No.1 in an event of earthquake. The probability of the simultaneous failure, P(j), for a cut set No.j is calculated by multiplication rule assumed statistically independent.

$$P(j) = \Pi \; p_n \qquad (1)$$

where, $p_n$: probability of failure for node n included in cut set j.

In the case of cut set No.1 in Table 2, the probability of failure, P(1), is calculated as follows.

$$\begin{aligned} P(1) &= p_1 \times p_4 \times p_{20} \times p_{21} \\ &= (2 \times 10^{-3}) \times (5 \times 10^{-3}) \times \\ &\quad (4 \times 10^{-3}) \times (4 \times 10^{-3}) \\ &= 1.60 \times 10^{-10} \qquad (2) \end{aligned}$$

As we can confirm the pattern of failure for this case in Fig.1, power from supply nodes will never reach the demanding nodes. This is an absolute system failure with total power loss of 2840MW as shown in Table 2. A list of the corresponding non-supplied nodes is also shown in Table 2. Actually, these non-supplied nodes (i.e., disconnected nodes) are determined by Dijkstra's shortest path algorithm included in the computer program.

Since cut sets No.1 ~ No.8 give the same amount of power loss (i.e., 2840MW), the probability of failure for this power loss can be calculated as a cumulative probability, F(j), by Boolean algebra. The value of F(j) for power loss of 2840MW is determined as $4.291 \times 10^{-6}$ as shown in the eighth line of Table 2.

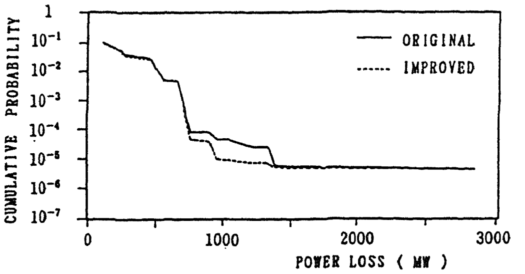

Figure 2. Improvement of the substation components

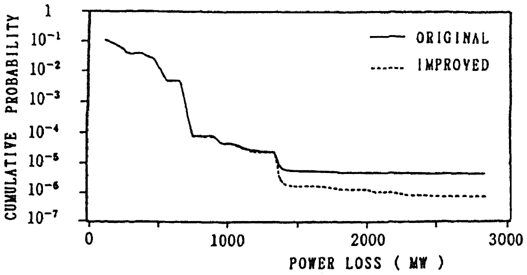

Figure 3. Improvement of the generation facilities

## 3.3 Parametric study

In order to demonstrate effects of failure probability of nodes on the total system reliability, we have carried out some parametric studies varying the value of failure probability of certain nodes in the network system shown in Fig.1. The calculated result is presented in terms of RISK CURVE which is a relationship between the amount of power loss, D(j), of the system and associated cumulative probability of failure, F(j).

An example of RISK CURVEs is shown in Fig.2. The full line represents the results corresponds to the given condition already shown in Table 1. On the other hand, the dash line represents an alternative reducing the probability of failure of nodes ⑦, ㉓, ㉔ to $5 \times 10^{-4}$, respectively. This means that the seismic reliability of this substation assumed to have improved by ten(10) times through some pre-earthquake counter measures. The reduction of cumulative probability is remarkable against the power loss around 1000MW.

Fig.3 shows another example of RISK CURVEs. This is a comparison of the original condition shown in Table 1 and another alternative. The alternative shown in the dash line represents the calculated results by reducing the probability of failure of nodes ① and ② (i.e., the supply nodes) to $2 \times 10^{-4}$, respectively. This means that the seismic reliability of these facilities assumed to have improved by ten(10) times through some pre-earthquake counter measures. The cumulative probability of failure decreases at larger amount of power loss. It can be concluded, therefore, that improvement of reliability of supply facilities reduces the risk of larger power loss of the total system. The probability for smaller power loss, however, will not be changed unless the substation facilities are improved.

## 4. CONCLUSION

We have found the proposed PRA approach to be used to assess and predict, in quantitative terms, the likelihood of power failure of an electric power supply system under a given scenario earthquake. This method is useful for the development of mitigations to reduce the impact of earthquakes on customer service.

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