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SEISMIC RELIABILITY OF ELECTRIC POWER TRANSMISSION SYSTEMS

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ABSTRACT

A comprehensive method for evaluating the reliability of electric power transmission systems is presented. The model provides probabilistic assessments of structural damage and abnormal power flow that can lead to power interruption under a given earthquake. Seismic capacities of the equipment are determined on the basis of available test data and simple modeling from which fragility functions of specific substations are developed. Earthquake ground motions are treated as stochastic processes. Probabilities of network disconnectivity and abnormal power flow are assessed through Monte Carlo simulations. The proposed model is applied to the San Francisco bay area network under the 1989 Loma Prieta earthquake, and the probabilities of power interruption are contrasted with the actual power failures observed during that earthquake.

1.0 INTRODUCTION

Electrical transmission equipment and facilities may be vulnerable to earthquake damage, particularly those in high-voltage transmission systems. Because electrical power is transmitted from the source (power plants) through various stages of voltage transformation to the consumers, failure of a high-voltage facility (e.g., a substation) can cause major power blackout to a large area. For a highly redundant and distributed network, damage to a few of the network components will not necessarily lead to a widespread blackout as a result of alternate paths within the system. Also, by virtue of its redundancy, the seismic performance and reliability of an electric power transmission system may be enhanced by upgrading just a few of the network components. Quantitative (probabilistic) information on the likelihood of different levels of damage and extent of affected areas under different earthquake intensities would be valuable for determining needed upgrading of an existing system, for designing future systems, and for emergency planning and disaster reduction preparedness. This paper presents a comprehensive (probabilistic) model developed to obtain such quantitative information, and describes its application to the power transmission system of the San Fernando Bay Area under the 1989 Loma Prieta earthquake.

2.0 PROBABILISITIC RELIABILITY MODEL

The proposed probability model for assessing the seismic reliability of an electrical power transmission system consists of the following components: (1) network models for two modes of transmission failure, namely: (i) failure through structural damage and disconnectivity, and (ii) failure through abnormal power flow; (2) Monte Carlo simulation procedures for calculating the probabilities of the above failure modes under a given earthquake scenario; (3) stochastic representation of site-specific seismic ground motions; (4) determination of the seismic capacity and fragility of each type of electrical equipment, and development of fragilities of the transmission substations.

2.1 Network Connectivity Model

The electrical power transmission system is modeled by a network of supply and demand nodes interconnected by links. The supply nodes represent power plants or substations which feed electric power to the demand nodes. Disconnectivity of a demand node will occur when it is isolated from all the supply nodes. The graphical connectivity of the network model is represented through the adjacency matrix $X = [x_{ij}]$ where, $x_{ij} = 1$, if node i is connected to node j and 0 otherwise. For undirected links, which is the case of electrical transmission systems, the adjacency matrix is symmetric. The connectivity between all pairs of nodes is then determined by the connectivity or reachability matrix, $C = [r_{ij}]$, which can be obtained from the adjacency matrix as[1]

$$C = X + X^2 + \ldots + X^n \tag{1}$$

Power failure at a demand node caused by disconnectivity, therefore, will occur when the demand node is totally disconnected from all the supply nodes in the network. A power system may be split into several isolated islands. The connectivity analysis will reveal such conditions and establish the reliability of each island to continue operating autonomously.

2.2 Power flow analysis

Power failure or disruption at a demand node can occur also because of abnormal flow conditions, e.g., abnormal voltage in the transmission lines. Such conditions can be identified through a power flow analysis. For an n-bus system, there are $2n$ unknown variables in the power flow analyses, e.g., the real and imaginary parts of the net power at a load bus, or the real part of the net power and the voltage magnitude at a generating bus. The $2n$ unknown variables are determined from the solution of $2n$ independent power flow equations[2]. These equations are nonlinear and iterative methods such as the Gauss-Seidel or the Newton-Raphson methods are required to obtain a solution. Abnormal power flow conditions are established as follows:

Power Imbalance — when some substations and/or power stations are damaged, the total generating power may become greater or less than the total power demand. Here, the power imbalance at a node is considered tolerable if the ratio between the total supply and the total demand is between 1.05 and 1.1.

Abnormal Voltage — If the power flow analysis shows that $|V_{base} - V_{damaged}|/|V_{base}| > \alpha$, where V_{base} and $V_{damaged}$ are the voltage magnitudes for the base case and for the damaged network, respectively, a blackout condition called abnormal voltage is reached. The quantity α depends on the type of transformers in the substation (node). Here, $\alpha = 0.2$ is used.

Unstable Condition — Cases for which a convergent solution of the power flow equations cannot be obtained are classified as unstable conditions.

Operational Power Interruption — Sometimes, a bus with an abnormally high or abnormally low voltage may be causing the aforementioned lack of convergence. If convergence is obtained when such a bus is removed from the network, the blackout conditon at the reference bus is referred to as an operational power interruption.

2.3 Monte Carlo Simulation

As mentioned before, power failure can be caused by either disconnectivity or abnormal power flow. The respective probabilities at each demand node in the network are calculated through Monte Carlo simulations. The Monte Carlo procedure for this purpose consists of the following steps: (1) define the base network model of the electric power transmission system; (2) define the fragility function for each node and link in the network model, and the probability distribution of the site-specific ground motions; (3) for each simulation run (trial), failure of a component (node or link) occurs if the sampled seismic load at the site exceeds the sampled seismic strength of the component; (4) remove every network component that is damaged from the initial network model (base model); (5) perform power flow analysis and connectivity analysis on the damaged network model obtained in Step 4; (6) evaluate power failure at each demand node; (7) repeat steps 3 through 6 for a sufficient number of trials to evaluate the probability of power failure at each demand node.

3.0 EARTHQUAKE GROUND MOTION MODEL

For the reliability assessment under a given earthquake scenario, e.g., the 1989 Loma Prieta earthquake, a proper characterization of the ground motion at the various demand and supply sites is needed. It is obvious, given the areal coverage of a transmission system, that ground motions at various distances from the earthquake source and for a wide variety of local site conditions are likely to be required. The maximum amplitude of the ground motions, e.g., the peak ground acceleration (PGA), can be determined through an appropriate attenuation equation. Corresponding to a given PGA, the ground motion time-history at a site can be modeled as a nonstationary random process. A frequency and amplitude modulated filtered Gaussian white noise[3] is used to represent the possible ground motion time histories.

4.0 SEISMIC CAPACITY AND FRAGILITY FUNCTION

Critical equipment — To simplify the proposed assessment model, it is assumed that there is effectively no redundancy in the substations and the critical pieces of equipment in these substations are simply all those that can cause the opening of a circuit[4]. On this basis, and on the basis of the structural profiles presented in [5] and [6] the equipment considered most critical are: (a) potential transformers, (b) circuit breakers, (c) current potential transformers, (d) coupling capacitor voltage devices (CCVD), (e) switch disconnects, and (f) bus supports. Bus supports are considred critical because if a bus support fails, the bus will most likely come in contact with the ground, a short circuit will be induced, and the associated circuit breakers will open.

4.1 Ultimate Capacity of Electrical Equipment

the level of shaking that can cause the interruption of power flow to a given substation depends on the ultimate lateral capacity of each critical piece of equipment. In general, the evaluation of these critical capacities involves many factors that influence the dynamic response of the equipment. Information or data on these factors are limited or very difficult to obtain. For these reasons, the use of sophisticated analytical models to estimate the needed ultimate capacity of critical equipment is not warranted.

In view of the above, a simple procedure is selected to estimate the required seismic capacities of the critical equipment. The dynamic properties of a given piece of equipment are first estimated from available test data (e.g., [7]). Then, its response to a given seismic excitation is calculated by means of a simplified response spectrum approach. Additionally, simplifying assumptions include the following: (1) the equipment and its support structure are linearly elastic and respond predominantly in the fundamental mode of the combined equipment-support system; (2) the ceramic elements of the equipment are its most fragile parts and will be the first to fail under a strong earthquake; (3) failure of a ceramic component implies failure of the piece of equipment, and (4) the bushings and other ceramic elements behave as cantilever beams. With these assumptions, the ultimate lateral capacity of a given piece of equipment can be determined in terms of the dimensionless spectral accelerations, $SA(\omega, \xi)/g$, as:

$$R = \frac{Z}{WH_{cm}}(f_t + N/A_r) \tag{2}$$

where A_r and Z are, respectively, the area and section modulus of the cross section of the ceramic element at its base, W is the weight of the equipment, H_{cm} is the distance from the base of the element to its center of mass; N is the axial force in the element induced by its own weight or a prestressing force, and f_t denotes the tensile strength of the ceramic.

The ultimate capacity of a piece of equipment, therefore, basically depends on the fundamental natural frequency and damping ratio of its equipment-support system, the geometric characteristics of its ceramic elements, and the tensile strength of ceramics. As these parameters vary widely, e.g., the tensile strength of ceramics varies between 400 MPa and 700 MPa[8], a range of values is estimated for each of the parameters with the assumption that the values in the range are equally likely. On this basis, a uniform probability distribution function is derived for both the natural frequency, ω, and seismic strength, R, for the ceramic components of the various pieces of equipment. The exception is the damping ratio, ξ, which, in most of the reported tests, is found to be close to 2 percent.

For a given ground motion intensity, $A = a$, the fragility of a ceramic element of a piece of equipment can be defined as the probability that the spectral acceleration response, $SA(\omega, \xi)/g$, will exceed the lateral capacity, R, of the component. Prescribing uniform probability density functions (PDF's) for both the ultimate capacity and frequency of the equipment and a constant damping ratio of 2 percent, the pertinent probability of failure is given by

$$P_F(A = a) = \frac{1}{(\omega_u - \omega_l)(R_u - R_l)} \int_{\omega_l}^{\omega_u} \int_{R_l}^{R_u} P\left[SA(\omega, 0.02)/g > r \mid A = a\right] dr d\omega \tag{3}$$

where the subscripts l and u, are used to identify the lower and upper bounds of the uniform random variables that describe the seismic resistance, R, and the equipment frequency, ω. In this study, Monte Carlo simulation is used to compute the mean and standard deviation of the spectral acceleration responses for the specified input ground motions and a Type I extreme value probability distribution is prescribed for $SA(\omega, \xi)/g$ for a given $A = a$.

4.2 Substation Fragility

The substation fragility depends on the fragility of the critical pieces of equipment in the substation which, in turn, depend on the fragilities of their ceramic elements. It is obtained assuming that the fragilities for the various ceramic elements are statistically independent. Failures of only one or a few of the critical ceramic elements in a piece of equipment have been observed[9] which lends validity to this assumption. As a simplification to the simulation procedure, a lognormal distribution with median λ_Y and coefficient of variation ζ_Y is fitted to each substation fragility.

5.0 APPLICATION TO THE LOMA PRIETA EARTHQUAKE

The electrical power transmission system in the San Francisco Bay Area was heavily impacted by the Loma Prieta earthquake of October 17, 1989. The major electrical network in the affected area covering the 500 Kv and 230 Kv facilities in the network and the 115 kv facilities in San Francisco is shown in Figs. 1 and 3. Some of the power plants and major substations experienced severe damage, and caused electric power disruption to over a million customers in the area[10].

During the Loma Prieta earthquake, ground motions were not recorded at the major substations where significant damages were observed and/or are located close to the fault rupture. The attenuation equation developed on the basis of the Loma Prieta earthquake data is used to obtain the median and coefficient of variation of the PGAs at the substation sites. The site conditions at the substations as well as their distance from the ruptured surface are obtained from Ref. 11. The parameters of the stochastic ground motion model are derived from the Anderson Dam (downstream) records of the Loma Prieta earthquake ground accelerations. The exception is the PGA and ground motion model for the San Mateo substation, a soft soil site, which are derived on the basis of the ground motion records of the Loma Prieta earthquake obtained at a nearby soft soil site in Foster City.

The natural frequencies and ultimate lateral capacities for the critical equipment in the Moss Landing, Metcalf, Monte Vista and San Mateo substations are calculated using reported experimental data and the procedure outlined above. The fragility functions for the major substations in the network derived on the basis that seismic damage or failure of any piece of equipment will lead to shutdown of that facility are shown in Fig. 2. Those fragility curves are fitted to a lognormal distribution to be used in the Monte Carlo simulation described above.

Comparison with blackout data — The Monte Carlo simulation results are summarized in Figs. 1 and 3. In Fig. 1 the numbers in the parentheses next to each substation indicate the loss of power probabilities for the substation resulting from disconnectivity and power flow, respectively. For the substations that were subjected to high ground accelerations such as Moss Landing, Metcalf, Monte Vista and San Mateo, loss of power failures were caused largely by disconnectivity, while for the stations in the areas of low ground accelerations, e.g., in the city of San Francisco, the major contributor to loss of power is power imbalance. These results can be contrasted with the actual line outages following the earthquake which are shown in Fig. 3. Also, according to post-earthquake reconnaissance reports(e.g.,[9]), the Moss Landing, Metcalf and San Mateo substations were severely damaged during the Loma Prieta earthquake and the damage to the San Mateo substation severed transmission service to the city of San Francisco, creating large generating/load imbalance (power imbalance).

6.0 CONCLUSIONS

A methodology for quantitative seismic probabilistic reliability assessment of electric power transmission systems is presented. The method uses network analysis and considers failure through disconnectivity and through abnormal power flow. Implementation of the model requires definition of site-specific ground motions at the major substations and of seismic fragility functions for the equipment of the various substations. Application of the methodology to the San Francisco Bay Area transmission network illustrates the effectiveness of the method.

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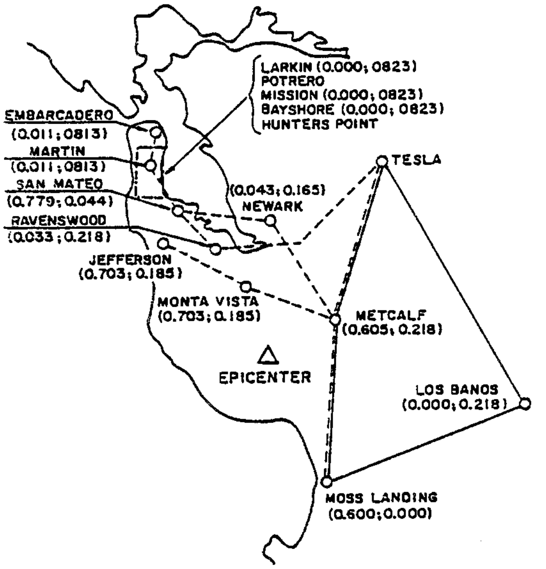

Figure 1. Bay Area transmission system and calculated probabilities of power failure

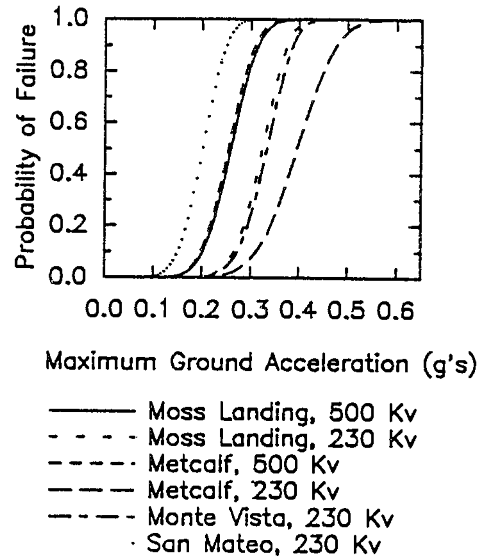

Figure 2. Fragility function of major substations

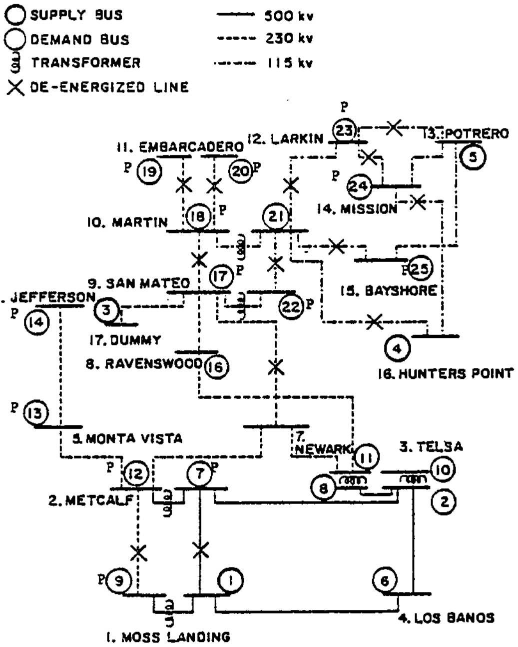

Figure 3. De-energized lines and station blackout following the earthquake