A New Methodology to Evaluate the Seismic Risk of Electrical Power Substations

M. Hosseini[1] and A.H. Khalvati[2]

[1] *Professor, Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*

[2] *PhD. Candidate,Graduate Program, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*

Email: hosseini@iiees.ac.ir, ah.khalvati@iiees.ac.ir

ABSTRACT:

Substations are among the most important parts in the electric power networks, and play a vital role in the stability, controllability and serviceability of the electric energy, yet the experiences gained from the earthquakes have shown that these elements are very vulnerable and the direct and indirect losses resulting from their damages are sometimes really considerable. This high degree of vulnerability is due to the using of brittle materials such as porcelains, using massive elements with a non-proper distribution of mass in height of the equipment, interaction of adjacent equipments, rigid connections, poor anchorage, insufficient lateral stiffness and strength and so on. In this paper a new methodology is developed in order to evaluate the seismic risk of an electrical substation due to the direct losses. In this method first a factor is introduced that shows the dependency of the substation to each certain equipment. Parameters such as the importance of the equipment, vulnerability, age, fragility, etc. are mentioned in the evaluation of this factor. A mathematical model is developed in order to calculate this factor based on the quantified parameters mentioned before. On the other hand, another factor that shows the dependency of the whole network to a certain substation is introduced. This factor depends on the redundancy, backup substations, age, importance, the area under coverage and etc. This factor is also calculated as well as the previous one. Based on these two factors and an introduced scoring technique the seismic risk of a substation for a defined probability of ground motion is evaluated. In this approach first a scenario of a ground motion is assumed. Based on this scenario, the probability of the failure of equipments is derived from the chosen fragility curves. The failure of each component can influence the function of the others and even can disturb the function of the whole substation due to the domino effect in the failures. In order to include this effect the single diagram of the substation that defines the connections and the electrical current should be studied because the substations have different layouts and configurations that could affect the results. Based on the assumed scenario, current diagram, introduced factors and using the event tree-fault tree technique the seismic risk of a substation for a defined probability of ground motion is evaluated.

KEYWORDS: Substations, equipments, risk, scenario, fragility

1. INTRODUCTION

Earthquakes usually cause extensive direct and indirect losses in which the damages to lifelines play an important role. Electric power network and its complex components are a key element among all other groups of lifelines such as transportation networks, pipelines, communication networks, etc. According to vast usage of electrical energy in different industries and its vital role in the industrial production of a country, saving the flow of this energy during and after an earthquake could prevent extensive direct and indirect losses, such as physical vulnerability and severe damages of electric equipments which are very expensive, or business interruption losses due to the electricity outage. On the other hand, it has been learned from the past earthquakes that the existence of electricity could facilitate the rescue and relief operations and this leads to saving more lives which is very important.

The electrical power networks usually consist of three basic parts:
1- Generation (i.e. power plants)
2- Transmission (i.e. transmission lines and substations between the cities having high voltages)
3- Distribiution (i.e. distribution lines and substations in cities which have low voltages)

All of these components are vulnerable to earthquakes, which may result in significant disruption of power supply.

An electrical substation is a facility that serves as a source of energy supply for the local area and has the main following functions:
- Change the level of voltage
- Provide the operation safety of the network by means of eliminating the lightning and surges
- Provide control of the power line by means of measuring instruments

Substations consist of different equipments. The most important equipments are:

- Power Transformers
- Current Transformers
- Voltage Transformers
- Circuit Breakers
- Disconnect Switches
- Lightning and Surge Arresters

These equipments are usually in the switch yard. The control panels and the battery room are located in the Control Building which is near the yard. These substations are classified according to their voltage. The high voltage substations are 400 kV and 230 kV ones.

The studied recent earthquakes have proved that substations are very vulnerable. There are some obvious reasons for the observed such as:

- Use of brittle materials as the main part of several equipments
- Inadequate anchorage to the base
- Insufficient lateral stiffness and strength
- Low redundancies
- Low level of damping
- Interaction between adjacent equipments
- Interaction between the equipment and its contents
- Having heavy mass
- Improper mass distribution at the height of some equipments
- Poor installation and maintenance besides their remarkable ages in some cases.

It can be seen that most of the imperfections and shortcomings mentioned above can be removed and fixed with an easy attempt.According to the high vulnerability of substations and their vital role in the stability of the network this study concentrates on this component of electric power network and the main objective of this paper is to introduce a new methodology to evaluate the seismic risk of electrical power Substations.

Several researchers have studied the effects of past earthquakes on the electric power systems since early 70s to recent years.Schiff (1973) has studied the response of electrical power systems to the San Fernando Valley earthquake of February 9, 1971.From that study he has made the following major recommendations:

1-Standards for system planning, operation, and performance should be established;
2-Standards enforcement procedures should be implemented;
3-Methods for modeling transmission systems should continue to be improved;

4-Instrumentation to provide data to check model validity should be added;
5-Special methodologies appropriate for evaluating system vulnerability to catastrophic disturbances such as earthquakes should be developed;
6-A “seismic safety inspector” position for earthquake related matters should be established;
7-A “damage evaluation log” should be established and maintained to document earthquake damage to electrical power systems; and
8-More extensive requirements for the use and security of emergency electrical power should be established.

Anagnos (1999) has developed a database that documents the performance of substation equipments in twelve California earthquakes.The purpose of the database is to provide a basis for developing or improving equipment vulnerability functions.Dta have been summarized by earthquake ,site,and equipment type.Probabilities of failure are calculated by dividing number of damaged items by the total number of items of that type at the site.Using peak ground accelerations as the ground motion parameter,failure probabilities are compared with opinion-based fragility curves for a few selected equipment classes.The comparisons indicate that some of the existing fragility curves provide reasonable matches to the data and others shoild be modified to better reflect the data.
Hwang et.al (1998) have evaluated the seismic performance of an electric substation using event tree/fault tree technique.In this study they have stablished event trees/ fault trees to delineate interrelationships of the equipments.Using the fragility data of each component and the chosen technique the probabilities that the substation as a whole fails at various levels of ground shaking can be determined and displayed as the substation fragility curves.Furthermore inthis study the most critical and vulnerable component in the substation can be identified.

2. NETWORK DEPENDENCY FACTOR (NDF)

In this study a factor named “Network Dependency Factor” is introduced.This factor indicates the degree of importance of a known substation in the network.The value of this factor is based on these parameters:

- Redundancy of the network
- Existance of backup substations
- Coverage area parameters(populations,important demands such as great industries or important hospitals and …)
- Important outgoing feeders

Inorder to obtain this factor,the network around the substation should be studied carefully and all the parameters mentioned above be derived and established.A mathematical equation is defined to calculate this factor.The conceptual form of this relation is given in Eqn. 2.1.

$$NDF = NDF_{\circ} \times \frac{IF_1 \times IF_2 \times IF_3 \times \ldots}{RF_1 \times RF_2 \times RF_3 \times \ldots} \qquad (2.1)$$

In Eqn. 2.1 $NDF_{\circ}$ is the basic factor and is increased or decreased by the IF or RF factors respectively.The IF or RF factors depend on the parameters mentioned above.One of the applications of the NDF factor is to proioritize the substations in a network inorder to begin the retrofit plans.

3. SUBSTATION DEPENDENCY FACTOR (SDF)

Another factor introduced in this study is the “Substation Dependency Factor”.Different equipments in a substation have different roles,this means some components could be very important and the others not or less important than those vital components.On the other hand this factor indicates the degree of importance of a known component(e.g. an equipment) in a known substation.The value of this factor is based on these parameters:

- The role of the component on the sustainability of the outgoing lines
- Existance of backup components(according to single line diagram of substation)
- Existance of redundancy(according to single line diagram of substation)
- Seismic vulnerability of the component
- Most probable failure modes of the component
- The age of the component
- Mechanical parameters of the component such as weight
- Geometrical parameters of the component such as height and other dimensions
- Availability of substituiting and spare components in the spare room
- The difficulty,performability and cost of the retrofit plans for the component

Inorder to obtain this factor one should study the substation,it's components and their interrelationships very carefully.Ofcourse the supervision of an electric expert is fully recommended.

A mathematical equation is defined to calculate this factor.The conceptual form of this relation is given in Eqn. 3.1.

$$SDF = SDF_{\circ} \times \frac{IF_1 \times IF_2 \times IF_3 \times \ldots}{RF_1 \times RF_2 \times RF_3 \times \ldots} \qquad (3.1)$$

In Eqn. 3.1 $SDF_{\circ}$ is the basic factor and is increased or decreased by the IF or RF factors respectively.The IF or RF factors depend on the parameters mentioned above.One of the applications of the SDF factor is to proioritize the components in a known substation inorder to present a management action plan.The table-1 presents an example action plan for different imaginary values of the SDF:

Table 1: An example action plan for different values of SDF

Action	SDF value
The component should be saved at any level of earthquake	SDF > a
The component should be saved at a defined level of earthquake	a ≥ SDF > b
Spare part should be provided	b ≥ SDF > c
Nothing to do emergency	c ≥ SDF

According to table-1 it's obvious that for higher values of the SDF the substation has a higher degree of dependency to the component and vice versa.It has to be noted that definition of a,b and c in table-1 is based on economical and administrative studies regarding the effects of direct and indirect losses.

4. DEMAND MODIFICATION FACTOR (DMF)

The current practice in design of the structures is based on using a factor to modify the design force of that.The codes usually give the values of 0.8 to 1.5 for this factor and is usually called occupancy factor and is noted by I.One of the applications of SDF and NDF is to define this factor for substation components inorder to modify their demand in design procedure.Table-2 presents imaginary DMFs as an example for different values of SDF and NDF.

Table 2: An example DMF table for different values of SDF and NDF

K > NDF	L ≥ NDF ≥ K	NDF > L	NDF / SDF
1	1.25	1.5	SDF > M
0.85	1	1.25	M ≥ SDF ≥ N
0.7	0.85	1	N > SDF

As it is shown in table-2 the higher values of SDF and NDF means the equipment in the substation and eventually in the network has a high degree of importance and should be designed for higher forces inorder to obtain the higher level of performances,hence higher DMF values are proposed. It has to be noted that definition of parameters K,L,M and N in table-2 is also based on economical and administrative studies regarding the effects of direct and indirect losses.

5.FRAGILITY CURVES

One of the most important elements in evaluating the seismic damage to a component is the so-called fragility curve.The fragility curves for certain type of an equipment are used to represent the probabilities that the damages,under various levels of seismic ground motion exceed specified damage states.In deriving the fragility curves experts generally adopt one of these methods:

1-empirical statistical method

2-experimental method

3-analytical method

4-expert opinion method

In this study the fragility curves are derived from analytical method and in some cases the experimental and expert opinion methods are used to verify the proposed curves for each component.

6.PROPOSED METHODOLOGY TO EVALUATE THE SEISMIC RISK OF SUBSTATIONS

In this study the sequential steps of the proposed method to evaluate the seismic risk of a specified substation are expressed below.The summary of these steps is illustrated in figure 1.

1-Study to evaluate the NDF of the substation based on the parameters highlighted in this paper

2-Study the single line diagram of the substation

3-Definition of the SDF for each component in the substation based on the parameters mentioned in this paper

4-Definition of the DMF or the importance factor of each component

5-Providing the suitable fragility curve of each component

6-Providing the earthquake hazard curve of the considered area

7-Considering an earthquake scenario with known PGA

8-Considering the initiating event that could take place in the proposed scenario

9-Definition of different probable paths of sequential events using event tree/fault tree technique

Given a level of PGA the probability of the outcome of each path is determined using the fragility data of the components in the specified path and the importance factor of those as a weight factor.By changing the scenario and the initiating event the procedure is repeated until one can reach the worst case which has the higher risk.The critical path then is identified.According to this critical path and considering the direct losses the seismic risk of the substation is evaluated.

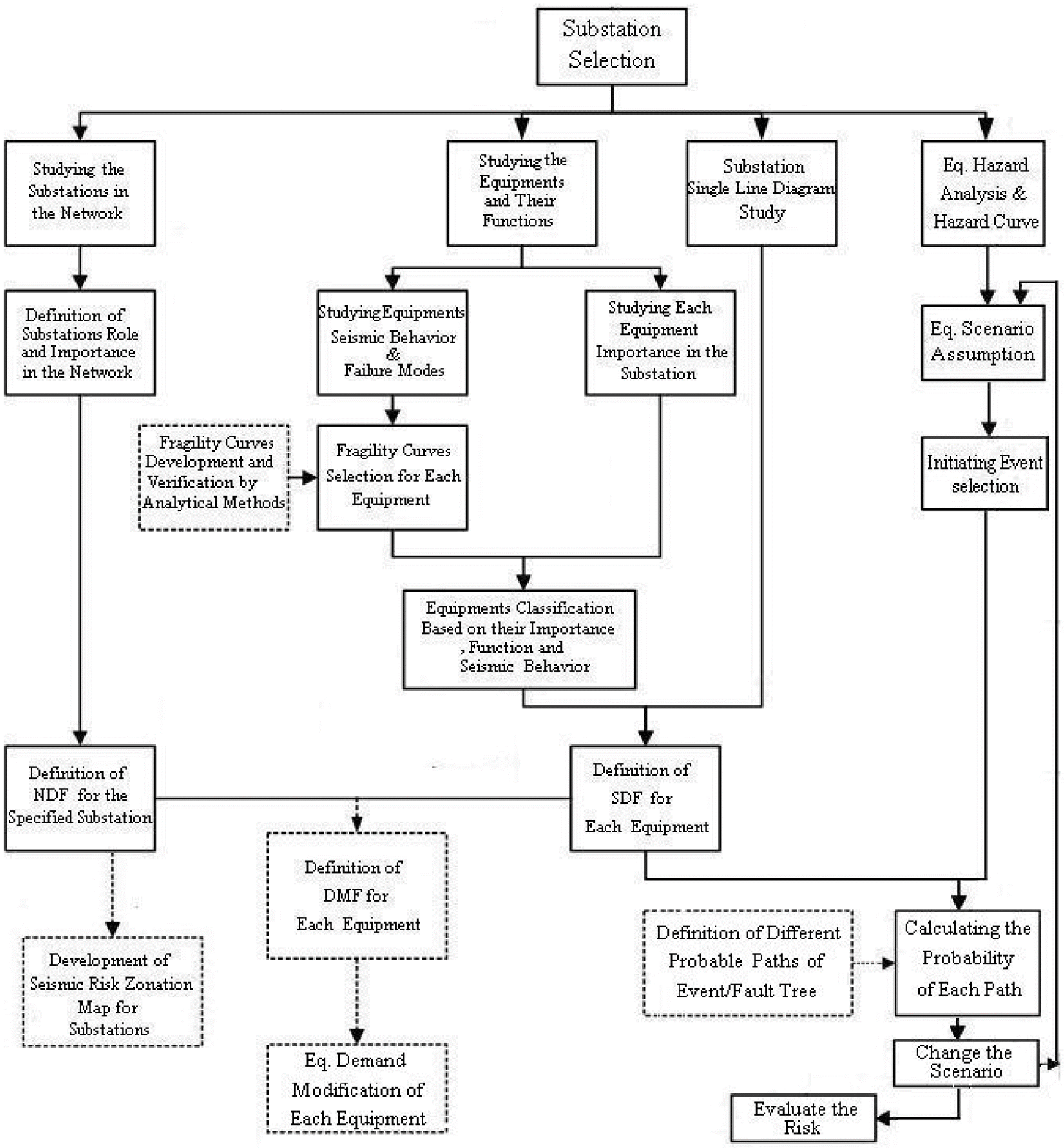

Figure 1: The Flowchart Illustrating the whole Process

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