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PRACTICAL STRATEGIES FOR POST-EARTHQUAKE RESTORATION OF ELECTRIC POWER SYSTEMS

Tomoaki ANDO,[1] Shigeru NODA[2] and Masanori HAMADA[3]

[1] Science and Engineering Division #2, Fuyo Data Processing and Development Co., Ltd., Minato-ku, Tokyo, Japan
[2] Dept. of Social Systems Engineering, Faculty of Engineering, Tottori University, Tottori-shi, Tottori, Japan
[3] Dept. of Ocean Civil Engineering, School of Marine Science, Tokai University, Shimizu-shi, Shizuoka, Japan

SUMMARY

The purpose of the present research is: (1) to develop a practical system, and (2) to examine the process of functional restoration and its dependence on the sequence patterns of repair work. A comprehensive methodology was developed through incorporating various new techniques on modeling of electric power system and its serviceability, as well as introducing new ideas in general recognition of the problem. In the present computer program, personnel and materials were considered to be allocated in the damaged facilities.

INTRODUCTION

Should an electric power system be damaged by an earthquake, the supply capability will fall drastically, a situation that will continue for a certain period of time. However, through subsequent system restoration re-routing using sound transmission lines and substations, the supply capacity of the sound section can be restored quickly. As the restoration of the damaged electric system progresses, the overall supply capability will gradually be restored.

The objective of this study is to develop a simulation program for the restoration of electric power supply networks that takes into account the timely, regional apportionment of required personnel and materials.

With this program, it will be possible to provide information useful for examining to what extent the power supplier can secure necessary power by restoration of the power supply network coping with the recovered demands that dropped temporarily immediately after the occurrence of an earthquake and to examine as to what strategy has to be used to proceed with the restoration activities.

RESTORATION SIMULATION BY MEANS OF SYSTEM RE-ROUTING

Overview The network restoration simulation consists of two parts. The first computes the functional loss, or in other words, the hindrances to electric power supply immediately after an earthquake. The second part simulates the network operation and computes the hindrance to power supply for each substation after the restoration of the network.

This simulation is composed of processes that judge damage to the network resulting from damaged equipment at each substation and the conductivity (coupling) of the output circuit due to system switching. The program also simulates the restoration of distribution capability, which consists of operations that can be accomplished within several hours after the occurrence of the earthquake by computing the amount of electric energy that can be restored by closing circuit breakers which were temporarily tripped by the earthquake.

Networking of Power Supply System Fig. 1 shows a simulation of the electric power system as a network. In the network, the electric power system was simplified by representing power station or substation as one node and two more transmission lines as one link.

In this simulation, the coupling between each substation in the electric power system that is viewed as a network was treated as a question of the shortest path. If the distance (load) between the nodes is finite, those two substations were assumed to be connected.

Model of Substation and Expression as a Network The functional loss of the electric power supply system will be lowered drastically immediately after the occurrence of an earthquake and will be rapidly restored several hours later. This is due to the restoration of the network performed using sound equipment. As such, the restoration of the network greatly affects the accuracy of the restoration simulation, which is governed by the restoration of the function of the substations. Consequently, the important point becomes how the substations should be modeled and processed. In modeling the substations, therefore, the switch gear connecting the busses was expressed using the graph theory as an element, and the functional loss was computed with the coupling of this tie set.

Model of Substations The distributing substations make up the greater part of the substations, whose standardized layout is shown in Fig. 2(a). If the layout is expressed in points and elements, it would be as shown in Fig. 2(b)

Most of the extra-high tension substations use a double bus system. If this is modeled similarly to the distributing substations using the graph theory, the computation of tie set of the substation would require an enormous volume of memory. Therefore, a method was employed in which the substation were classified for convenience into upstream systems and downstream systems with the transformer as a center to judge the coupling. Because of the adoption of such a method, the substation were treated as two nodes in the entire network of the electric power system as shown in Fig. 1.

Evaluation of Functional Loss of Damaged Substations To compute the functional loss of the damaged substations, for which one of the points and elements of the substation modeling the damaged equipment correspond according to the data, the corresponding points and elements can be processed as service interruptions. Also, the recovery of function following restoration of the substation network can be computed by giving data of points and elements that become live through restoration and their recovery time.

In order to do this, a data table to evaluate functional loss of the substations was prepared. From this table, points and elements that stop immediately after the earthquake were processed, and a substation network was composed as shown in Fig. 3(a). The electric power that was being supplied was computed by judging live points. In addition, points and elements that become live by means of restoration were read from the table to formulate a substation network after restoration as shown in Fig. 3(b); the functional loss was computed in the same manner.

Computation of Hindrance to Power To compute hindrance to power supply, the functioning substations were used as subjects. The power being supplied by each substation and the hindrance to power supply was computed by subtracting it from the normal load before the occurrence of the earthquake. The normal load can be roughly divided into 77 kV, 22 kV and 6 kV. The following method was used for computing substation power supply. The hindrance to power supply $M(M_{06}, M_{22})$for the loads 6 kV and 22 kV can be obtained from the equation below.

$$M = \bar{M}\ (m+n-m \cdot n/\ell)/\ell$$

where, $\bar{M}(\bar{M}_{06}, \bar{M}_{22})$: The normal load (MW)
$\ell(\ell_{06}, \ell_{22})$: The total number of outgoing circuits
$m(m_{06}, m_{22})$: The number of stopped outgoing circuits
$n(n_{06}, n_{22})$: The number of stopped distribution lines

The hindrance to power supply (M_{77}) for the load of 77 kV was computed from the equation below:

$$M_{77} = \bar{M}_{77} \cdot m_{77}/\ell_{77})$$

where, $\bar{M}_{77}$: The normal load for 77 kV (MW)
ℓ_{77}: The total number of outgoing circuits for 77 kV
m_{77}: The number of stopped distribution lines of 77 kV

Restoration Work The restoration of the network was considered in two ways, i.e. the case where personnel move to the site for cut-off and the case where cut-off is done by remote control from the control center, depending on the type of equipment damaged. The basis of judgement was that if there is damage to any one piece of equipment that requires the deployment of personnel, the workers would move to the site. The hours needed for restoration were assigned to each substation as input data, and the changes due to the amount and type of damage were not taken into account.

In this study, the capability of the power supply system was confirmed from the situation of each substation and the conditions of damage of power supply equipment, and the power that can be supplied within the subject region of the analysis was computed. In addition, the restoration of power than can be supplied was evaluated while simulating whether or not personnel were required, the number required, work and a deployment program for the restoration of the network.

EMERGENCY RESTORATION SIMULATION

Overview In this simulation, the time needed for the restoration of equipment, interrupted distribution lines and transmission facilities, and the recovery conditions of the power supply (or hindrance to power supply) were computed from one minute to the next and the required man-hours, etc., were estimated.

Restoration Strategy Four restoration strategies were prepared in this program. It was so designed that the restoration process can be simulated by selecting any one of the strategies. Each strategy had an ordering of priority for restoration of substation facilities and restoration of transmission lines that follows. Basically, however, it is a repeated operation of temporary ordering of priority for restoration of substation facilities and distribution area → determination of transmission route → checking of capacity → ordering of priority from higher to lower → reordering of priority for restoration of substation from higher rank. Four strategies for restoration are shown as follows:

a) Strategy A: Strategy that restores most important facilities first. First loads of substation are ranked (Rank I-IV) and ordering of priority is performed so as to restore more important substations first.

b) Strategy B: Strategy aimed at restoring maximum power. Supply hindrance in the substation system is determined by three types of main causes which interrupt the sending of power to substations, i.e. outage in distribution area and reduction in sound drawer lines due to outages of equipment in the substation and in the transmission route. Therefore, the features of this strategy are that the hindrance load is divided into M_S that covers the substation side and M_H that covers the distribution side, and restoration is performed from whichever side is larger in load hindrance with the aim of restoring the power quickly. M_S and M_H are computed by distributing the respective number of drawer stoppage. Depending upon whether 1) substation does have load 2) substation does not have load and, even in the case of 1) whether 3) substation does have power 4) substation does not have power due to outage of transmission route, 0, M_S, M_H, normal $(\bar{M}_{06}+\bar{M}_{22}+\bar{M}_{77})$ load or stationary load is adopted.

c) Strategy C: Strategy that restores from higher rank network to lower rank network. By comparing the voltages at the distribution side of the substations as given by input data, preference is given to the substations that have a higher voltage (higher rank network) for restoration.

d) Strategy D: Strategy that emphasizes easily restored substations. This strategy uses the method in which the route that needs the shortest time for restoration takes precedence. In other words, the priority would change depending on the seriousness of damage. As the transmission route adopted is a normal one, no capacity checking is performed. Strategy D concentrates on more easily restored locations first, in other words, locations that require fewer man-hours for restoration. It aims at distribution power as widely as possible in a short time.

Restoration Process The restoration process minutely establishes the restoration program which consists of personnel required for restoration, personnel for assistance, materials required for restoration, movement to the site, commencement of work, recess, completion of work, return trip, etc., by substation transmission lines and distribution lines and their conditions, and then implements the simulation. Fig. 4 shows the flow of personnel and materials required for restoration and Fig. 5 an example of a pattern of the progress of the restoration program.

NUMERICAL EXAMPLES

A case study was carried out using the model of the electric power supply system shown in Fig. 6.

Against the fixed damage shown in Fig. 6(a), personnel required for restoration, materials required for restoration, loads, system switching data, etc., were assumed. The simulation for prediction of restoration was performed and the effect of the differences in each strategy were examined. Fig. 6(b) shows the damage situation after system re-routing. Comparing this with Fig. 6(a), it can be seen that the number of hindered substations with a o mark decreased (from 11 to 7) and the number of interrupted service lines with an X mark also decreased (from 17 to 13). In this case study, by restoring the network through system switching, the power output was brought back to 80 MW in 20 minutes after the commencement of restoration works (30% of 280 MW, the overall output).

For all cases A through D, the emergency restoration of damaged equipment was completed in about 7 days as shown in Fig. 7, suggesting that the difference in supply capability due to differences in strategy was very small. Looking at the results in detail, there was hardly any difference in supply capability between strategies B and C. In the case of strategy D, the recovery in supply capability was relatively quick until 2 hours from the commencement of restoration work, but it became rather slow thereafter. In the case of strategy A, recovery was the slowest among all four strategies.

CONCLUDING REMARKS

Consideration was given to drawing up the network between substations as close to the actual form as possible so that the program reflects the damage and process of restoration of the electric power system as realistically as possible. In order to simulate the functions of each individual substation as close to the actual conditions as possible, the systems within the substations were made a network so as to be able to treat the lowering of distribution capability due to equipment damage and restoration thereof in more detail. In addition, consideration was also given to establishing the conditions for various peripheral situations, such as classification of each jurisdiction of restoration work, organization of personnel, receiving of materials at warehouses, types of materials required, differences between restoration program depending on the subject facility damaged, etc.

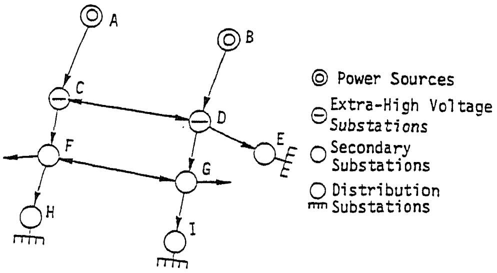
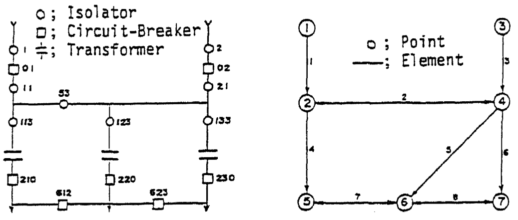
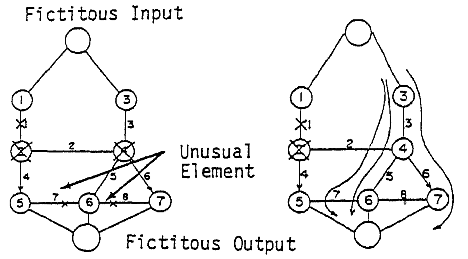


Fig. 1 Networking of power supply system



(a) Skeleton (b) Model

Fig. 2 Model of distributing substation



(a) Immediately after damage (b) After restoration

Fig. 3 Substation network

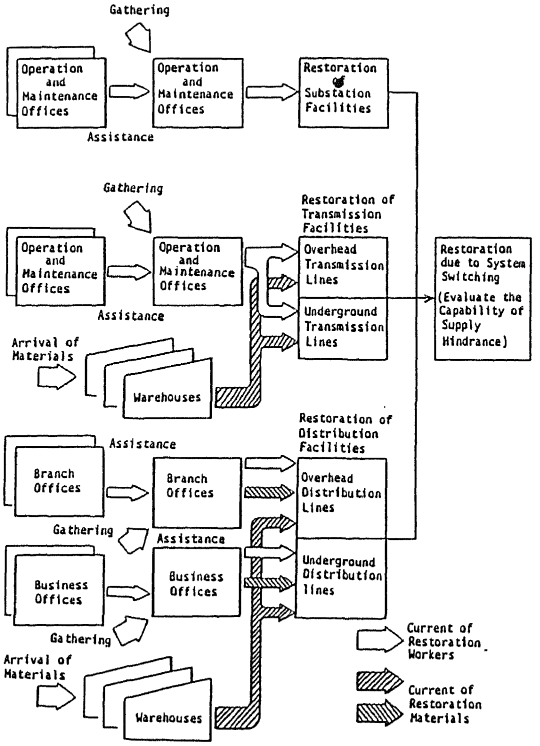


Fig. 4 Flow of personnel and materials required for restoration

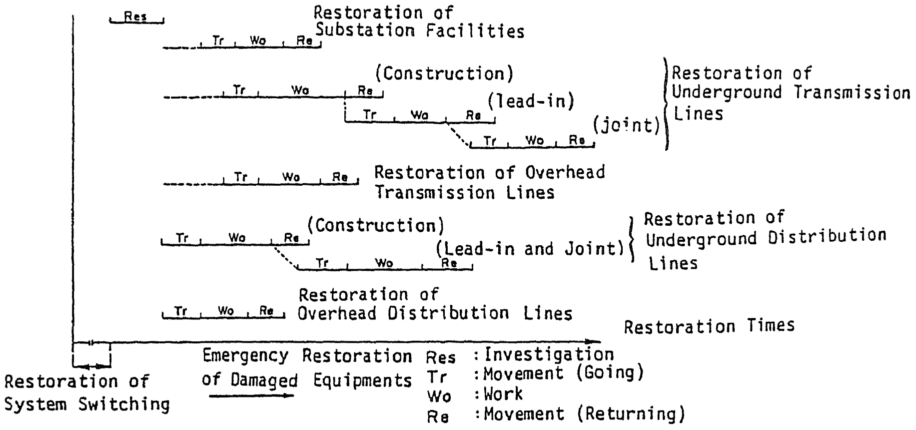
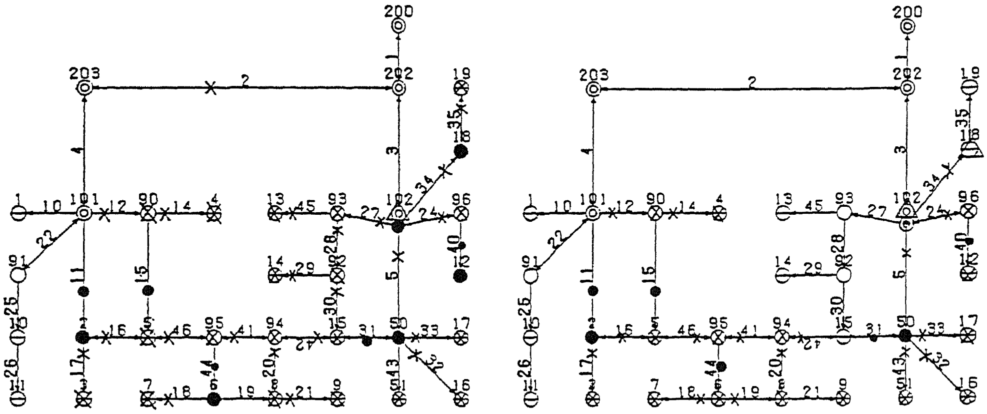


Fig. 5 Example of pattern of progress of restoration program



(a) Immediately after earthquake

(b) After restoration due to system switching

Fig. 6 Typical example for damaged state of network

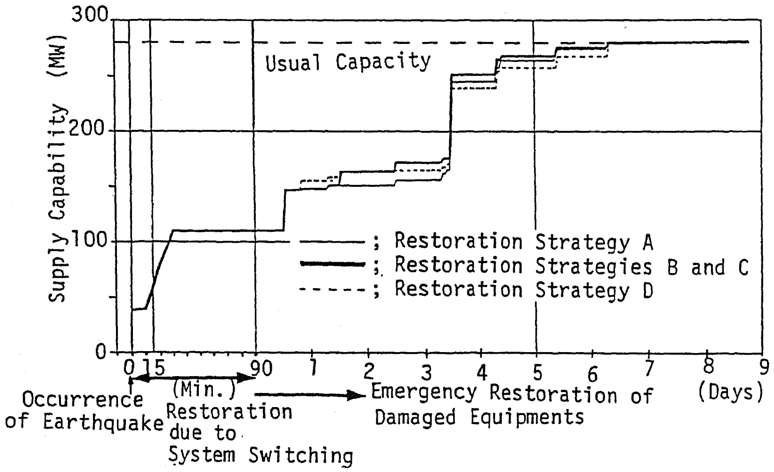


Fig. 7 Result of simulated functinal evaluation during restoration