SEISMIC FRAGILITY AND RISK ANALYSIS OF ELECTRIC POWER SUBSTATIONS

By

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Abstract

Electric power substations are very vulnerable to earthquakes. This study has analyzed the seismic risk index of electric power substations of Hydro-Quebec. The critical parameters responsible for vulnerability of substations are identified by statistical analysis of field data. Correlation of different parameters with vulnerability, sensitivity of the weighting factors of critical parameters and sensitivity of seismic exposure levels to seismic risk index are also studied by statistical analysis. Study shows that year of manufacture of equipment, anchoring of heavy equipment, load-bearing system of the building, and control systems are the four most critical parameters for vulnerability.

Vulnerability of substations largely depends on the performance of circuit breakers and control buildings during earthquakes. An analytical approach is used to determine the seismic fragility of circuit breakers. Risk based design concepts are used to determine the probability of failure of circuit breakers for a range of peak ground accelerations. The fragility curves are obtained by plotting the probability of failure as a function of peak ground acceleration. The fragility curves are used to determine the appropriateness of circuit breakers on various seismic zones. ATB 735 and 120 KV, BBC 735 KV, PK4 and S&S circuit breakers are found to very vulnerable and not acceptable under the specifications of NBCC 2005. ATB 230 and 330 KV GE, DLVF 230 KV BBC, Delle, Merlin Gerin, and Brown Boveri circuit breakers have medium and acceptable reliabilities under NBCC2005 loads. ABB circuit breakers have high reliabilities for all zones. The fragility assessment of circuit breakers is compared with field performance of circuit breaker during past earthquakes as well as with the Utility Working Group fragility curves.

The seismic base shear of a substation control building is calculated using NBCC 1995 and NBCC 2005 procedure. Substation control buildings are found to be much more vulnerable to seismic base shear under NBCC 2005 provisions than with the NBCC 1995.

Résumé

Les postes de distribution électriques sont généralement reconnus pour leur grande vulnérabilité sismique. Une base données sur les caractéristiques des postes de distribution électrique du Québec a été analysée afin: (1) d'identifier les facteurs les plus influents sur la vulnérabilité sismique, (2) d'analyser la sensibilité de la vulnérabilité par rapport à ces facteurs, et (3) évaluer le risque sismique global du réseau sous divers scénarios sismiques. L'analyse indique que l'année de fabrication, le système d'ancrage des équipements lourds et le système structural des bâtiments sont les quatre paramètres les plus critiques pour la vulnérabilité sismique des installations existantes.

La vulnérabilité des postes de distribution est très dépendante de la vulnérabilité des disjoncteurs et des bâtiments. Une approche analytique a été utilisée afin de définir les courbes de fragilité des disjoncteurs. Une approche fiabiliste est utilisée afin d'obtenir la probabilité de défaillance des disjoncteurs en fonction de l'accélération (PGA). Ces courbes sont utilisées afin d'identifier les zones pour lesquelles les différents types de disjoncteurs sont adéquats. Les disjoncteurs ATB 735 et 120 KV, BBC 735 KV, PK4, et S&S sont très vulnérables et ne rencontrent pas les critères du CNB2005. Les disjoncteurs de type ATB 230kV GE, ATB 330 kV GE, DLVF 230 kV BBC, Delle, Merlin Gerin,and Brown Boveri ont une fiabilité acceptable. Finalement, les disjoncteurs ABB et GL-318 4LM SF6 ont la plus grande fiabilité. Les courbes obtenues par analyse sont comparées aux courbes de fragilité obtenues par consensus par le Utility Wirking Gourp et à des statistiques sur la performance des disjoncteurs lors de séismes.

Finalement, la vulnérabilité sismique des bâtiments de contrôle est évaluée suivant les procédures de CNB 1995 et CNB 2005. Cette dernière analyse confrme que ce genre de bâtiment est très vulnérable aux séismes.

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Chapter 1

Introduction

1.1 Background

Considering the electric transmission and distribution network, substations are generally considered most vulnerable to earthquake damage. Past earthquakes around the world showed that high intensity earthquakes can cause severe damage to substations and can result in major service disruptions over large areas. Substations are composed of a variety of components such as: substation building, transformers, circuit breakers, disconnect switches, lightning arresters, current transformers, wave traps, and circuit switchers which are very vulnerable to earthquake ground shaking. The 1994 Northridge earthquake demonstrated that damage to electrical substation components in California also affected power service to British Columbia, Montana, Wyoming, Idaho, Oregon and Washington (Schiff, 1995).

Earthquake damage to substations in Quebec is also likely. Quebec is located in an intraplate region of medium seismicity that can be affected by severe earthquakes. For example, the electric network was affected during the 1988 Saguenay earthquake in Quebec. The damage was related to failure of electrical equipment, cracks in control buildings and false tripping of some relays. It took several hours after the earthquake to restore the power service in Quebec City. Total damage to equipment during the earthquake was estimated at $ 7 Million (Pierre, 1989).

Considering the potential of earthquake damage to electric power substations, Hydro-Quebec has recently developed a methodology to evaluate the seismic vulnerability and importance (consequences of failure) of different substations in Quebec. The proposed thesis is relative to the seismic hazards associated with the electric distribution network for the province of Quebec.

1.2 Objectives

1. Statistical analysis of the data compiled by Hydro-Quebec on electric distribution facilities was performed in order to evaluate the overall performance of the network during seismic events.

2. Identify critical parameters of vulnerability and the proper means to reduce the potential risk of future earthquakes on the electric distribution system.

3. Develop fragility curves for circuit breakers used by Hydro-Quebec in different substations.

4. Perform reliability assessment of substation control buildings under NBCC 1995 and proposed NBCC 2005 provisions.

5. Develop proper seismic criteria for new equipment for electric substations

1.3 Organization of the Thesis

Chapter 2 presents a review of the literature on the performance of substations during past major earthquakes, the theory for the development of fragility curve, and the result of risk and vulnerability studies previously carried out for substations. Chapter 3 describes the electric power distribution system of Hydro-Quebec and the data sets analysed in the thesis. Chapter 4 presents the statistical analysis of the data on substations. Chapter 5 describes the development of fragility curves of circuit breakers and suitability of different types of circuit breakers as a function of seismic zone. Chapter 6 identifies the critical parameters for the seismic vulnerability of substation control buildings under NBCC 1995 and the proposed NBCC 2005 provisions. A summary of the thesis and recommendations for future research are presented in Chapter 7

Chapter 2

Literature Review and Previous Studies

2.1 Introduction:

Electric power systems are very vulnerable to earthquake ground shaking. Power failure after an earthquake can interrupt other lifelines components and recovery operation. Substations are the most vulnerable part of an electric distribution network and their failure can cause power outage to a large area. Damage to power station components and consequences of failure during the recent earthquakes are described in this section.

2.2 Vulnerability and Consequences of Damage of Substations in Past Earthquakes

2.2.1 Saguenay Earthquake, Quebec:

On November 25, 1988, at 18.46 Eastern Standard time, an earthquake of magnitude (M_s) 5.7 occurred in the Saguenay region of Quebec. This earthquake represents the first strong event in eastern North America for which the seismic performance of a power system is presented. Pierre (1991) describes the seismic performance of electric power systems during the Saguenay earthquake. Significant damage occurred within epicentral distances of 145 to 210 km, at Montmagny, Quebec II, Bersimis II and Madawaska substations (Figure 2.1). Several pieces of equipment such as circuit breakers, switches, power transformers and lightning arresters were totally damaged. Eight 315 KV BBC air pressure circuit breakers and two switches were damaged in the Bersimis II substation. The local topography of the Bersimis II substation located at the top of a hill probably caused an adverse dispersion of seismic waves at the base of equipment. The effects of the earthquake on power systems were generally of three kinds: failure of some large

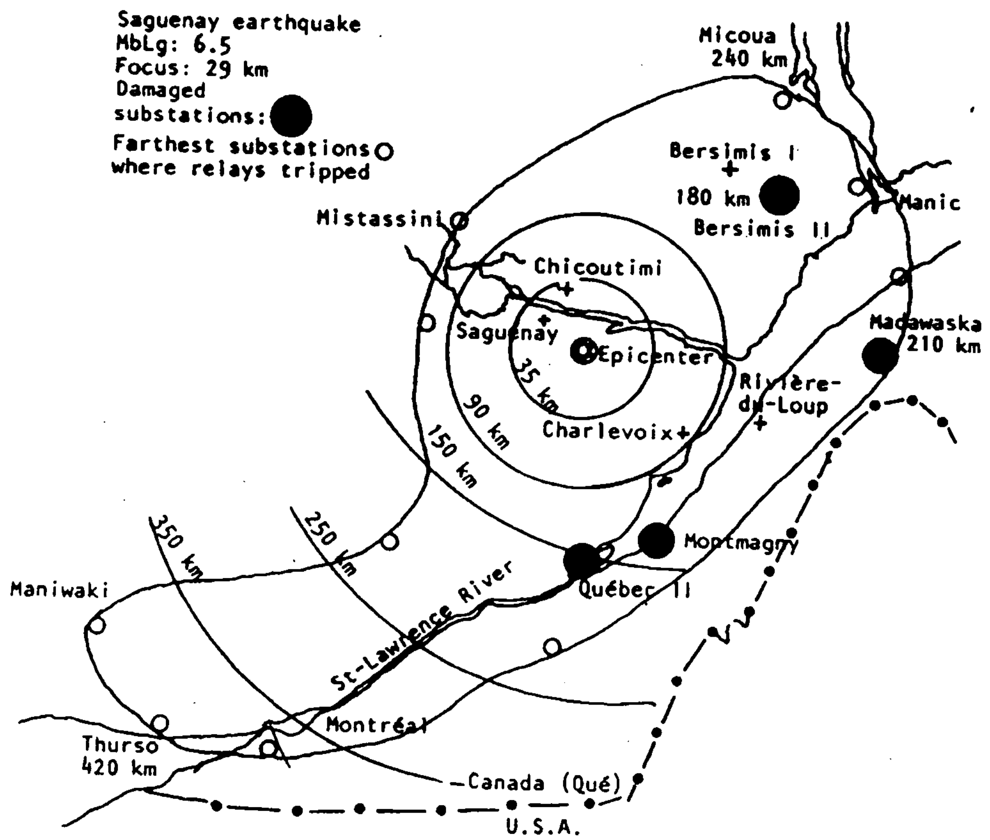


Figure 2.1: Electric Network Affected by Sagqenay Earthquake (Pierre1991)

electrical equipment, cracks in control building, and false tripping of some relays. A total power loss of 2800- MW was recorded for triggering of relays due to seismic vibrations (Mitchell et al, 1990).

Most of the damage was due to dynamic weakness of equipment, insufficient bus slack between adjacent apparatus, and local soil effects. It is seen that for the most part, the damaged equipment was rather old and not designed considering seismic standards. The new equipment designed according to present seismic standards behaved well during the earthquake.

2.2.2 Kobe Earthquake:

Pierre (1995) has described in details the damage caused by the Kobe earthquake on electric substation. Kansai Electric Power Co. Inc. services the earthquake-affected area. The transmission system is serviced with 500 KV, 275 KV, 154 KV, and 77 KV line. The primary distribution line voltage is 6.6 KV with some 22 KV and 33 KV lines. Substations were severely affected by the earthquake. A summary of damage to substations is given in Table 2.1. About 1 million customers were out of power at the onset of the earthquake.

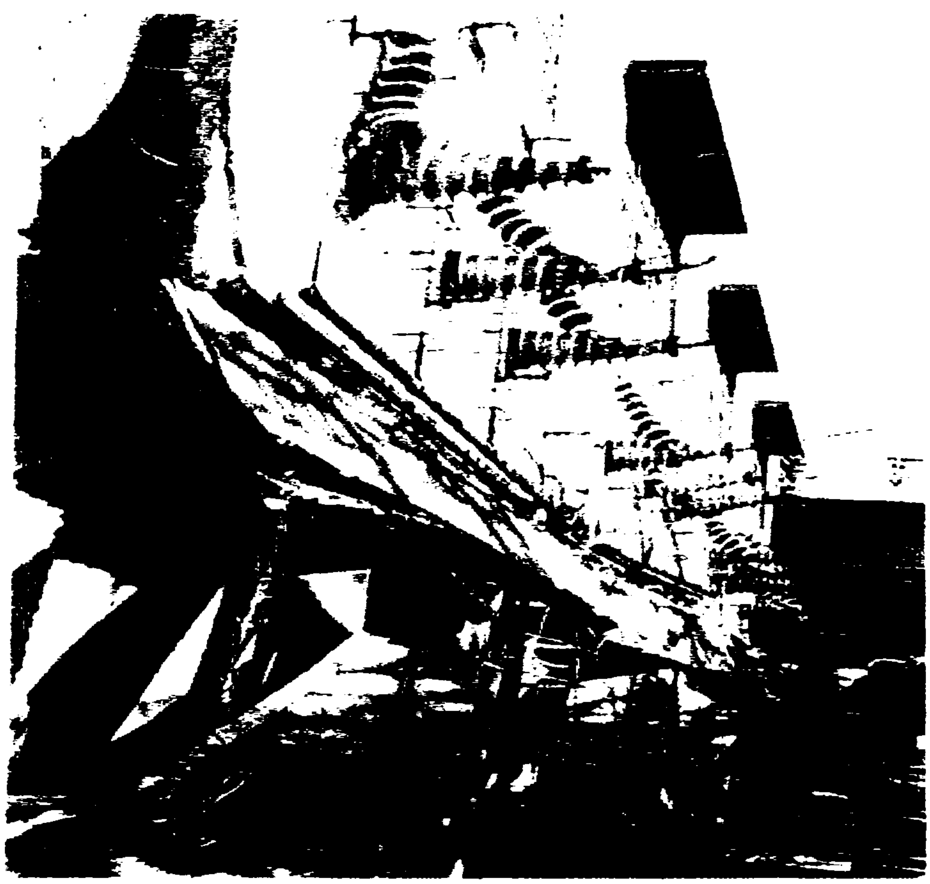


Figure 2.2: Damage of Control Building with Suspension and Wall Insulators
(Pierre, 1995)

The distribution system was also severely damaged. Many transformers in the affected substations slided from their bases, failure of bushings connected to vertical conductors drops, support structures cracked and the conservators fell down, oil leaks occurred at the conservators and cut-off valves. A large number of porcelain breaks were observed in different equipment. Some substations control buildings were damaged during the earthquake (Figure 2.2).

	Damaged Main Facilities	Slightly Damaged Main Facilities	Total
Substations	17	30	47
Transformers	23	29	52
Circuit Breakers	9	1	10
Power Capacitors	4		4
Shunt Reactors	5		5
Disconnect Switches		41	41
Lightning Arresters		15	15
Busses		7	7
Buildings		12	12
Distribution Lines (22KV, 33KV)	11		11
Overhead-Wire	1 span		1
Overhead-Insulator	1		1
Underground –Cable	11		11
Underground-Duct		8 spans	8
Underground Manholes		125	125
Distribution Lines (6.6KV)	649		649
Overhead-Wire	6,188 spans		6188
Supporting Structures	7869		7869
Transformers		4512	4512
Underground –Cable	185	1317	1322
Underground-Duct		247 spans	247
Underground Manholes		125	125

Table 2.1: Summary of Damage to Power Facilities (Schiff, 1998)

Damage to the distribution system are presented in Table2.1. Damage to the distribution system contributes the most to power outage. Concrete poles were severely damaged by ground vibrations, by soil liquefaction, and due to collapsed structures. Extensive damage to conduits in downtown Kobe occurred due to ground deformation associated with soil liquefaction. Total cost of damage and upgrading to the power system was reported at about $2.3 billion by Kansai Electric (Schiff, 1998)

From the Kobe earthquake, it is observed that seismic performance of high voltage equipment in Japan is different than that observed during past earthquakes in the United States.

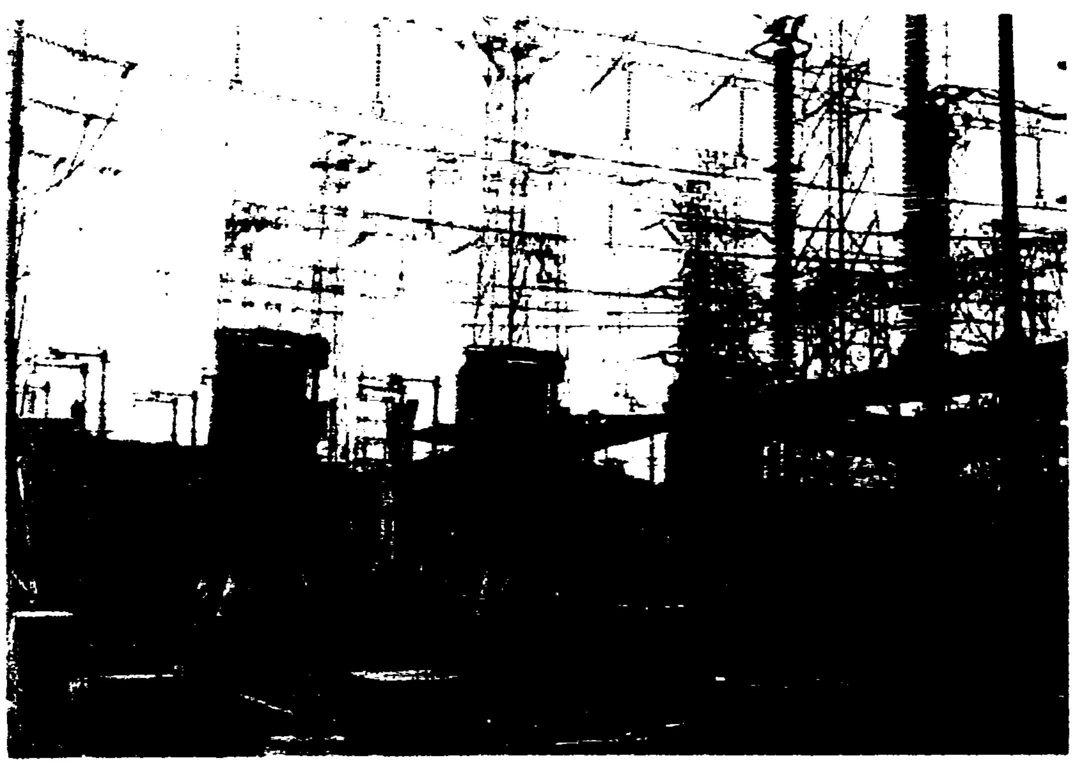


Figure 2.3: Failure of All Bushing of 275 KV Circuit Breakers with Large Volume of Oil (Pierre, 1995)

In Japan, many dead-tank circuit breaker bushings were damaged (Figure 2.3) but with in the United States damage was mainly associated with transformer bushings, current-voltage transformers, and disconnect switches. Equipment anchorage failure was more common in Japan than in the United States.

2.2.3 Northridge Earthquake

On January 17, 1994, an earthquake of magnitude 6.7 (M_w) occurred in the densely populated San Fernando Velley, in northern Los Angeles. This earthquake caused significant damage to electric power facilities of the Los Angeles Department of Water and Power (LDWP). Earthquake caused severe damage to high voltage substation equipment (Figure 2.4). Substation damage was responsible for local power outages over large areas. Seven western states of the USA and British Columbia were also affected by power disruptions. Over 9000 homes and business were out of electricity for several days (EQE International, 1994). Some substations experienced peak ground accelerations greater than 0.5g and were greatly damaged. Structural failures of transmission towers caused by ground failures were also reported (Figure 2.5). High voltage substation equipment designed after the 1971 San Fernando earthquake suffered less damage than older equipment.

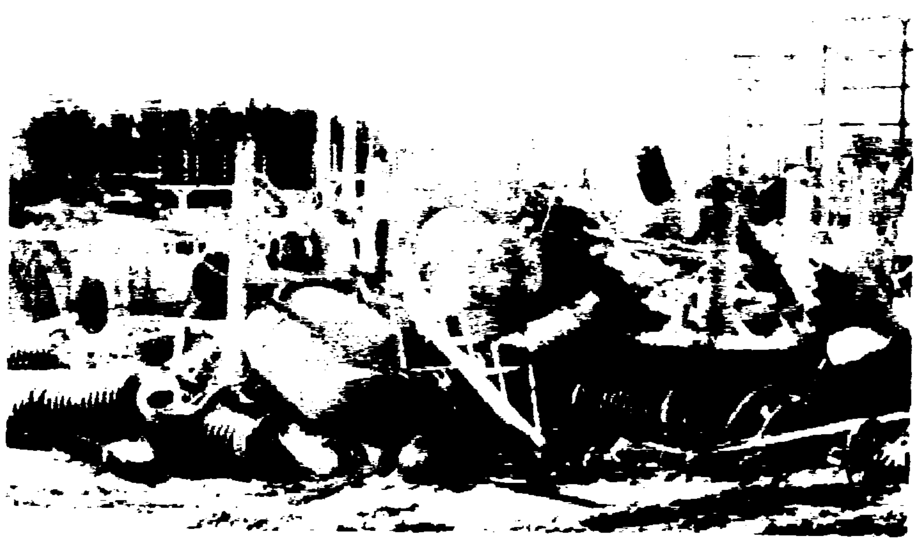


Figure 2.4: Damage to High Voltage Substation Equipment
(EQE International, 1994)

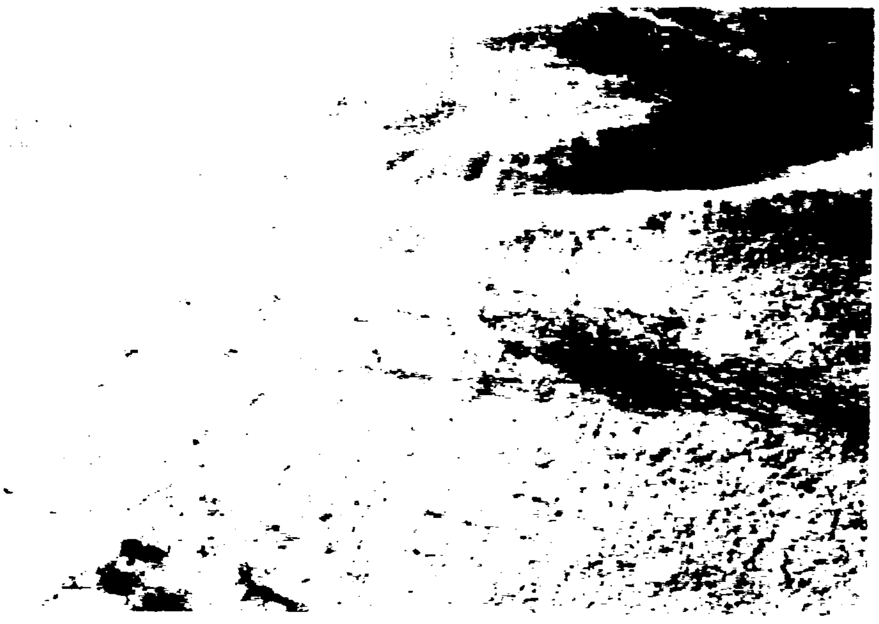


Figure 2.5: Transmission Towers Collapsed Because of Ground Failure
(EQE International, 1994)

2.2.4 Izmit, Turkey Earthquake:

On August 17, 1999, a 7.4 magnitude earthquake hit the northern part of Turkey. Total cost of damage to electric power systems of was reported at US$70 million (Tang, 2000). Major damage was limited to 380 KV and 154 KV substations. Damage to circuit breakers, disconnect switches, lightning arresters and transformers were most common. Most of the "T" shape 380 KV circuit breakers failed during the earthquake. "Y" shape circuit breakers performed very well. The transmission network performed well in the earthquake and no transmission tower failures were observed. In most places, power was restored within a day. In some places, cleaning up operation of collapsed buildings caused further power disruptions. Considering the total duration of power outages, overall performance of the electric power system was rated as good. Due to the low peak ground acceleration, damage to equipment during the Izmit earthquake was less compared to other earthquakes of similar magnitude.

2.2.5 Bhuj Earthquake, Gujarat:

A 7.7 (M_w)- magnitude earthquake hit on January 26, 2001 at 8.46 local time, in the seismically active area of Kutch district of Gujarat state of India. Eidinger (2001) described the damage to power systems as follows. Most of the severe damage occurred to 60 KV, 132 KV and 220 KV substations. The earthquake affected a total of 45 high voltage electric power substations. Four three- phase 220 KV transformers and power reactors failed out of ten which led to a complete power blackout of Kutch district. It took 3 days to restore the first 220 KV circuit at this substation. Most high voltage transformers were mounted on wheels on rails with small blocks. The transformers rolled sufficiently and bushings of these transformers broke significantly where PGA exceeded 0.2g causing substantial damage to adjacent lightning arrestors, circuit breakers, and current transformers. Three SF-6 circuit breakers broke at Madhapar when the adjacent transformer rolled and the attached conductor pulled down the circuit breakers (Figure 2.6). 5 % to 20 % circuit breakers of various substations failed during the earthquake.

Figure 2.6: Failed Circuit Breakers at 66 KV Madhapur (Eidinger, 2001)

SF-6 live tank "candle stick" circuit breakers performed well. Other live tank circuit breakers performed relatively well compared to the performance of similar circuit breaker in the US during strong earthquakes. Most of the control buildings in locations where PGA exceeded 0.15g were moderately to heavily damaged. More than 12 control buildings suffered partial or total collapse and another 45 were lightly damaged. In some cases, control panels were damaged due to the collapse of the buildings. Transmission towers performed well, only a few towers were affected by liquefaction or landslide. Gujarat Electric Board reported a $110 million loss due to damage to their equipment.

2.3 Seismic Fragility

Fragility curves display the seismic vulnerability of structures or equipment in the event of an earthquake. Seismic reliability of electric power systems is defined in terms of the fragilities of its components. Fragility studies are required for risk and reliability assessment of components. The seismic performance of a component during an earthquake is often expressed as a function of Peak Ground Acceleration (PGA).

Kiureghian (2002), defines seismic fragility as the conditional probability of failure of a component or system, given one or more measures of ground motion intensity. The fragility of an electrical substation component can be developed with respect to a single measure of ground motion intensity, e.g., the peak ground acceleration. So, the 'fragility curve' is a plot of the probability of failure of the component as a function of peak ground acceleration.

Ravindra (1983) states that the objective of fragility evaluation is to estimate the Peak Ground Acceleration for which the seismic response of a given equipment exceeds its capacity resulting in failure. Equipment fragility can be described by means of a family of fragility curves; a probability value is assigned to each curve to reflect the uncertainty in the fragility estimation. The Major steps in developing seismic fragilities curves are: component selection, determination of failure modes and peak ground acceleration capacity evaluation.

2.3.1 Utilities Working Group (UWG) Fragility Curve

In September 1993, a group of experts from several California utilities convened and developed a standardized classification system to substation equipment for developing equipment damage relationship. Thalia (1999) described the opinion-based fragility curves developed by the Utilities Working Group (UWG). Four parameters are needed to develop this opinion-based fragility for each type of electric component: minimum peak ground acceleration for the onset of damage, and PGA at 16th, 50th, and 84th damage percentiles. The fragility curves are plotted by combining two normal distributions: one for probabilities less than 0.5 with standard deviation σ_1 and the other for probabilities greater than 0.5 with standard deviation σ_2. The 50th percentile is the median (m) value of the normal distribution, $m-\sigma_1$ = 16th percentile and $m+\sigma_2$ = 84th damage percentile. Fragility parameters for different types of circuit breakers and their failure modes are presented in Table 2.2.

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th (g)	50th (g)	84th (g)
CB9	230 KV live tank General Electric ATB4, ATB5, ATB6	Column base gasket leak	0.08	0.10	0.25	0.35
		1 porcelain column fails	0.10	0.15	0.30	0.45
		2 porcelain columns fail	0.10	0.20	0.35	0.50
CB14	230 KV live tank General Electric ATB7	1 porcelain column fails	0.04	0.08	0.15	0.30
		2 porcelain columns fail	0.04	0.13	0.20	0.40
CB15	500 KV live tank General Electric ATB	Column base gasket leak	0.10	0.15	0.25	0.35
		1 porcelain column fails	0.10	0.15	0.30	0.50
		2 porcelain columns fail	0.10	0.15	0.35	0.55

Table 2.2: Fragility Parameters for Circuit Breakers (Thalia, 1999)

2.3.2 Derivation of Fragility Curve

Haldar (2000), describes the reliability index and probability of failure for load and resistance variables as follows. Consider two variables, one related to applied loads S, and the other to the resistance of the structure, R. Both are normal random variables and characterized by N (μ_s, σ_s) and N (μ_R, σ_R) and corresponding probability density functions $f_S(s)$ and $f_R(r)$ respectively as shown in Figure 2.7. A safety factor, S_F can be determined by considering the nominal resistance R_N and the nominal load S_N:

$$S_F = R_N/S_N$$

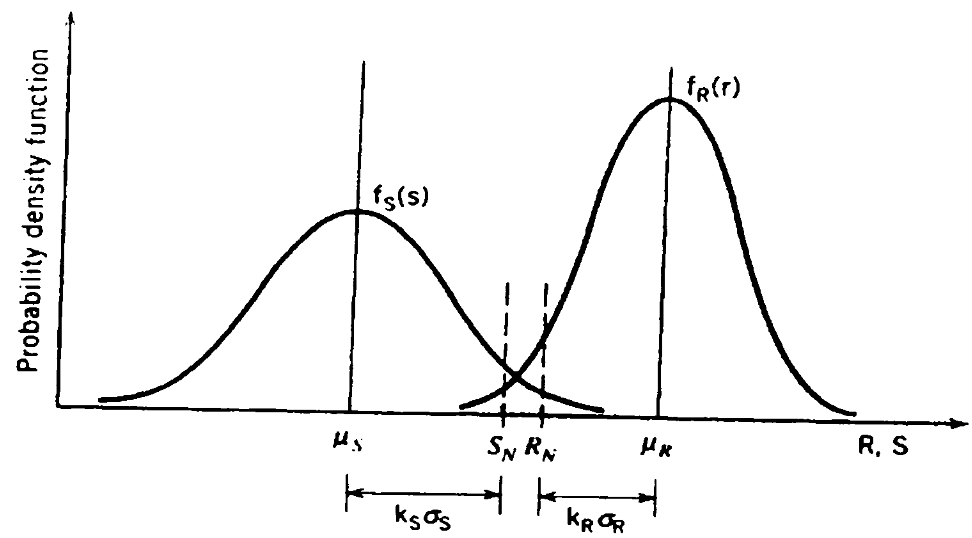


Figure 2.7: Effect of Relative Position Between $f_{S(s)}$ and $f_{R(r)}$ on P_f (Haldar, 2000)

This nominal safety factor may fail to convey the actual margin of safety in a design. But with the risk-based design concepts we can express the measure of risk in terms of the probability of the failure event or P(R < S) is

$$P_f = P(R < S)$$

$$= \int_0^\infty \left[\int_0^S f_R(r)dr \right] f_S(s)ds \text{ ....2.1}$$

$$= \int_0^\infty F_R(s) f_S(s) ds$$

Where $F_R(s)$ is the CDF of R evaluated at s

Consider a structure whose load carrying capacity, R, is a normal random variable N (μ_R, σ_R). Similarly, the load, S is also normal N (μ_S, σ_S). The probability distribution of the safety margin, Z = R-S is also a normal random variable, N (μ_Z, σ_Z), in which

$$\mu_Z = \mu_R - \mu_S$$

For statistically independent R and S

$$\sigma_Z^2 = \sigma_R^2 + \sigma_S^2$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2}$$

Equation 2.1 can be used to define the probability of failure as

$$p_f = P(Z < 0)$$

or,

$$p_f = \phi\left[\frac{0 - (\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right]$$

or,

$$p_f = 1 - \phi\left[\frac{(\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right] \quad \text{..................2.2}$$

Where ϕ is the CDF of the standard normal variate. Equation 2.2 can be rearranged to develop a risk-based design

$$\mu_R \geq \mu_S + \phi^{-1}(1 - p_f)\sqrt{\sigma_R^2 + \sigma_S^2} \quad \text{...............2.3}$$

Where $\phi^{-1}(1 - p_f)$ is the value of standard normal variate at the probability level $(1 - p_f)$. Now introducing $\beta = \phi^{-1}(1 - p_f)$ in equation 2.3 and considering the equality condition,

$$\mu_R = \mu_S + \beta\sqrt{\sigma_R^2 + \sigma_S^2}$$

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

Where β, is the reliability index or safety index

The probability of survival is therefore,

$$p_S = \phi(\beta)$$

and the corresponding probability of failure is,

$$p_f = 1 - \phi(\beta)$$

2.3.3 System Reliability of Series System

Most equipment is composed of multiple components. The components can be classified as series-connected, parallel-connected, or mixed-connected systems.
Ang (1984), defines series systems as systems for which failure of any component constitutes failure of the system. Therefore, series systems have no redundancy and the reliability or safety of the system requires that none of the components fail (Figure 2.8).

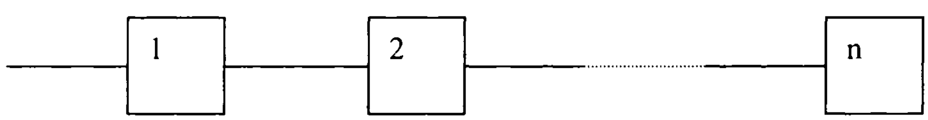


Figure 2.8: Components Connected in Series

A series system only survives if all components survive,

$$p\,[\text{system survive}] = \prod_{i}^{n} p\,[\text{component } i \text{ survive}]$$

Assuming independence,

$$1 - p_S = \prod_{i=1}^{n} (1 - p_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.4$$

$$= 1 - \sum_{i=1}^{n} p_i + [\text{Higher order terms in } p_i\ ]$$

For small probability,

$$\approx 1-\sum_{i=1}^{n} p_i \quad \text{if} \quad \sum p_i << 1$$

Where p_i is the probability of failure of component *i* and $(1-p_S)$ is the reliability of the system.

2.4 Previous Vulnerability Studies:

Thalia (1999) developed an electrical substation equipment performance database on the basis of twelve California earthquakes. The purpose of the database is to provide a basis for developing or improving equipment vulnerability functions. In this study, data have been summarized by earthquake, site, and equipment type. Total number of damage items of each type of equipment was recorded and probability of failure was calculated by dividing number of damage items by the total number of items of that type at the station. Peak ground acceleration was considered as the ground motion parameter in this study. Failure probabilities were compared with opinion based fragility curves. Probability of failure of General electric 230 KV live tank ATB4, ATB5, ATB6 circuit breakers and Westinghouse 500 KV live tank SF6 circuit breakers was calculated from damage data for different earthquakes. The probabilities of failure of circuit breakers from actual damage data are higher than expert based Utility Working Group fragility curves. Thus, according to this study, Utility Working Group fragility curves underestimate the failure rate of circuit breakers and should be adjusted upward to reflect the actual performance of circuit breakers during earthquakes.

Hwang and Huo (1998) performed fragility analyses of equipment and structures in an electric substation in the eastern United States using substation 21 in Memphis. They used an analytical approach to perform fragility analyses of substation equipment such as Transformer Type I, Transformer Type II, Control House, Capacitor Bank, 12 KV Oil Circuit Breaker, FK 115 KV Oil Circuit Breaker, GM-5 115KV Oil Circuit Breaker, Lightning Arrester and Regulator. Here failure is defined as the state at which the component fails to perform its function. The capacity corresponding this damage state is then established. They determined the seismic response of structures and equipment by performing either a response spectral analysis or a static analysis. The site specific ground motions were generated by developing a seismic hazard curve in bedrock using probabilistic seismic hazard analysis. Peak Bedrock Acceleration (PBA) values corresponding to various annual probabilities of exceedance were determined from the seismic hazard curve. A probability based scenario earthquake in terms of hazard consistent magnitude and hazard consistent distance was then established for each PBA value. The uncertainties in seismic response and capacity were quantified and the probability of failure determined. The fragility curves were developed from the probabilities of failure corresponding to various level of ground shaking. From the study it is seen that some components such as 115/12 KV Transformers are very vulnerable to earthquakes even with moderate magnitude.

Oikama *et al.* (2001) conducted a study on the seismic capacity of electrical equipment in substations and transmission towers using damage records from the Kobe earthquake. Damage was found mostly in equipment manufactured before a revision of seismic design guidelines in 1980. Seismic capacity of electrical equipment was evaluated separately for equipment manufactured before and after 1980. Failure modes for each equipment were classified into three damage classes: 1) cause for losing function 2) need of repairing for long use 3) minor damage not affecting long use. The following steps were used to evaluate seismic capacity: 1) Determination of Peak ground Accelerations for each substation 2) the damage ratio for each type of equipment in each substation was calculated by dividing the number of damaged equipment by the total number of equipment of the same type in each substation. 3) Uncertainty due to randomness was determined by considering four factors: seismic ground motion, soil type, material property and ductility. The total uncertainty due to randomness, βr was calculated as 0.29 by using the Square Root of the Sum of the Squares method (SRSS) and this value was applied to all equipment. 4) Using the values of PGA, damage ratio and uncertainty due to randomness, median values of each type of electrical equipment in each substation was calculated by the following equation:

$$p = \varphi[Ln(A/M)/\beta r]$$

Where p is damage ratio, A is PGA, M is median capacity, and φ is standard normal cumulative distribution function. 5) Assuming the median capacities calculated in the previous step were log-normally distributed, the representative median values and its logarithmic standard deviation were calculated. 6) Then uncertainty was determined by the logarithmic standard deviation calculated in the previous step and engineering judgment. Median capacities and logarithmic standard deviations of electrical equipment manufactured before 1979 were calculated for higher than 187KV and lower than 187 KV. The study shows that seismic capacity of equipment for lower voltage class is larger than that for higher voltage class. Based on engineering judgment a multiplier factor 2 is used with the median capacity of equipment manufactured before 1979 in order to obtain the capacity for those manufactured after 1980. A fragility curve for circuit breaker (SF6) was developed and compared with a fragility curve evaluated by Ang *et al* (1996). The median capacity of circuit breaker manufactured before 1979 evaluated in this study was about half of that estimated by Ang *et al.* in USA. However, the median capacity of circuit breaker manufactured after 1980 was almost the same as that in USA.

Singhal and Bouabid (1995) presented a methodology for the seismic risk assessment of electric power systems. They used fragility curves and restoration functions in evaluating damage and loss of functionality of electric power components. Fragility curves and restoration functions are extracted from the GIS-based regional loss estimation methodology developed for the United States. In the loss estimation methodology four damage states are defined: minor, moderate, extensive and complete. Each of these damage states describes the level of physical damage sustained by the substation and is defined in terms of the percentage of subcomponents being damaged. The functionality of substations is evaluated by combining the probabilities of different damage states with restoration function. Component damage during the Northridge earthquake was used to benchmark the methodology.

Eidinger (1995) examined the performance of several types of high voltage substation equipment in past earthquakes. A survey of damage to substation electrical equipment was made of the following earthquakes: Kern County (1952), San Fernando (1971), Managua (1972), Morgan Hill (1984), Palm Springs (1986), San Salvador (1986), Whittier Narrows (1987), Tejon Ranch (1988), Saguenay (1988), Loma Prieta (1989), Guam (1992), Landers (1992) and Northridge (1994). This data is then developed into a tool for analyzing the performance of different type of equipment. The data has been plotted in such a way that each point represents the damage rate for a particular type of equipment at a particular substation, in a particular earthquake. Based on the empirical data, fragility curves are developed for different types of substation equipment. The fragility is described as a two parameter lognormal model. The median point where 50% of all similar components would be functionally damaged, expressed in terms of peak ground acceleration and the beta is the lognormal standard deviation. Beta represents the uncertainty in the equipment type, uncertainty in equipment performance and randomness in the ground motion to some extent. These fragility curves are considered only suitable for first-order estimation of possible damage at a particular substation. From the data set it is observed that: 500 KV class of equipment is more vulnerable than 230 KV class of equipment, live tank circuit breakers are very vulnerable to earthquakes, dead tank circuit breaker have a100% functional success record in past earthquakes, anchored transformed have performed much better than unanchored transformers, Disconnect switches are very vulnerable, specially in the 500 KV class.

Matsuda, *et al.* (1991) studied the vulnerability of various types of electric equipment in the event of earthquakes. They have developed and applied a methodology to analyze earthquake impacts on Pacific Gas and Electric Company's (PG&E's) high voltage electric distribution network in central and northern California. The four key elements of this seismic vulnerability analysis are: (1) identify high probability, large magnitude future earthquakes, called scenario earthquakes, (2) select and rank the substations according to their exposure to the scenario earthquakes and their importance to the system. Site specific ground motions and geotechnical effects (including site amplification and liquefaction) are assessed for each selected substation site, (3) the type and amount of damage expected at various levels of seismic ground motion are assessed for different types and models of substation equipment, based largely on performance records of similar equipment in past earthquakes, (4) for each scenario earthquake, the system damage and post- earthquake system status is predicted. The methodology they developed was tested and verified during the Loma Prieta earthquake. The Loma Prieta earthquake confirmed the validity of many of the assumptions made in this study. As for example, this study assumed that local soil conditions have a significant influence on substation damage. Amplification of ground motion and the change in response spectra associated with site soil conditions played an important in the damage level of substation equipment during Loma Prieta earthquake. The study assumed that dead tank and bulk oil circuit breaker would not be damaged. Accordingly, no dead tank or bulk oil circuit breaker was damaged during the Loma Prieta earthquake. Some live tank circuit breakers were estimated to be vulnerable and all of these breakers were destroyed at an estimated ground acceleration of 0.20 g. The study also assumed that most of the damage would occur to 500 KV substation equipment, little damage would occur to 115 KV substations and no damage would occur to control room equipment. Loma Prieta earthquake damage occurred according to the assumptions of the study.

Chapter 3

Study Area, Data Collection and Methods

3.1 Study Area

Electric substations operated by Hydro- Quebec in the province of Quebec were selected for this study. Hydro- Quebec has divided Quebec into three main territories: East, South and West. The total number of substations in Hydro-Quebec network is 512. The number of substations according to voltage and length of transmission lines are presented in Table 3.1. One hundred and thirty three electric substations located in the above territories were selected for this study. These substations are classified according to electric voltage 735kV, 315kV, 230kV, 120kV and 69kV substations. The transmission system map is illustrated in Figure: 3.1. According to peak horizontal ground accelerations of NBCC 1995 it is observed that some parts of Quebec have significant earthquake exposure. On the basis of peak horizontal ground accelerations and seismic exposure Quebec was divided into six different zones (Table: 3.2).

Voltage	Substations	Lines (Km)
735 KV	37	11,280
450 KV (DC)	2	1,218
315 KV	59	4,940
230 KV	48	3,081
161 KV	39	1,788
120 KV	221	6,581
49 KV and 69 KV	106	3,339
Total	512	32,227

Table 3.1: The Transmission System of Hydro-Quebec (Hydro-Quebec, 2000)

Zone	Area	Acceleration On rock	Seismic Exposure	Threat
0	Canadian shield	0-0.04g	0.05	Weak
1	Montagnais	0.04g-0.08g	0.25	Weak
2	Arnaud	0.08g-0.11g	0.4	Moderate
3	Repentigny, Lanaudiere, Becancour, Carignan, Vercheres, Saint-Cesaire	0.11g-0.16g	0.55	Moderate
4	Montreal, Laval, Longueuil, La prairie, Chateauguay, Huntingdon, Quebec	0.16g-0.23g	0.7	Serious
5	Charlevoix, Kamouraska, Saguenay	0.23g-0.32g	0.9	Significant
6	Center of Charlevoix, Kamouraska, La Malbaie, Riviere-du-Loup	0.32g-0.70g	1	Very significant

Table 3.2: Seismic Level of Exposure of the Substations at Different Zones (Hydro Quebec)

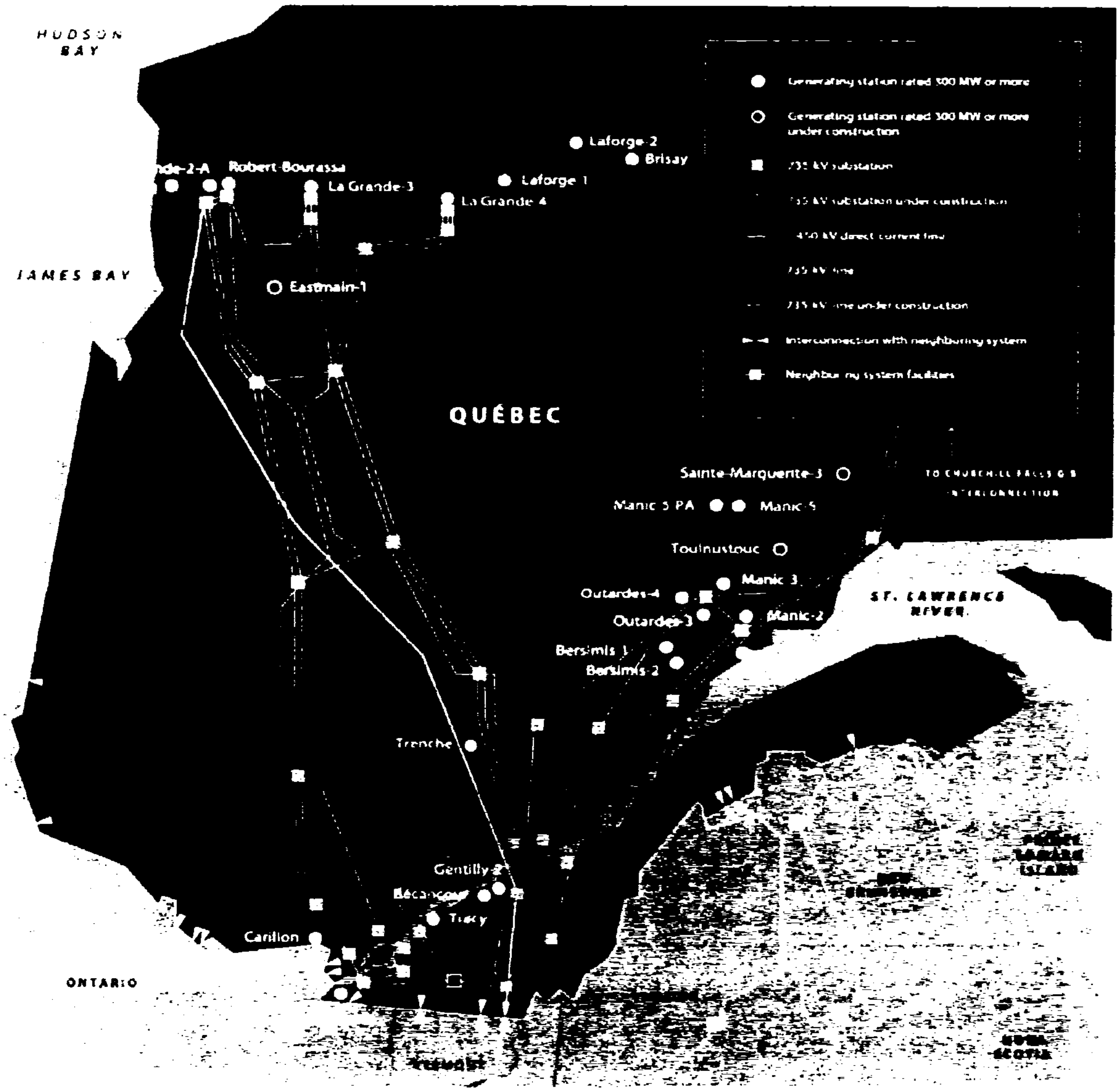


Figure 3.1: Transmission System Map of Hydro-Quebec (Hydro-Quebec, 2003)

3.2 Electric Substations and Their Layout

3.2.1 What is a Substation?

A substation plays an important role for the control and protection of a transmission and distribution network. It serves as a source of energy supply for the local distribution area in which it is placed. Substations are used for voltage transformation, connection point for local networks, and monitoring point for control center. Normally equipment of substations are installed outdoors. The substation equipment includes circuit breakers, disconnectors, transformers, current transformers, voltage transformers, surge arresters, busbars, other connections, supporting structures and insulators (Figure 3.2). A circuit breaker is capable of making, carrying and breaking current under normal circuit conditions. It is also capable of breaking currents under abnormal circuit conditions such that in case of a short circuit. The function of a disconnector is to isolate a circuit for maintenance. It is capable of opening and closing a circuit when negligible current is broken or made.

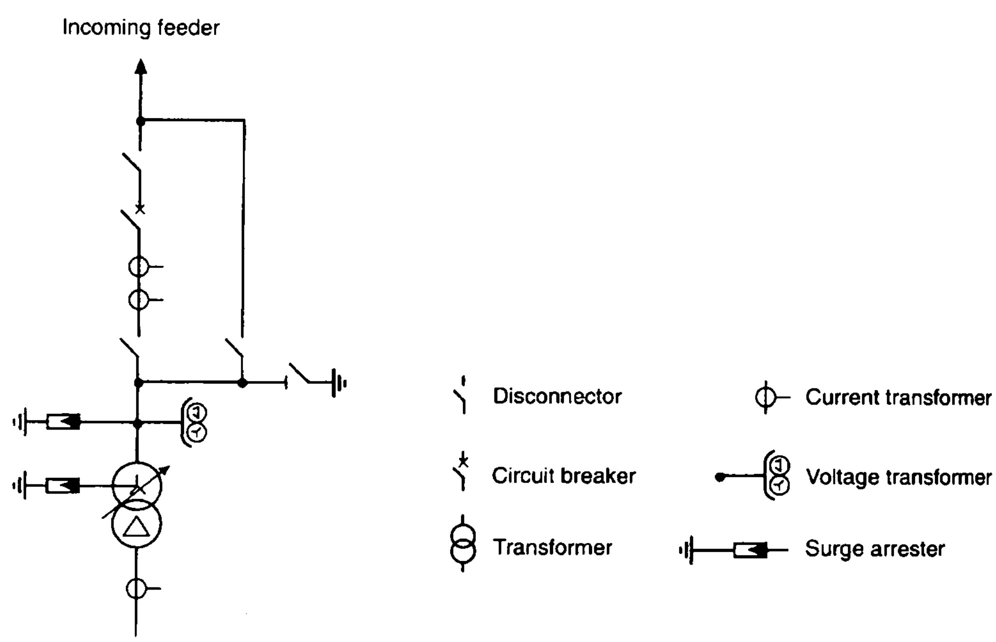


Figure 3.2: Schematic Diagram of Substation Components
(Lakervi and Holmes, 1995)

Busbars are used to interconnect circuits. All of the above components should be coordinated properly to provide a suitable substation arrangement. Lakervi and Holmes (1995) have described the layout and components of a substation. Figure 3.3 shows the layout of a typical single 110/20 KV substation. In front of the transformer there is only a disconnecting switch and a circuit breaker with current transformers. For servicing the110 KV circuit breaker, a bypass facility is provided without disconnecting the transformer.

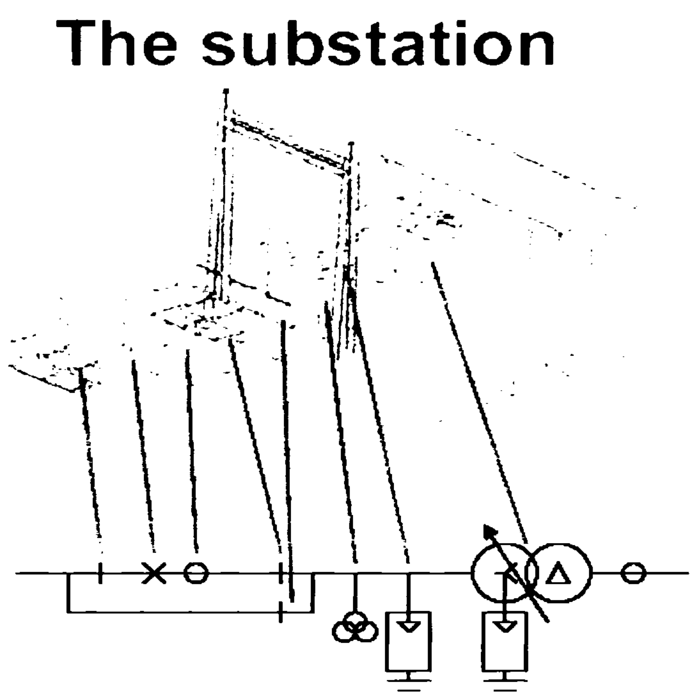


Figure 3.3: Layout of a Simple One-Transformer Substation
(Lakervi and Holmes, 1995)

3.2.2 Single Busbar Substations

Lakervi and Holmes (1995), describe the single busbar and double busbar arrangement as follows. In single busbar arrangements, a number of incoming medium voltage feeders are bussed together with local HV/MV transformers (Figure: 3.4). For the arrangement of Figure 3.4a, a circuit or transformer has to be taken out of service to carry out maintenance of associated breakers. A bus bar fault causes all circuit breakers to trip thus isolating the switchboard. Figure 3.4b shows the addition of a bus-section circuit breaker

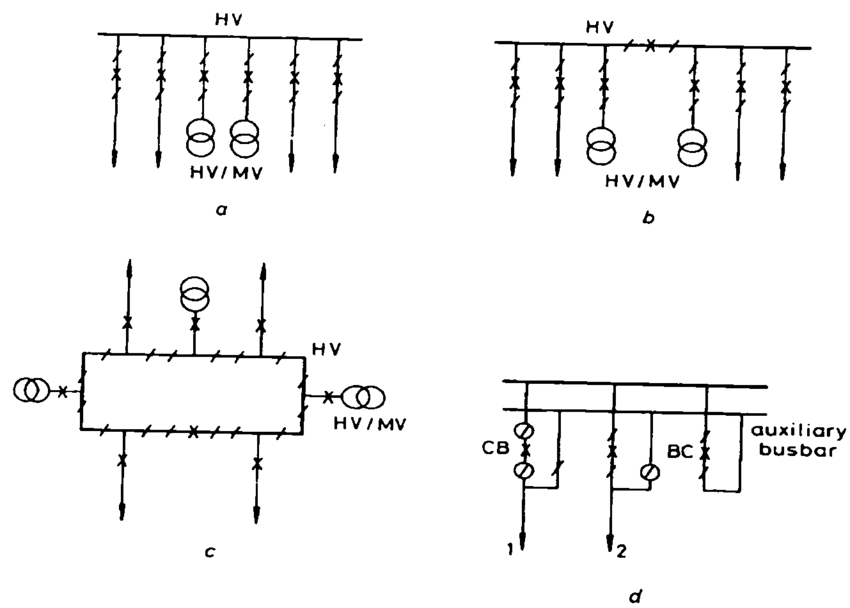


Figure 3.4: Single Bus-bar Arrangement (Lakervi and Holmes, 1995)

That leads to the loss of one half of the circuits connected to the substation when a busbar fault occurs. The arrangement of ring busbar is shown in Figure 3.4c. Here additional busbar disconnectors are used to provide adequate electrical clearance. In this system, only one circuit breaker has to be taken out of service during maintenance. An auxiliary transfer busbar and a bus-coupler circuit breaker is provided with the original single bus-bar in Figure 3.4d. Routine maintenance or repair of circuit breakers can be done after fault clearance with the circuit still in operation.

3.2.3 Double Busbar Substations

Figure 3.5a shows the two busbars arrangement in which each circuit can be selected to either busbar. In this arrangement, one busbar can be made free for maintenance by selecting all the circuits in the other busbar. Addition of a bus-coupler circuit is shown in Figure 3.5b that permits load.

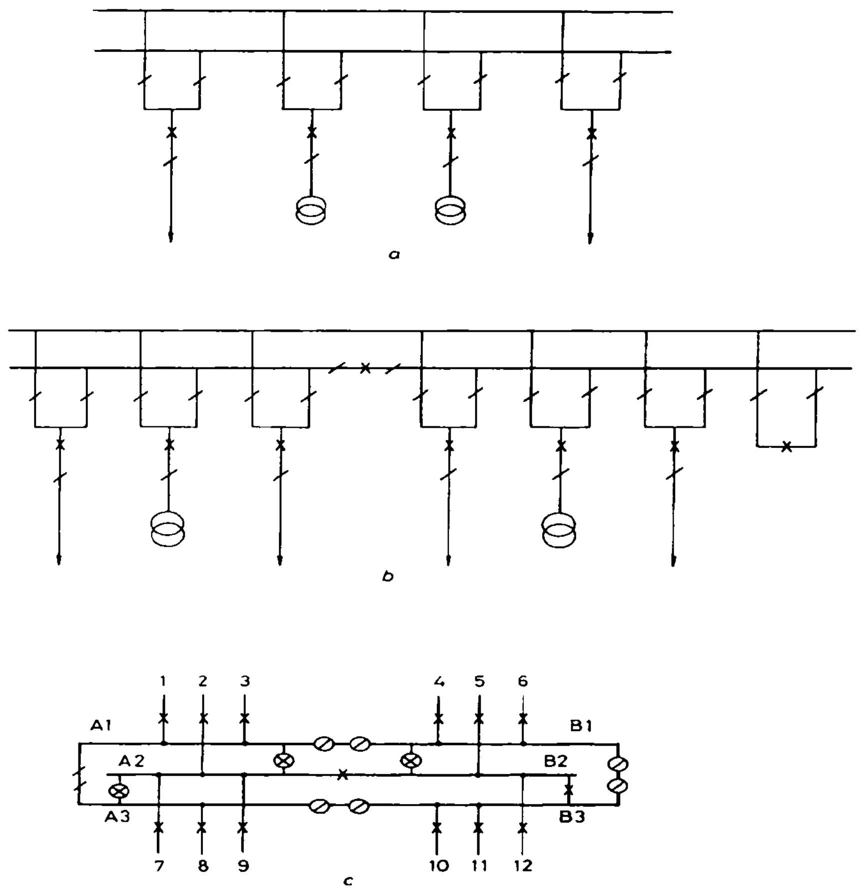


Figure 3.5: Double Bus-bar Arrangement (Lakervi and Holmes, 1995)

transfer of a circuit from one busbar to the other. The arrangement shown in Figure 3.5c is used for a wide variety of systems operation. In this arrangement 12 circuits are connected with six sections of busbar. Sometimes two circuits from the same area are connected to different sections of a busbar to avoid power failure on busbar faults. Maintenance work on busbars can be performed without interruption of the power supply.

3.3 Hydro-Quebec Seismic Risk Index for Substations

The seismic risk of a substation during an earthquake is calculated as,

Risk = Vulnerability (V) X Consequences (C)................3.1

3.3.1 Vulnerability (V)

Vulnerability varies from 1 to 10. A value greater than 4 is considered critical. Vulnerability of a substation depends on the following parameters: geology of the site, topography of the site, liquefaction potential, year of manufacture of electrical equipments, sensitivity of equipment to lateral forces, anchoring of heavy equipment, type of foundation for heavy equipment, steel cross bracing, High tension wire layout, year of design of the building, load bearing structure of the building, control systems, stability and operability of emergency generator, redundancy of protection system, and protection and auxiliary relays. Vulnerability of a substation is calculated according to following equation:

$$\text{Vulnerability} = \text{Seismic Exposure} \times \frac{\sum c \times W.F}{\sum W.F} \quad \ldots\ldots\ldots\ldots\ldots 3.2$$

Where,

c = value of each parameter according to different condition

WF = Weighting factor

The seismic exposure is obtained from Table: 3.2. Values of c and WF for different parameters are obtained from Table 3.3 to Table 3.5. Each parameter has different weighting factors (WF). Weighting factors were developed by considering:

1) History of damage of power transformers during the Long Beach (1933), San Fernando (1991), Saguenay (1988), Loma Prieta (1989), Northridge (1994), Kobe (1995), Izmit (1999) and Bhuj (2001) earthquakes

2) Overturning of control panel inside the control building

3) Old equipment with ceramic supports not been designed to modern earthquake standards

4) Soft soil amplification during earthquakes.

Parameters	**Different Conditions**	**c**	**W.F**
Geology of the site	Rock/dense or compact ground with coarse grains; firm and consistent ground with fine grains, of depth =< 15 m	1	4
	Not very deep ground of characteristic intermediary enters coast 1 and coast 5	2.5	
	Compact ground with coarse grains > 15m/not very dense ground with coarse grains, ground furnishes with fine grains, soft clay < 15m	5	
	Not very dense ground with coarse grains, soft ground with fine grains > 15m	7.5	
	Movable and very movable ground with fine grains or soft clay > 15 m	10	
Topography of the site	Installation in flat ground	1	
	Valley steep sided/or with hillside	5	
	Installation on a ridge	7.5	
	Installation on a very marked ridge	10	
Liquefaction Potential	Rock, clay	1	3
	Weak if N > 30 and or Dr. > 90 %:/	2.5	
	Gray zone: 30> N>20, to refer being studied specific of liquefaction of the site,	5	
	Raised if N < 20 and or Dr. < 33 %/and or size particles between 0.07 mm and 0.6 mm	10	
Year of manufacture of the equipment	1987 - 2000 (3 rd generation)	1	5
	1976 - 1986 (2 nd generation)	5	
	1957 - 1975 (1st generation)	10	
Sensityvity of equipment to lateral forces	Equipment 69 KV	1	3
	120- 161 KV conventional/or 230 KV SF6	5	
	230 KV conventional/or 315 KV SF6	7.5	
	315- 735 KV conventional	10	
Anchoring of heavy equipment	Adequate anchoring for all heavy equipment	1	5
	Approximately 75 % of the heavy equipment are anchored	2.5	
	Approximately 50 % of the equipment are anchored/or part of the equipment are anchored and another are on rails with elements of blocking	5	
	Approximately 25 % equipment are anchored/or all the equipment are on rails with elements of blocking	7.5	
	Anchoring non-existent for all the equipment/or all the equipment are on rails without elements of blocking	10	

Table 3.3: c and WF of geology of the site, topography of the site, liquefaction potential, year of manufacture of electrical equipment, sensitivity of equipment to lateral forces, and anchoring of heavy equipment (Hydro-Quebec, 2001)

Parameters	Different Conditions	c	W.F
Type of foundation for heavy equipment	The foundations of heavy equipment are not conventional but monolithique concrete base or bottom rest on piles with reaction at a peak, connected at the head.	1	2
	Part of the heavy equipment of the installation is placed on conventional monolithic bases and the other on somewhat narrow bases compared to their bearing surfaces (tank)	2.5	
	Part of the equipment is on conventional bases and the other on low walls.	5	
	Part of the equipment installed on low walls and the other on narrow bases on flexible piles, or not armed or floating	7.5	
	The whole of the equipment is installed on low walls/or the unit is on piles standard floating either of behavior or resistance doubtful.	10	
Steel cross bracing	Out of shaped lattices or (bolted), /Frame standardized or equivalent/generally in good condition	1	2
	Out of shaped lattices or (welded)/Out of reinforced or prefabricated concrete.	5	
	One of these preceding types in bad conditions: corroded or deformed	7.5	
	One of the preceding types, not out of lattices (section) very slim and not or badly braced (315 KV and more)	10	
High tension wire layout	The whole of the sets of overhead cables of various tensions is posed without possibility of crossing (for example in a parallel way)	1	2
	The crossings of the sets of overhead cables of various tensions are very few/or the crossing are numerous and the clamps of anchoring are posed since 1975.	2.5	
	The crossing of sets of overhead cables are many /or crossing of some cables installed on braced frameworks, with clamps of anchoring of doubtful quality or installed before 1975	5	
	Crossing of sets of rather many cables/or crossing of some drivers installed on braced frameworks, with clamps of anchoring of doubtful quality or installed before 1975	10	
Year of design of the building	1986 - 2000 (3rd generation: conform to the earthquake standards)	1	3.5
	1971 - 1985 (2nd generation)	5	
	1957 - 1970 (1st generation)	10	

Table 3.4: c and WF of type of foundation for heavy equipment, steel cross bracing, high-tension wire layout, year of design of the building (Hydro-Quebec, 2001)

Parameters	Different Conditions	c	W.F
Load bearing structure of the building	Metal structure adequately braced/ structure meet resistant to the moment/ prefabricated building conformity with the standards, anchored positively on adequate foundations or low walls/ the roof is heavy compared to the conventional	1	6
	Reinforced concrete frame resistant to the moment/combined structure of precast and prestressed concrete with anchoring and detail of adequate assembly/simple metal framework with wall of filling in masonry not armed, and braced with rigid elements/ roof or the floor is heavy compared to a conventional	2.5	
	Metallic framework braced by ties/masonry armed in the two directions/metal building with 1st flexible level/prefabricated building anchoring with friction/the roof or the floor is heavy compared to the conventional	5	
	Prefabricated concrete framework of non-adequate assembly, joint or anchoring (or not resistant to the moment)/badly anchored on non-adequate low walls / metal framework (simple, articulated) with not armed masonry wall filling/framework metal resistant with weakness or deficiencies in the joints/ or anchoring the roof or floor is defective	7.5	
	Load-bearing wall in not armed masonry/prefabricated building simply deposited on low walls	10	
Control point	Rigid panels with adequate anchoring	1	3
	Doubtful anchoring/anchoring with friction/or existing anchoring but the panel (structure) are flexible or of doubtful quality	5	
	Non-existent	10	
Stability and operability of emergency generator	Adequate anchoring and shelter/connection and reserve in good condition/periodic operational test is up to date	1	1
	Doubtful anchoring and doubtful operation	5	
	Non-existent of anchoring	10	
Redundancy of protection systems	Redundancy with physical separation of the components	1	1
	Redundancy without physical separation of the elements	5	
	Absence of redundancy	10	
Protection and auxiliary relays	1991 – 2000	1	1.5
	1971 - 1990	5	
	1957 - 1970	10	

Table 3.5: c and WF of load bearing structure of the building, control systems, stability and operability of emergency generator, redundancy of protection system, and protection and auxiliary relays (Hydro-Quebec, 2001)

3.3.2 Consequences of Damage (C)

The scale for consequences of damage varies from 1 to 10. The value of consequences depends on the strategic importance of the substations. Strategic importance is evaluated by considering the following factors:

1) Impact of loss of the substation on continuity of service

2) The cost of the substation

3) Time required to repair the substation if there is damage

4) Public and employee safety

5) Energy channeled through the substation

Consequences according to different range of strategic importance are presented in Table 3.6

Strategic Importance	**Value of Consequence**
Strategic importance < = 8	1
Strategic importance 9 @ 14	2.5
Strategic importance 15 @ 20	5
Strategic importance 21 @ 26	6.5
Strategic importance 27 @ 32	7.5
Strategic importance 33 @ 38	8.5
Strategic importance 39 @ 44	9
Strategic importance 45 @ 50	9.5
Strategic importance > 50	10

Table 3.6: Consequences According to Strategic Importance of Substations
(Hydro-Quebec, 2001)

Chapter 4

Statistical Analysis of Hydro-Quebec Data

4.1 Basic Statistics

Basic statistical analysis was performed with STATISTICA^{R}. The summary of values for all parameters is shown in Table 4.1. The mean value of vulnerability is 4.26, which is more than the critical level 4.0. The mean risk of all 133 substations is 27.75, which is in the range of moderate risk level. The mean values for all parameters are presented in Figure 4.1.

Parameter	Mean	Minimum	Maximum	Variance	St. Dev.	COV
Geology of the site	5.25	1.00	10.00	7.24	2.69	0.51
Topography of the site	2.03	1.00	10.00	4.49	2.12	1.04
Liquefaction potential	2.77	1.00	10.00	6.68	2.59	0.93
Year of manufacture of equipment	6.39	1.00	10.00	9.32	3.05	0.48
Sensitivity to lateral forces	6.40	1.00	10.00	11.06	3.33	0.52
Anchoring of heavy equipment	9.32	1.00	10.00	4.71	2.17	0.23
Type of foundation for heavy equipment	2.72	1.00	10.00	5.73	2.39	0.88
Steel cross bracing	2.13	1.00	10.00	5.47	2.34	1.10
High tension wire layout	3.43	1.00	10.00	7.47	2.73	0.78
Year of design of the building	6.17	1.00	10.00	10.25	3.20	0.52
Load bearing structure of the building	7.27	1.00	10.00	8.18	2.86	0.39
Control systems	7.79	1.00	10.00	9.94	3.15	0.40
Stability and operability of emergency generator	1.26	1.00	10.00	2.01	1.42	1.12
Redundancy of protection systems	6.27	1.00	10.00	11.99	3.46	0.55
Protection and auxiliary relays	5.71	1.00	10.00	7.20	2.68	0.47
Vulnerability (V)	4.27	1.16	7.57	1.00	1.00	0.23
Consequence (C)	6.48	1.00	10.00	4.33	2.08	0.32
Risk	27.76	3.11	55.59	122.99	11.09	0.40

Table 4.1: Basic Statistics of All Substation Parameters

From Figure 4.2 we can see that 40% of the substations in Quebec are located on compact soils with large particles thicker than 15 meter, or on semi-compact soils with large particles or soft soil with fine particles or soft clay less than 15-meter thick.

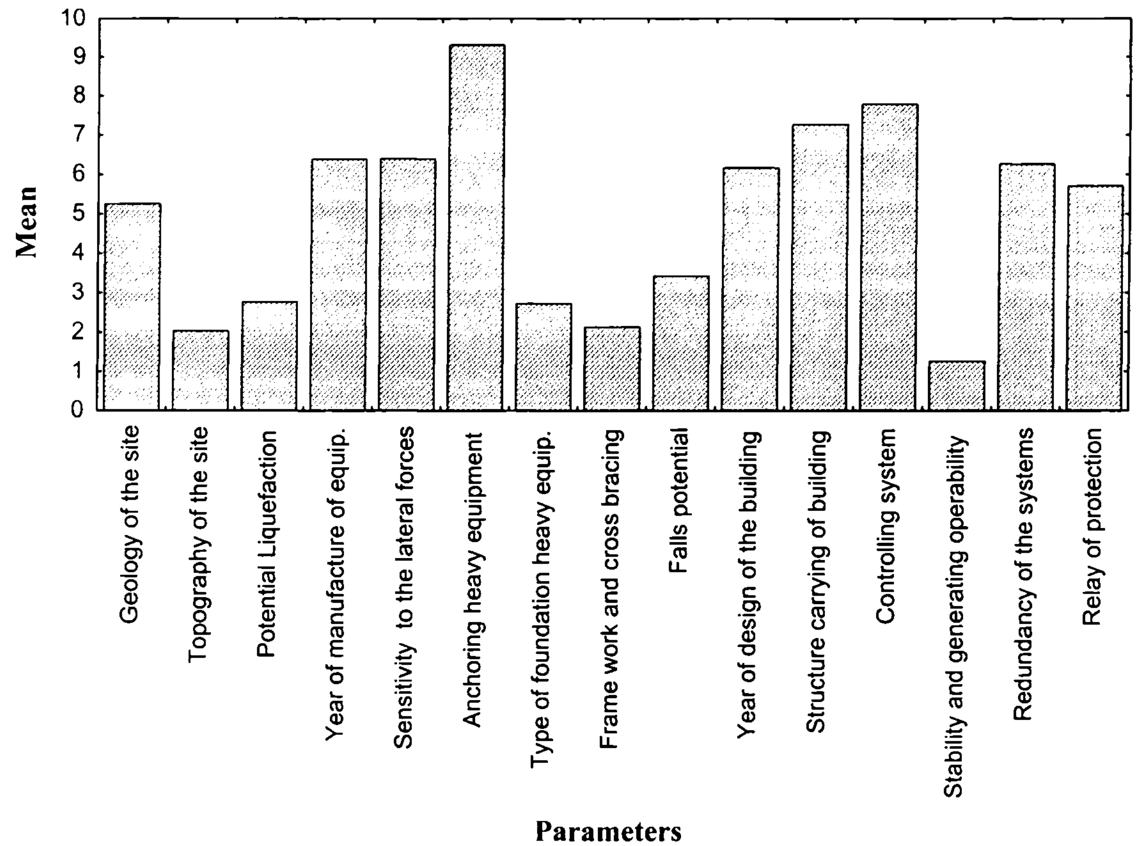


Figure 4.1: Mean Dimension of Different Parameters

Next, 17% of the substations are located on semi-compact soils with large particles on soft soil with fine particles thicker than 15 meter. Next, 16.5% of the substations are located on loose to very loose soils with fine particles thicker than 15 meter. The latter type of soil is most at risk during earthquakes. We can also note that 90% of substations lack proper anchoring of equipment. Unanchored equipment is very vulnerable to ground shaking. The structure of the substation building is an important parameter in the risk index. Control panels are located inside the building and damage to the building is likely to result in a power outage. The survey indicates that 52% of the substation buildings are masonry structures. This type of structure is very vulnerable to earthquakes since load bearing walls are unreinforced and made of hollow clay bricks resting on low foundation walls. Only 10% of the buildings are steel structures that are adequately braced and anchored to their foundations. The latter type of building has the highest earthquake resistant capacity.

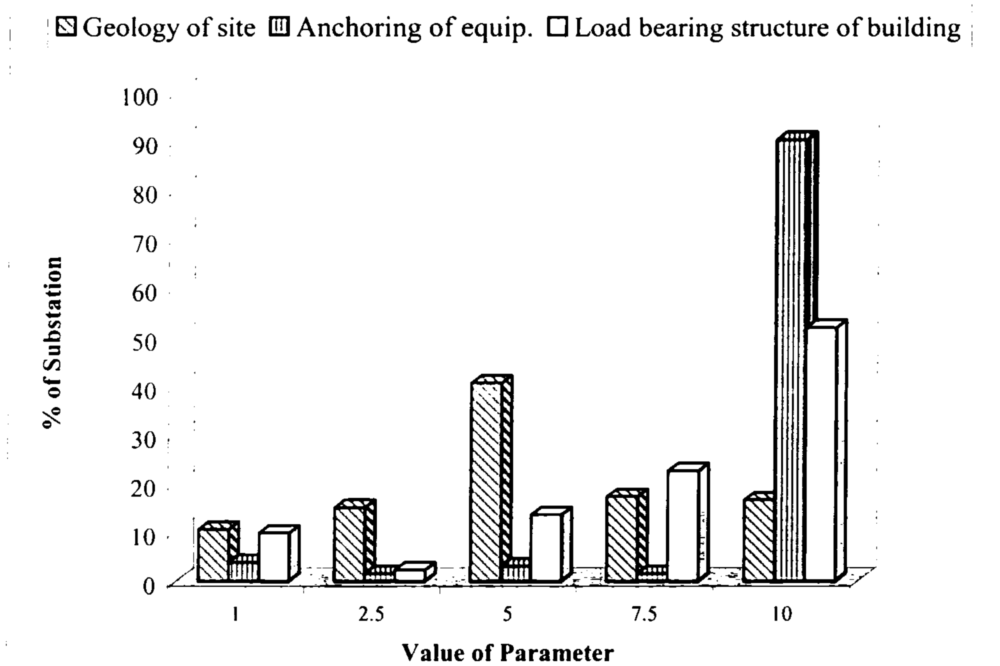


Figure 4.2: Histograms of Parameter for Geology of the Site, Anchoring of Equip, and Load Bearing Structure of Building

Old equipment not designed to current earthquake standards is very vulnerable. Figure 4.3 shows that equipment in 42% of the substations was manufactured between1957 and 1975. In 45% of the substations equipment was made between 1976 and 1986. Equipment was manufactured after 1987 and designed following current earthquake standards in only 13% of the substations. Figure 4.3 shows that 48% of substation buildings were designed during the period from1971to 1985. Only 16% of substation buildings were designed after 1986 using modern earthquake standards. The remaining substation buildings were designed before 1970 without considering earthquake standards and are very vulnerable. In almost 70% of substations, the control panels are not anchored. Anchorage is deficient for 19% of the stations and anchorage is adequate for 11% of the stations.

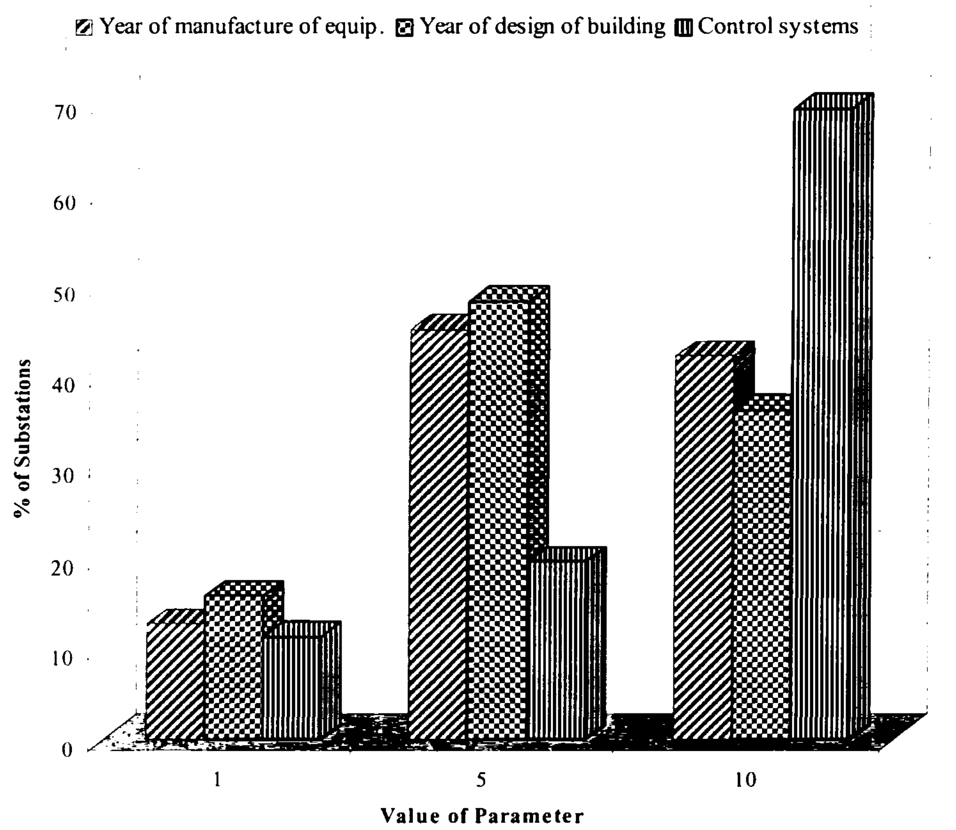


Figure 4.3: Histograms of Parameters for Year of manufacture of Equip, Year of Design of Building and Control Systems

4.2 Contribution of Parameters to the Vulnerability Index

The relative importance of different parameters to the vulnerability index is presented in Table 4.2. The minimum, mean, and maximum contributions of parameters for the 133 substations to the vulnerability index are shown in Figure 4.4. Anchoring of heavy equipment is the most important deficiency for substations. The other important deficiencies are the load bearing structure of the building, year of manufacture of equipment, control systems, geology of the site, year of design of substation building and sensitivity of equipment to lateral forces. Higher voltage substations are more vulnerable due to sensitivity of equipment to lateral forces than the lower voltage substations.

Parameter	Mean Contribution In (%)	Minimum	Maximum	Variance	St. Dev.	COV
Geology of the site	8.56	1.44	23.19	19.73	4.44	0.52
Topography of the site	1.29	0.44	10.87	2.17	1.47	1.14
Liquefaction potential	3.39	0.88	14.42	9.56	3.09	0.91
Year of manufacture of equipment	12.32	2.09	24.04	28.02	5.29	0.43
Sensitivity to lateral forces	7.90	0.93	31.25	22.66	4.76	0.60
Anchoring of heavy equipment	18.87	2.68	43.29	33.38	5.78	0.31
Type of foundation for heavy equipment	2.18	0.60	13.27	3.88	1.97	0.90
Steel cross bracing	1.64	0.61	7.19	2.40	1.55	0.94
High tension wire layout	2.62	0.64	9.59	3.33	1.82	0.70
Year of design of the building	8.17	1.39	14.94	12.46	3.53	0.43
Load bearing structure of the building	16.98	2.73	32.17	38.85	6.23	0.37
Control systems	9.58	1.02	26.79	19.84	4.45	0.46
Stability and operability of emergency generator	0.53	0.29	4.16	0.33	0.57	1.08
Redundancy of protection systems	2.65	0.00	8.93	3.31	1.82	0.69
Protection and auxiliary relays	3.33	0.59	7.21	1.98	1.41	0.42

Table 4.2: Statistics of Contribution of Different Parameters to Vulnerability

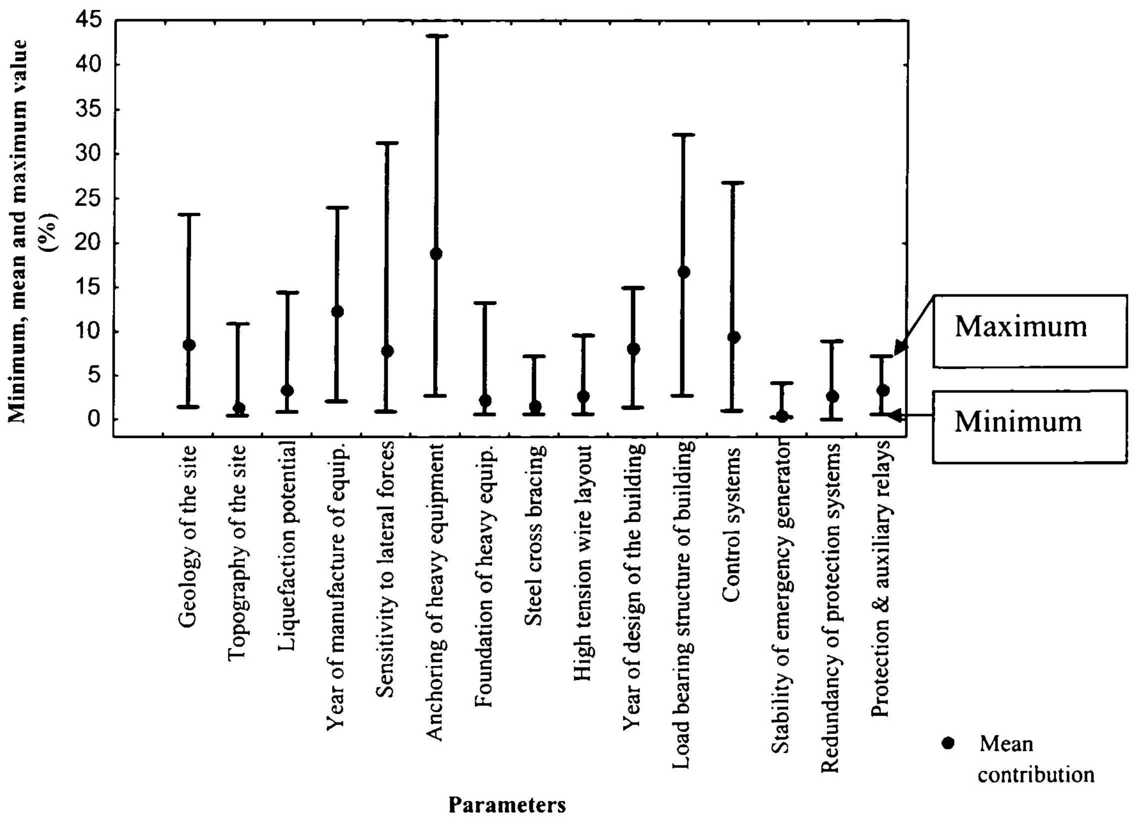


Figure 4.4: Contribution (%) of Parameters to Vulnerability Index

4.3 Correlation

Table 4.3 lists the correlation between vulnerability with different parameters for substations in Quebec. Topography, liquefaction potential, sensitivity of equipment to lateral forces, stability and operability of emergency generator, and redundancy of protection systems have low correlations with vulnerability. The load bearing structure of the substation building has the highest correlation with vulnerability. Year of design of the substation-building, year of manufacture of substation equipment and anchoring of substation equipment are all highly correlated with vulnerability.

Parameter	Vulnerability (V)
Geology of the site	0.23
Topography of the site	0.06
Liquefaction potential	0.02
Year of manufacture of equipment	0.49
Sensitivity to lateral forces	0.04
Anchoring of heavy equipment	0.42
Type of foundation for heavy equipment	0.13
Steel cross bracing	0.30
High tension wire layout	0.31
Year of design of the building	0.53
Load bearing structure of the building	0.62
Control systems	0.20
Stability and operability of emergency generator	-0.03
Redundancy of protection systems	0.03
Protection and auxiliary relays	0.32

Table 4.3: Correlations of Parameters with Vulnerability

Using data on vulnerability, consequences and risk for the 133 substations correlations between vulnerability and risk and correlation between consequences and risk were calculated (Figure 4.5 and Figure 4.6). Vulnerability has a correlation of 0.6 with risk and consequences has a correlation of 0.8 with risk. So consequences has a higher linear relationship with risk than vulnerability.

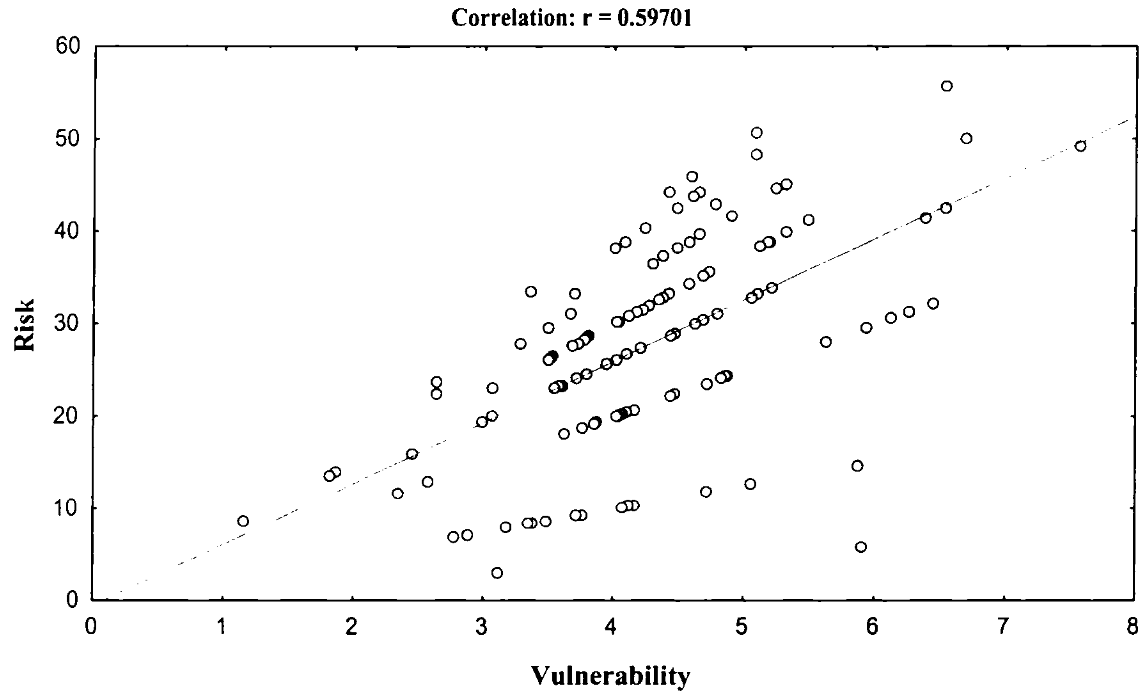


Figure 4.5: Correlation of Vulnerability with Risk

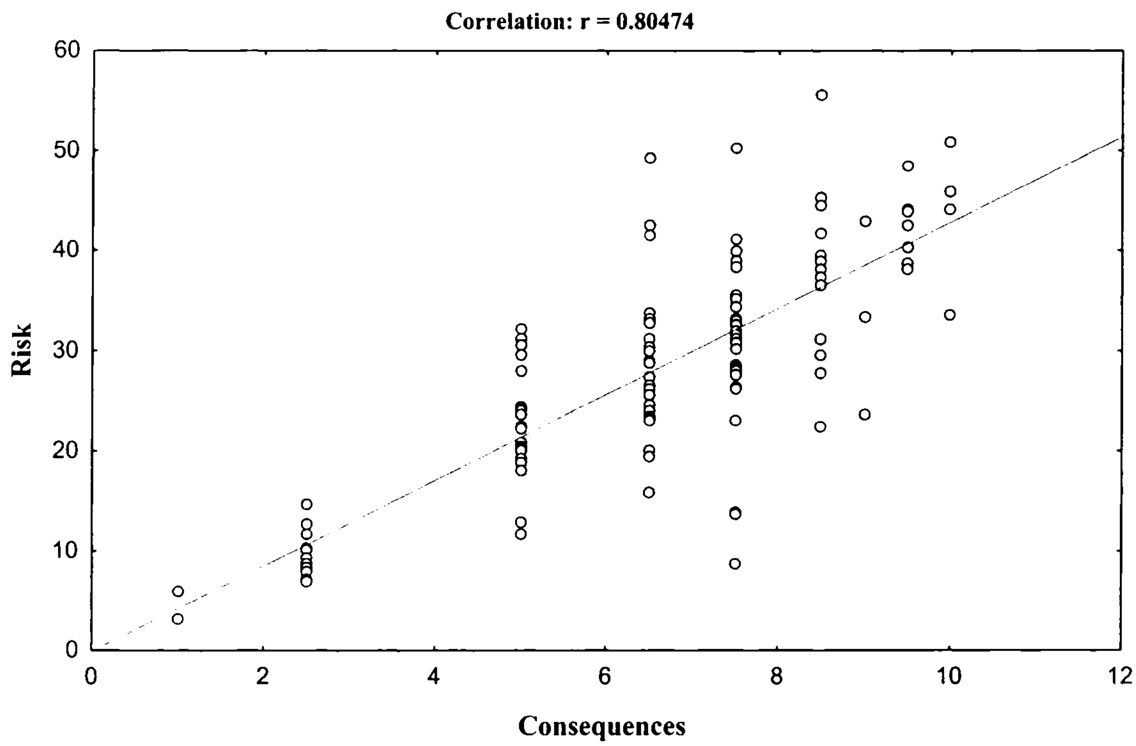


Figure 4.6: Correlation of Consequences with Risk

4.4 Distribution Analysis of Vulnerability and Risk

The Normal distribution of vulnerability for 133 substations is presented in Figure 4.7. The mean value of vulnerability is 4.26 and the standard deviation is 1.0. Using these mean value and standard deviation the probability of vulnerability having any value 0 to 10 can be calculated. The critical value of vulnerability is considered 4.0 and almost 70% substations have the vulnerability greater than the critical value.

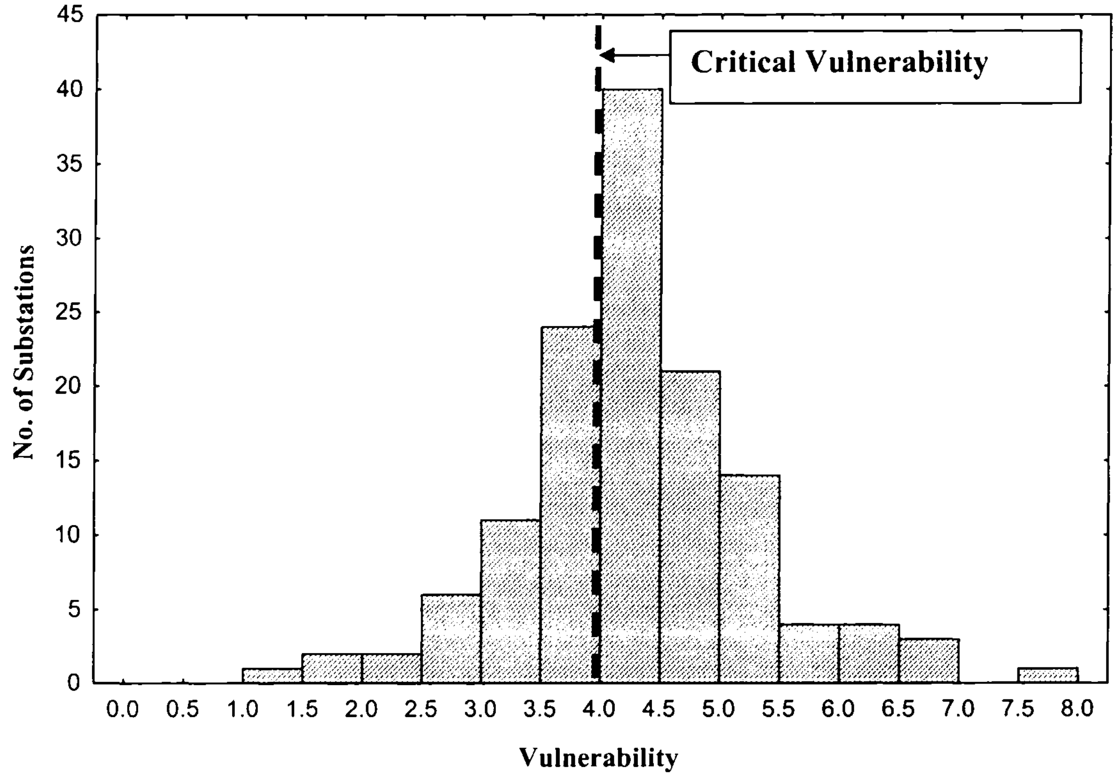


Figure 4.7: Probability Density Function of Vulnerability

Observed and expected frequency of risk of 133 substations has presented in Table 4.4. Cumulative distribution of risk is shown in Figure 4.8. It is observed from Figure 4.8 that 29 substations have negligible or no risk, 86 substations have moderate risk and 18 substations are in the high-risk level.

Risk	Observed Frequency	Cumulative Observed	Percent Observed	Expected Frequency	Cumulative Expected	Percent Expected
<= 4.00	1	1	0.75	2.14	2.14	1.61
8.00	4	5	3.00	2.84	4.97	2.13
12.00	11	16	8.27	5.35	10.33	4.03
16.00	6	22	4.51	8.89	19.22	6.68
20.00	7	29	5.26	12.98	32.20	9.76
24.00	19	48	14.28	16.66	48.86	12.52
28.00	16	64	12.03	18.80	67.66	14.13
32.00	24	88	18.04	18.65	86.31	14.02
36.00	15	103	11.28	16.27	102.59	12.23
40.00	12	115	9.02	12.48	115.07	9.38
44.00	8	123	6.01	8.42	123.49	6.33
48.00	5	128	3.76	4.99	128.48	3.75
52.00	4	132	3.01	2.60	131.08	1.95
< Infinity	1	133	0.75	1.91	133.00	1.44

Table 4.4: Observed and Expected Distribution of Risk

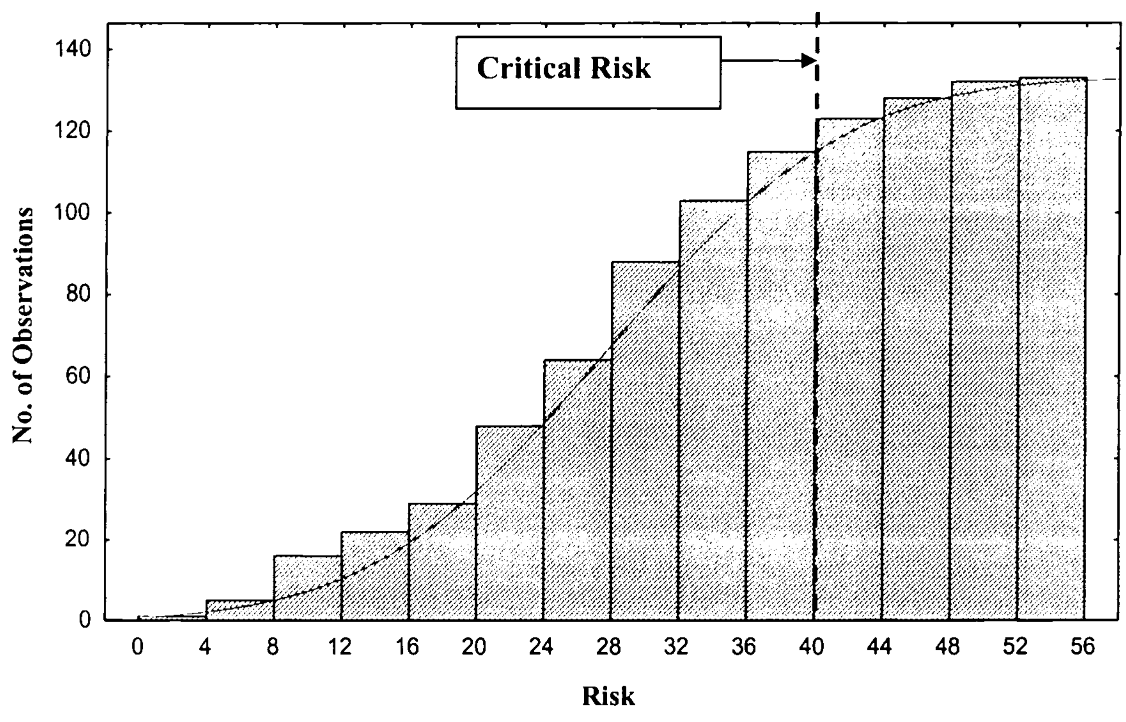


Figure 4.8: Cumulative Distribution of Risk of Different Substations

4.5 Critical Parameters and High Risk Substations

The four most critical parameters responsible for high vulnerability and high risk are: year of manufacture of equipment, anchoring of heavy equipment, load-bearing structure of the building and control systems. According to Hydro- Quebec 18 electric substations in Quebec fall in the high-risk category (Table 4.5).

Substation No.	Risk			
	From study	Value of all critical parameters=1	Value of all critical parameters=5	Value of all critical parameters=10
6	55.59	28.82	43.67	62.24
70	50.81	27.32	39.54	54.83
22	50.17	22.24	35.34	51.72
7	49.23	23.68	35.04	49.24
1	48.38	26.45	38.06	52.59
2	45.90	21.20	33.43	48.72
72	45.21	25.24	35.63	48.62
8	44.59	27.90	38.30	51.29
23	44.18	20.33	31.95	46.47
71	44.17	25.51	37.73	53.02
73	43.84	23.81	35.43	49.95
9	43.01	21.07	32.08	45.84
3	42.57	18.34	29.96	44.49
31	42.44	20.62	31.98	46.17
74	41.65	18.26	28.65	41.65
46	41.46	19.65	31.00	45.20
24	41.15	23.41	32.58	44.05
10	40.32	18.76	30.38	44.91

Table 4.5: High Risk Substations and Risk Level

Figure 4.9 shows the graphical representation of Table 4.5.It is observed from Figure 4.9 that when all 4 critical parameters are equal to 1 then all 18 high risk substations become moderate risk substations. If the values of all 4 critical parameters are equal to 5 then only one electric substation remains in high risk position. Figure 4.10 to Figure 4.13 show the sensitivity of 18 high-risk substations with different values of critical parameters.

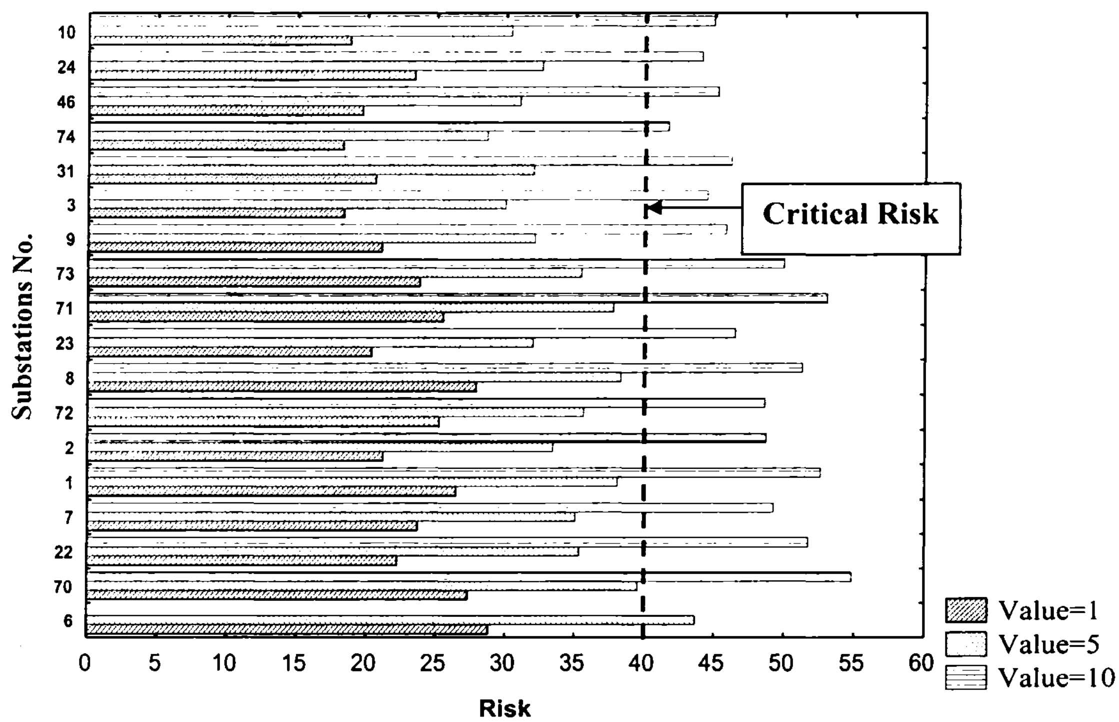


Figure 4.9: Risk Vs High Risk Substations for Different Values of all Critical Parameter

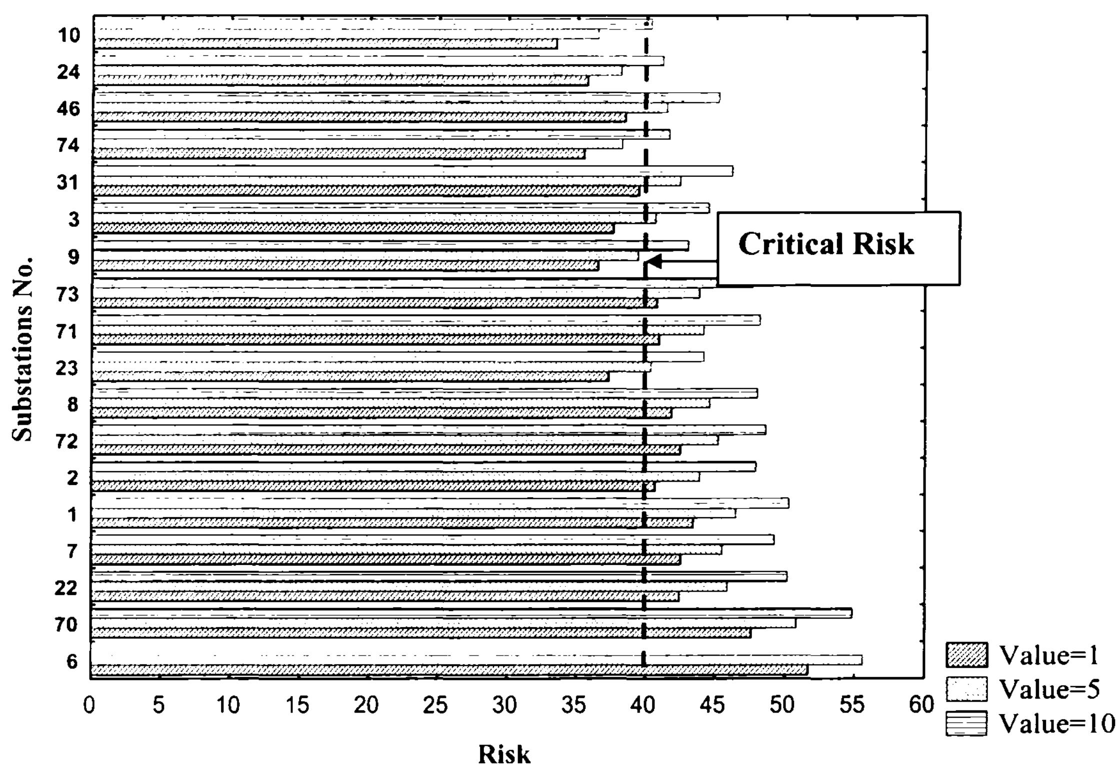


Figure 4.10: Risk Vs High Risk Substations for Different Values of Critical Parameter of Year of Manufacture of Equipment

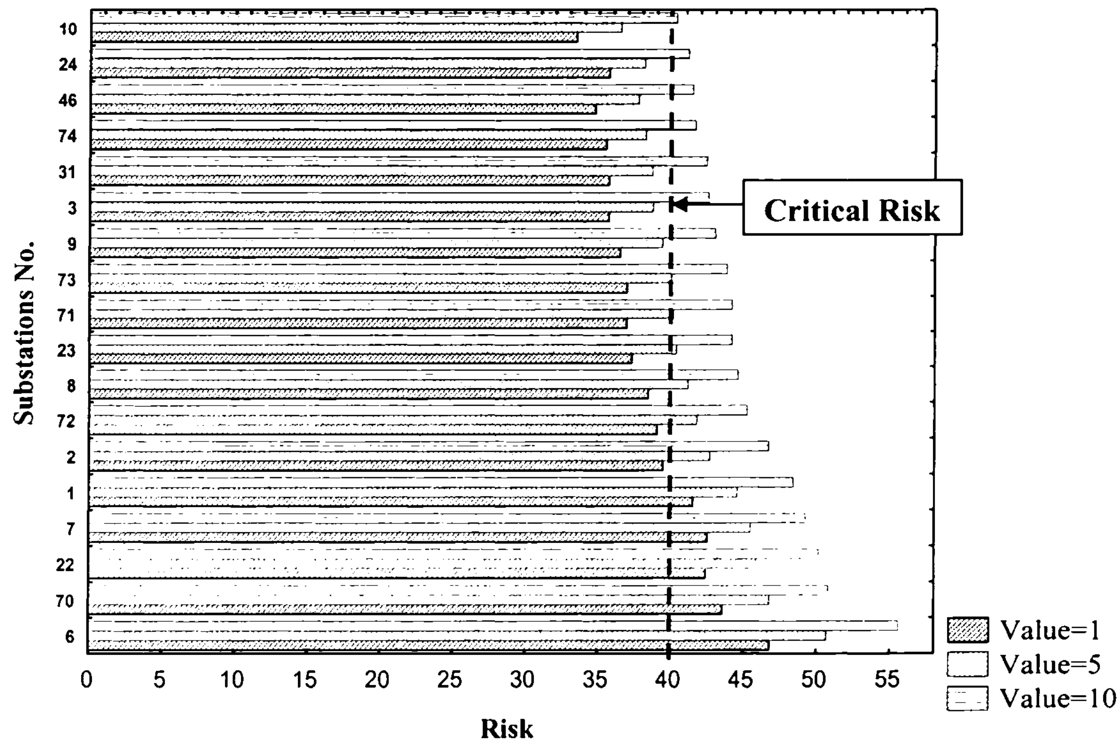


Figure 4.11: Risk Vs High Risk Substations for Different Values of Critical Parameter of Anchoring of Equipment

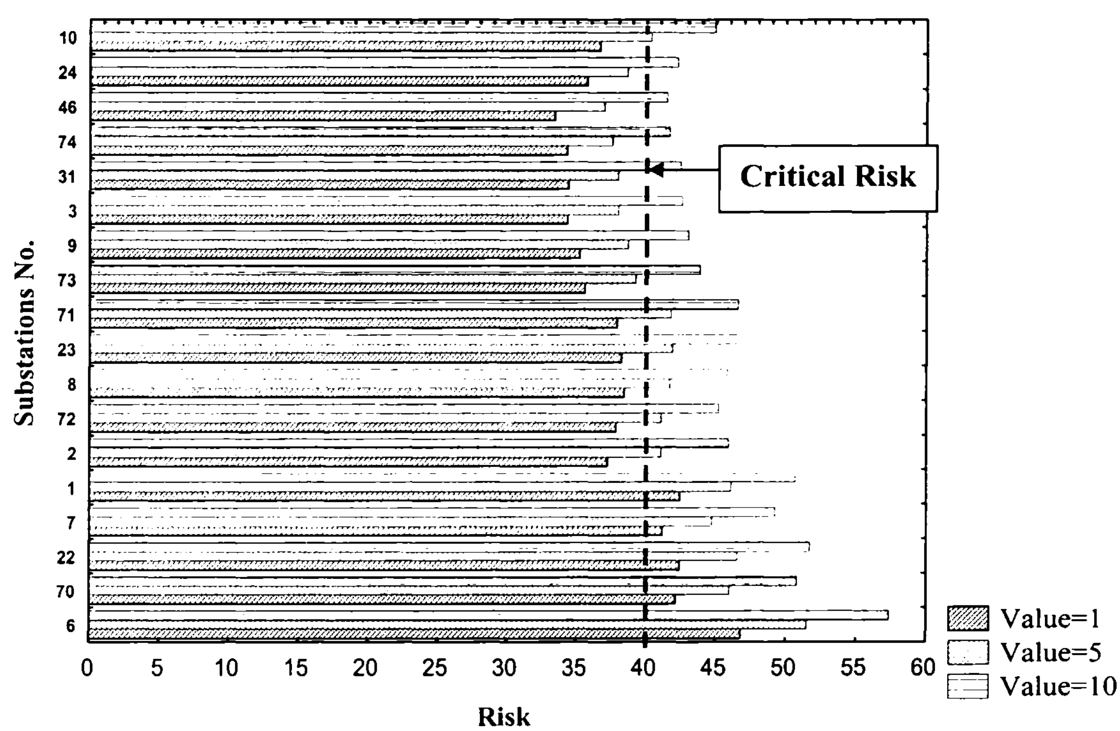


Figure 4.12: Risk Vs High Risk Substations for Different Values of Critical Parameter of Load Bearing Structure of the Building

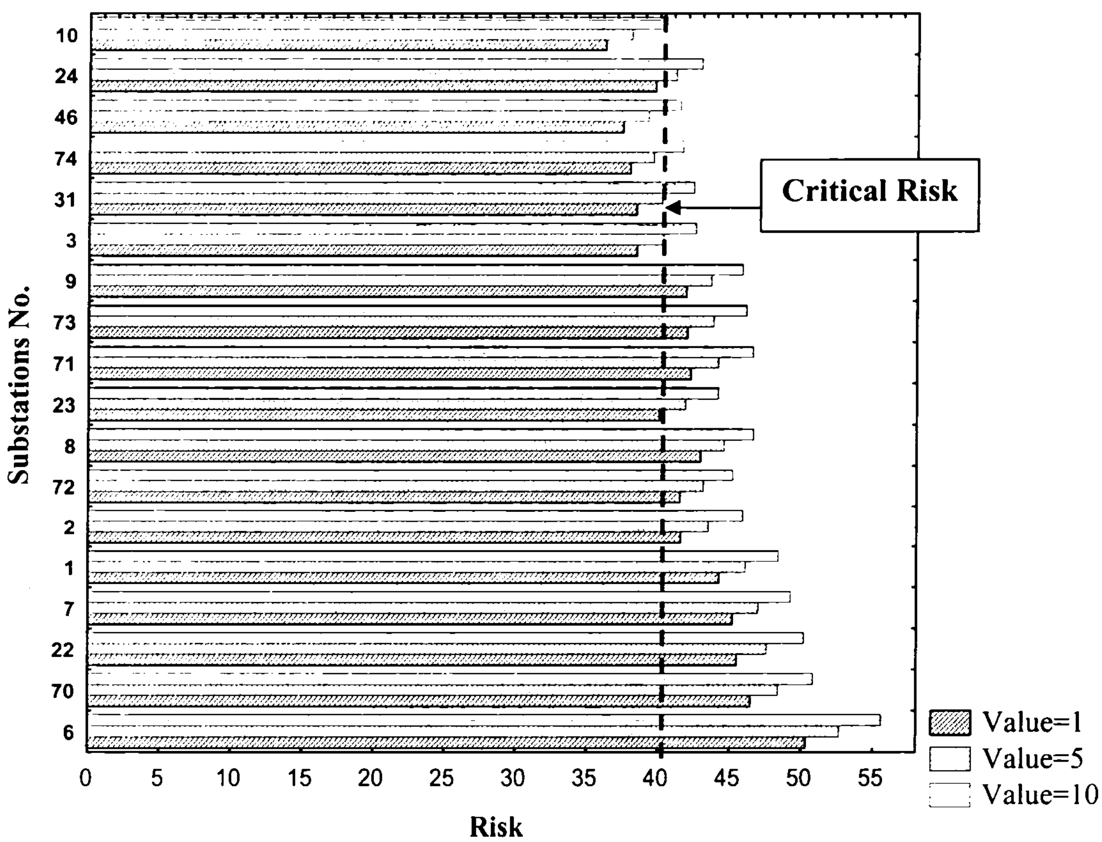


Figure 4.13: Risk Vs High Risk Substations for Different Values of Critical Parameter of Control Systems

4.6 Sensitivity of Weighting Factors

Figure 4.14 shows the number of substations at various risk levels for different weighting factors of geology of the site. It is observed that with an increase in the value of the weighting factor the numbers of high-risk substations decreases. When weighting factor is 1, the number of high-risk substations is 21 and when weighting factor is 10, the number of high-risk substations becomes 15. Figure 4.15 compares the % of substations at different risk levels for different geology weighting factors. Risk levels 0 to 20 are negligible or weak risk, 20 to 40 are moderate risk and more than 40 are high-risk substations. Almost 16 % substations are at a high risk level when soil weighting factor is 1, compared to 13.5% from the Hydro-Quebec study.

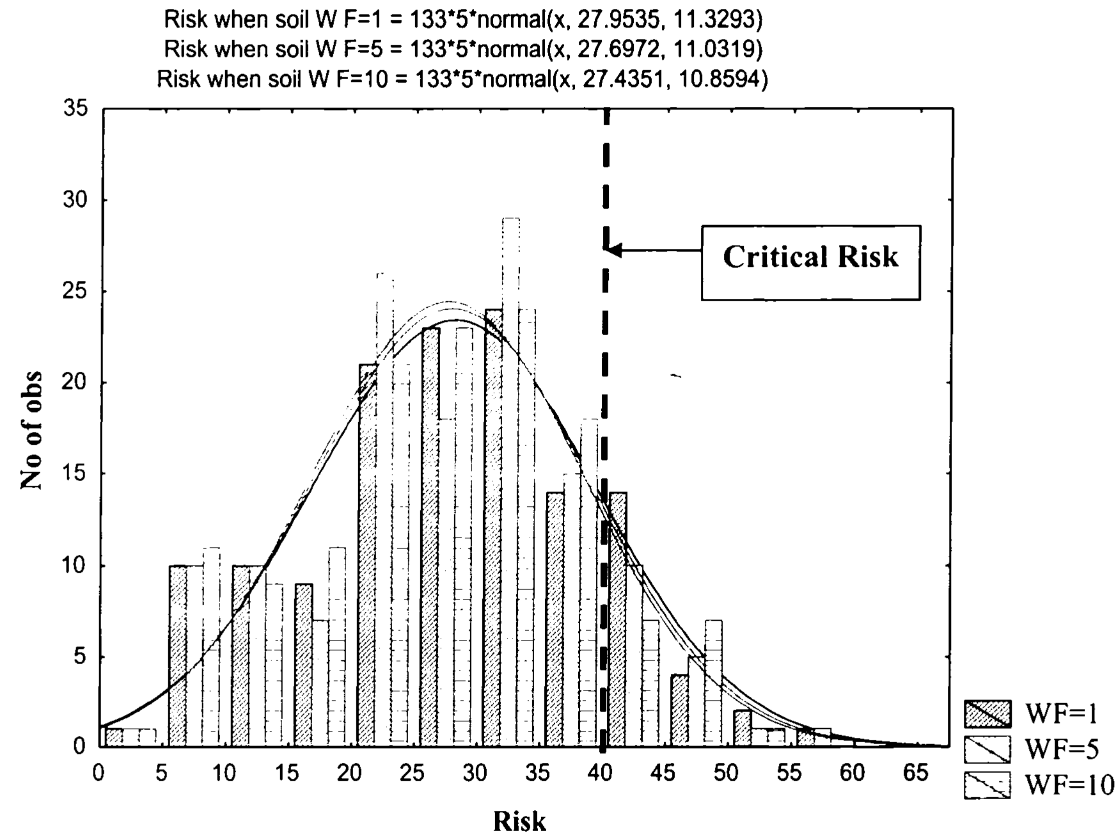


Figure 4.14: Histograms of Substation Risk for Different Weighting Factors of Geology of the Site

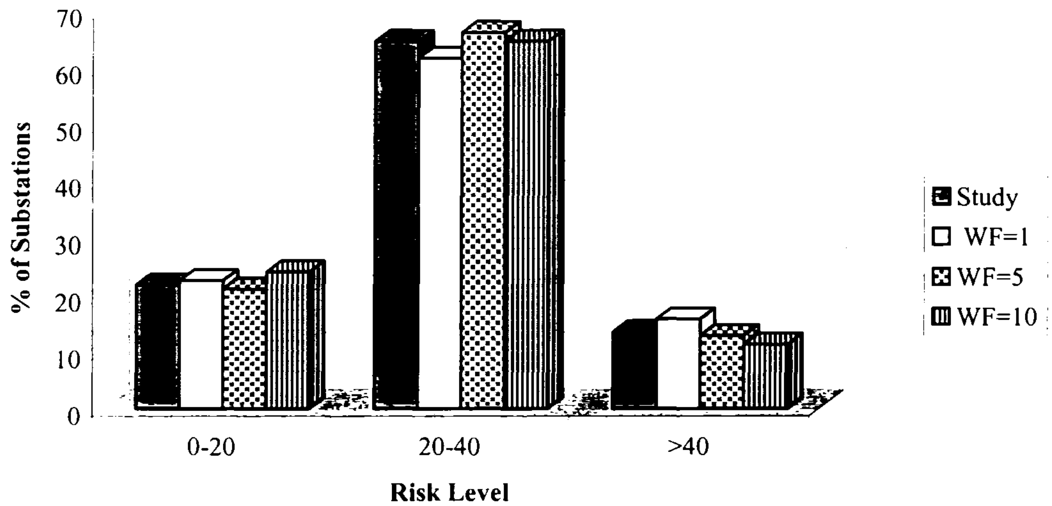


Figure 4.15: Substations at Different Risk Level for Different Weighting Factors of Geology of the Site

Figures 4.16 and 4.17 represent the number and % of substations at different risk levels for different values of weighting factors to lateral forces. With a weighting factor of 10, the number of high-risk substations increases to 23.

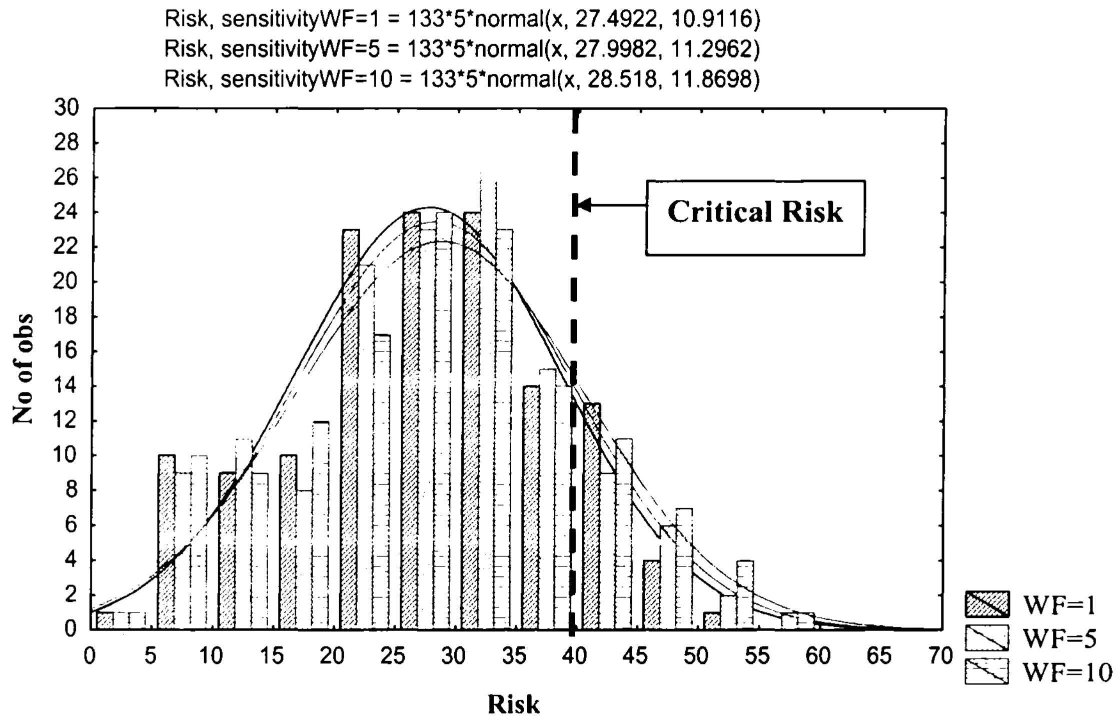


Figure 4.16: Histograms of Substation's Risk for Different Weighting Factors of Sensitivity of Equipment to Lateral Forces

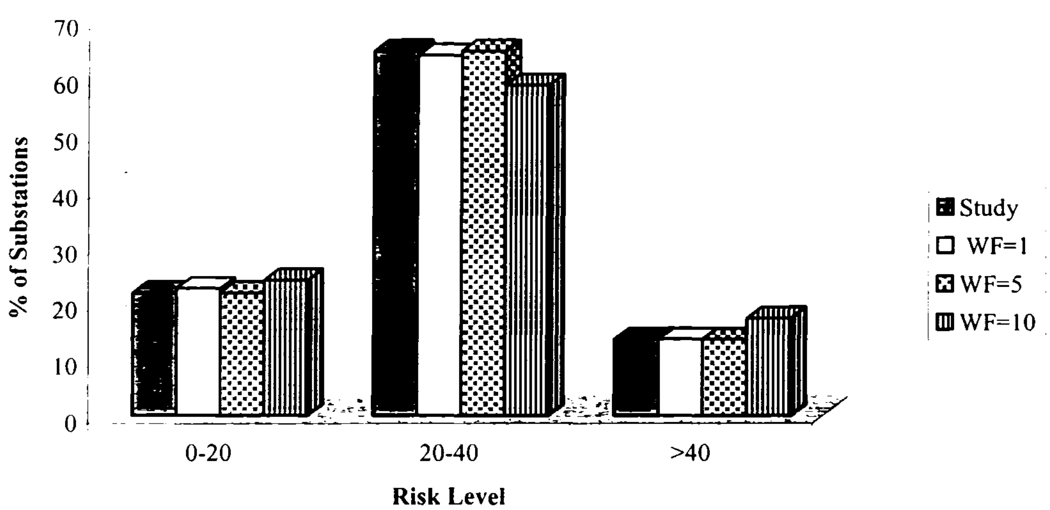


Figure 4.17: Substations at Different Risk Level for Different Weighting Factors of Sensitivity of Equipment to Lateral Forces

Figures 4.18 and 4.19 represent the number and % of substations at different risk levels for different values of the weighting factor for "anchoring of equipment". Up to 20 % substations are at high-risk level when the weighting factor is 10.

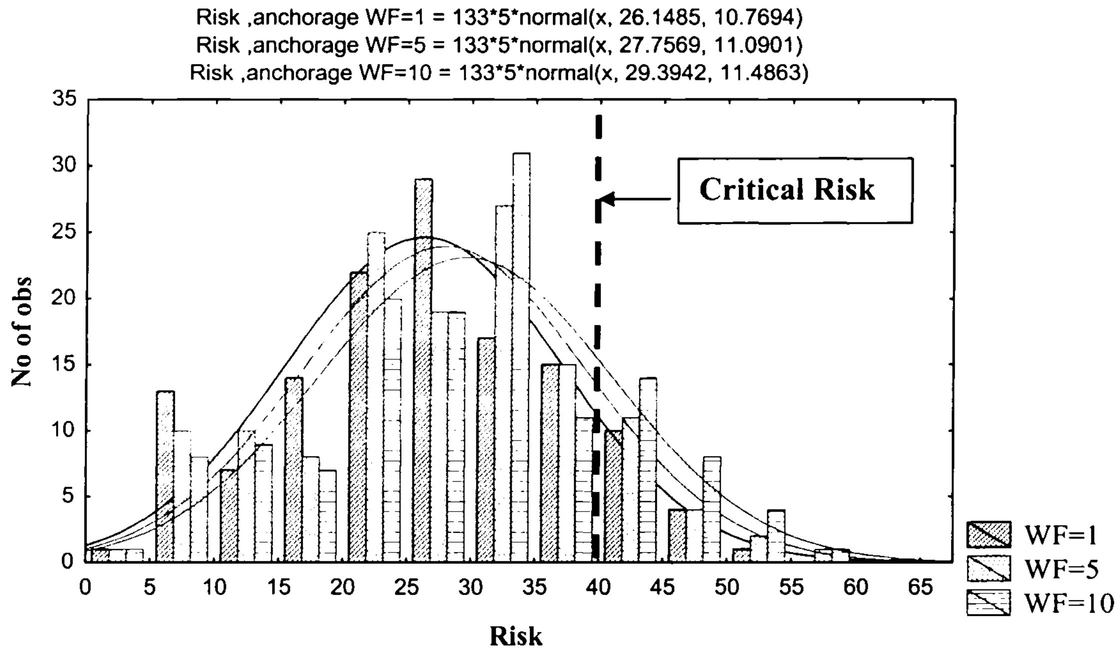


Figure 4.18: Histograms of Substation Risk for Different Weighting Factors of Anchoring of Heavy Equipment

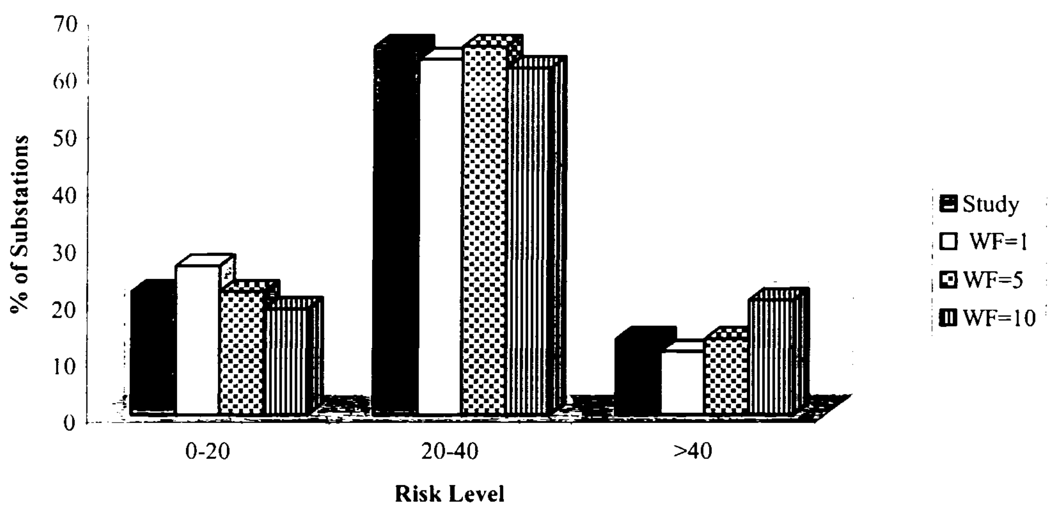


Figure 4.19: Substations at Different Risk Level for Different Weighting Factors of Anchoring of Heavy Equipment

Figures 4.20 and 4.21 show the number and % of substations at different risk levels for different values of the weighting factor of "load bearing structure of the buildings". Number of high-risk substations increase with the increasing value of weighting factor.

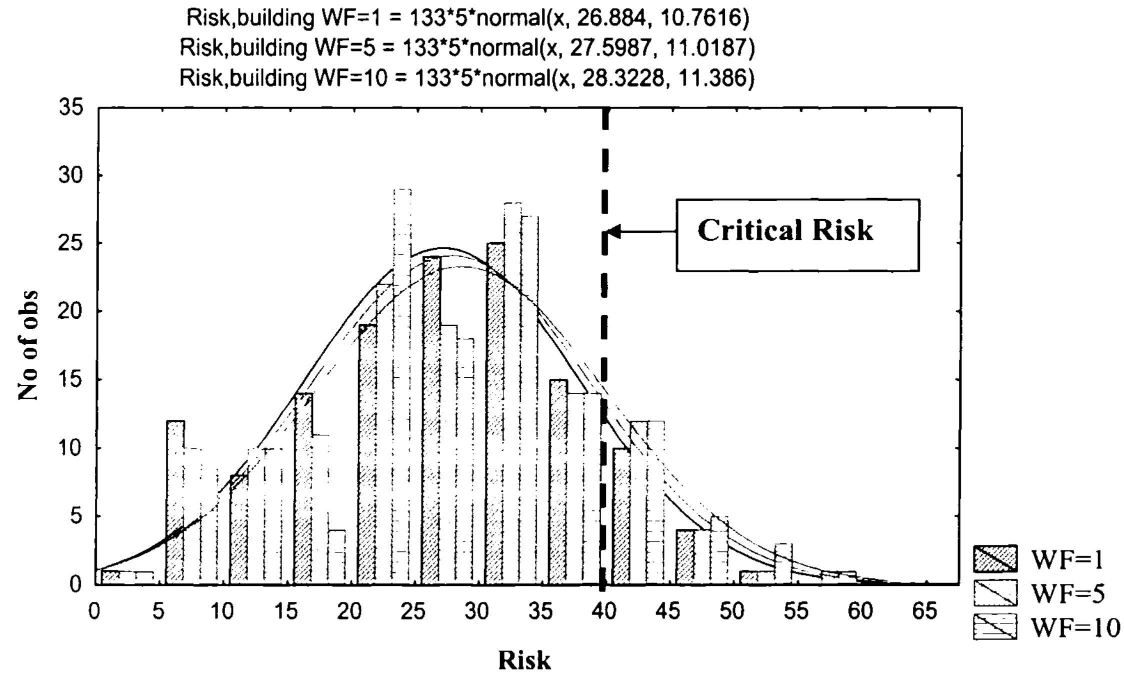


Figure 4.20: Histograms of Substation Risk for Different Weighting Factors of the Load Bearing Structure of the Building

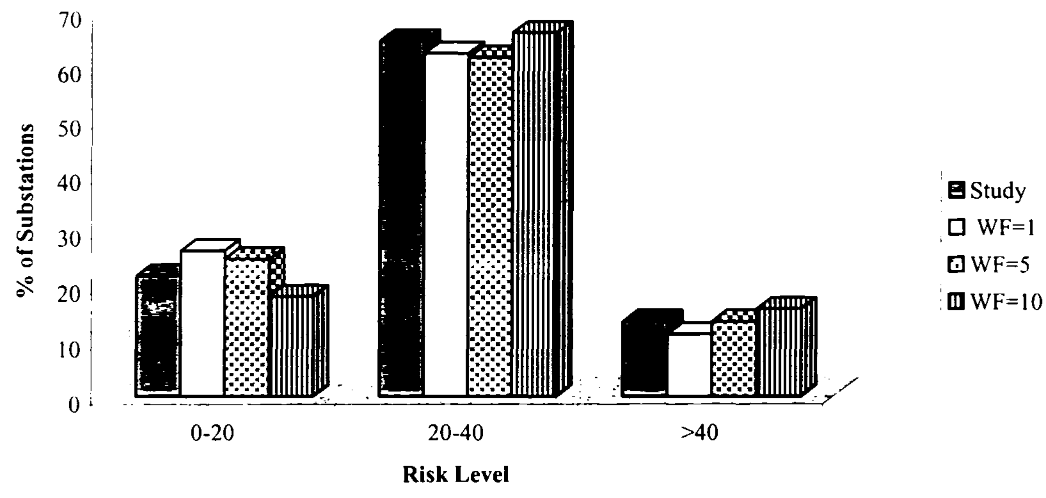


Figure 4.21: Substations at Different Risk Levels for Different Weighting Factors of the Load Bearing Structure of the Building

Figure 4.22 illustrates the cumulative distribution of risk of substations for different weighting factors for "geology of the site", "sensitivity of equipment to lateral forces", "anchoring of heavy equipment", and "load bearing structure of the buildings". When weighting factors of the 4 parameters are equal to 1, then 43 substations are in negligible or weak risk levels, 83 substations are at the moderate risk level and 7 substations in Quebec are in high-risk level. When the weighting factors of the 4 parameters are 5, then the number of high-risk substations is 18. This number is the same as the one from the Hydro-Quebec study. The number of high-risk substations increases to 24 when the weighting factor of each of the four parameters is 10.

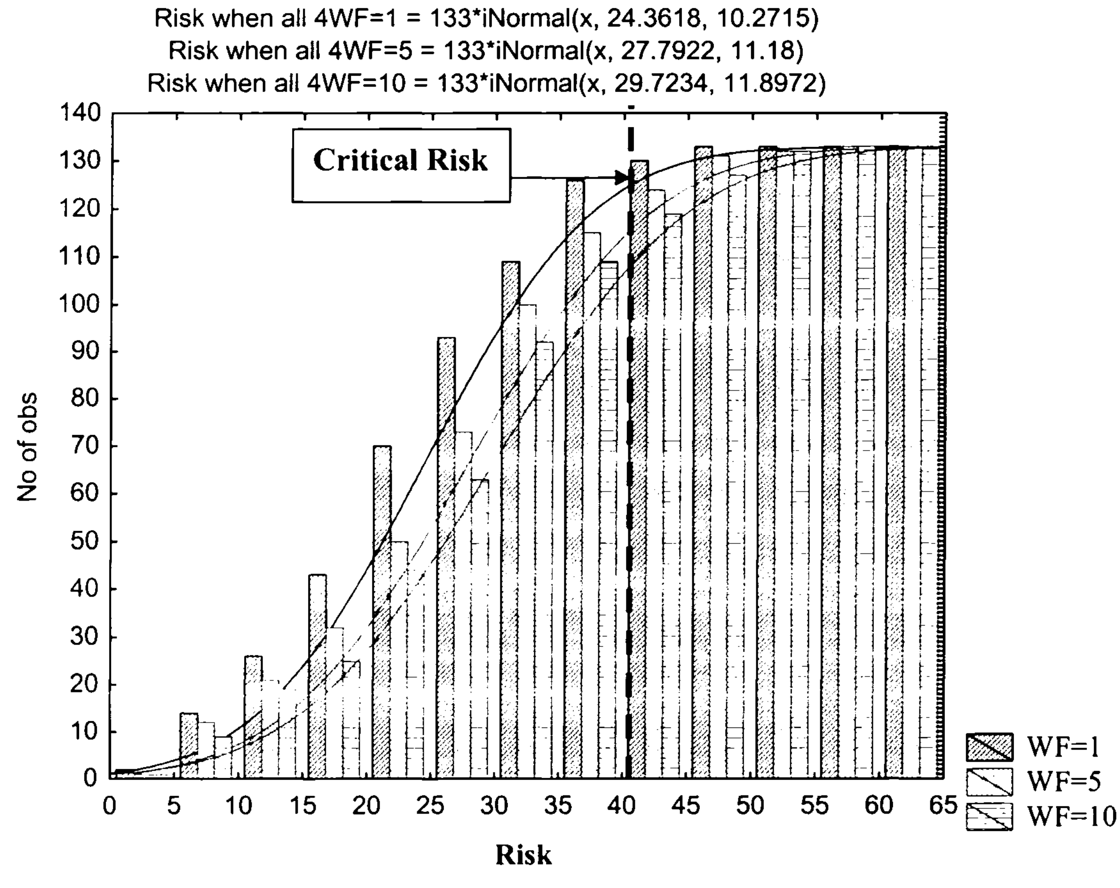


Figure 4.22: Cumulative Distribution of Substation Risk for Different Weighting Factors of Geology, Anchoring, Lateral Load and Structure of Building

4.7 Sensitivity of Seismic Exposure

Figures 4.23 and 4.24 explain the variability of substation risk during an earthquake for different seismic exposure levels. 42% of substations are at high-risk when seismic exposure level is 1.0. For seismic exposure 0.7, 12% substations are at high-risk level. 56% substations are at moderate-risk level for seismic exposure 0.55. For seismic exposure 0.55, no one substation exceeds the critical earthquake risk level.

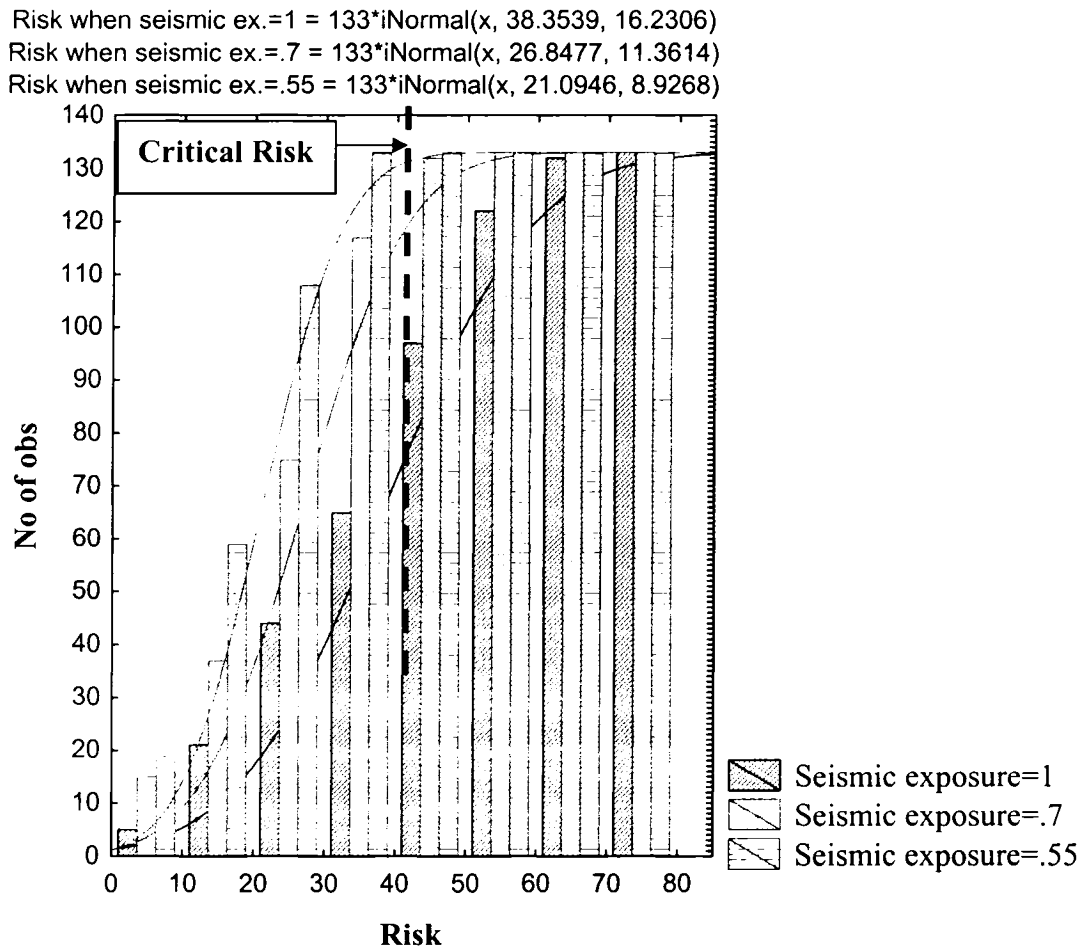


Figure 4.23: Cumulative Distribution of Substation Risk for Different Seismic Exposure

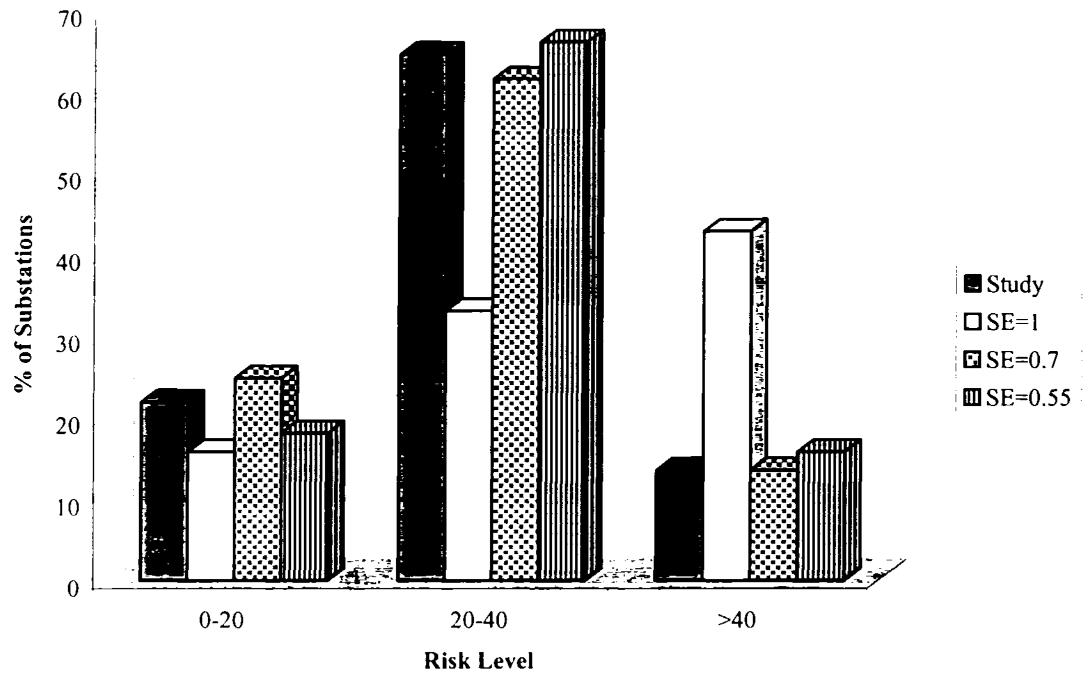


Figure 4.24: Substations at Different Risk Level for Different Seismic Exposure

4.8 Sensitivity of Consequences

Figures 4.25 and 4.26 show for a consequences value 10, almost two- third of the 133 substations would be in high-risk level. It decreases to less than one third for a consequence value is 8.5. For a consequence value 2.5, all the substations are below the high-risk level.

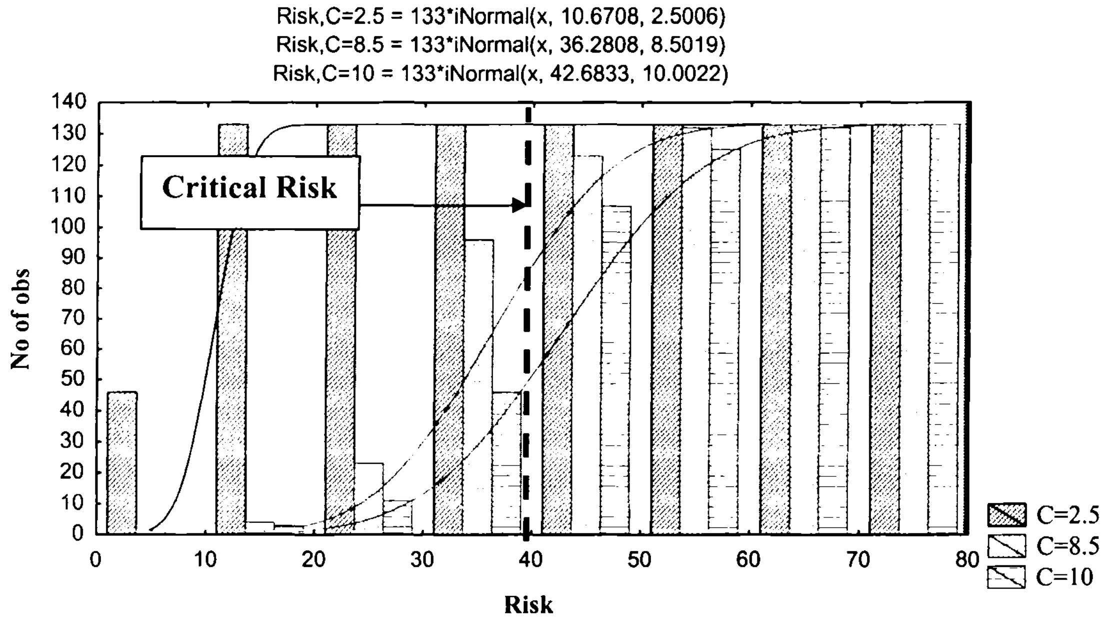


Figure 4.25: Cumulative Distribution of Substation Risk for Different Consequences

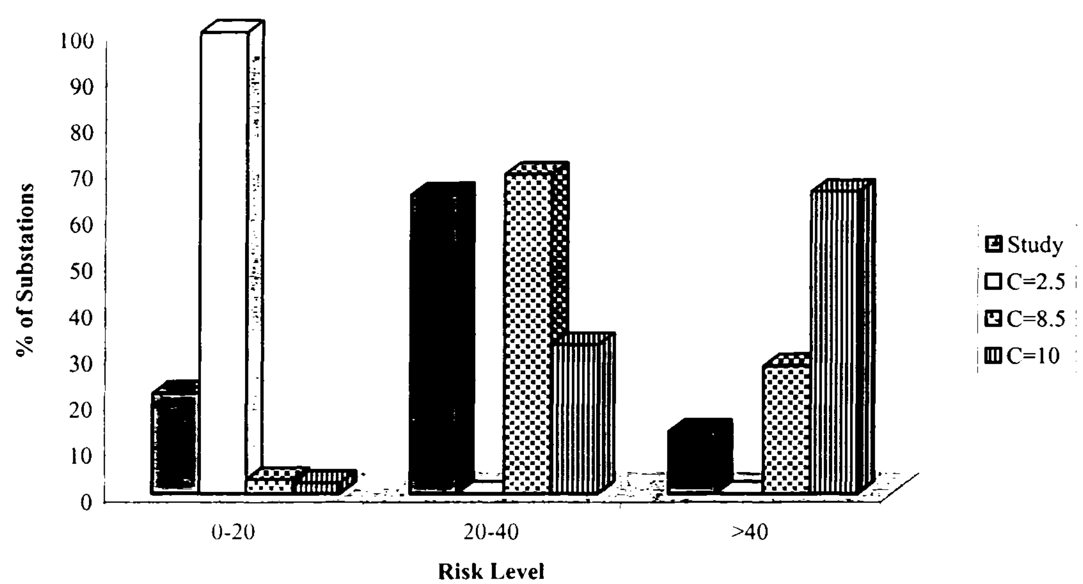


Figure 4.26: Substations at Different Risk Level for Different Consequences

4.9 Analysis of Montreal Data

Figure 4.27 shows the electric distribution network for the island of Montreal. Data from 11, 315 KV substations and 8, 120 KV substations on the Island of Montreal were considered in the analysis.

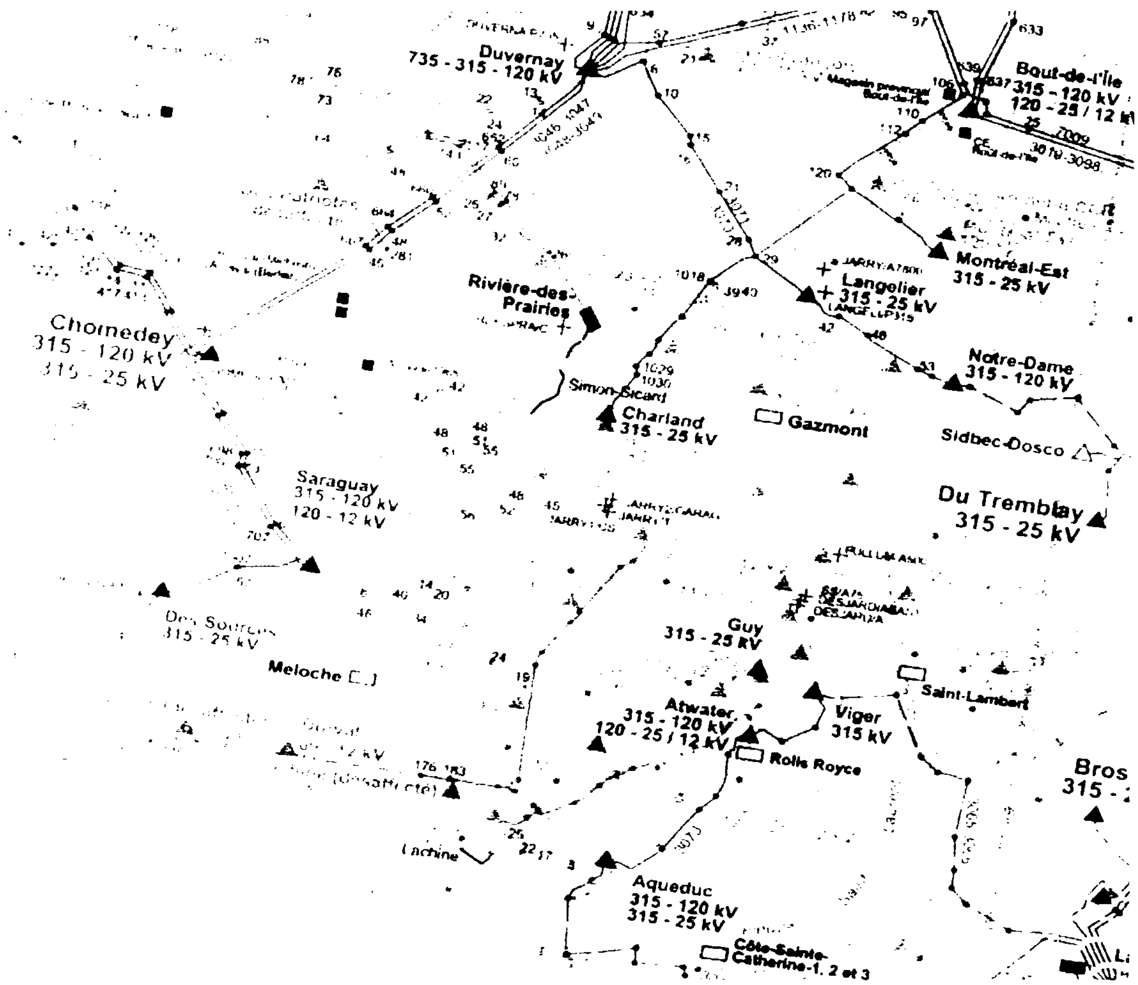


Figure 4.27: Substations and Transmission Map of Island of Montreal
(Hydro-Quebec)

Figure 4.28 represents the vulnerability, consequences and risk level of these substations. Substation 72 is in high-risk category and all other substations are in moderate risk category. From the analysis it is observed that the parameters "anchoring of heavy equipment", "load bearing structure of substation buildings" and "year of manufacture of equipment" are responsible for the vulnerability of substations. In all 18 substations, anchoring is either non-existent for all equipment or all the equipment is set on rails without blocking elements. On average 18.5% of the vulnerability of all substations is due to deficiency in anchoring of equipment. Almost half of the substations building structures are load bearing walls designed before 1970. This type of building is very vulnerable to earthquakes and accounts for 17% of the total vulnerability of the substation. The equipment of 10 substations was manufactured before 1975 and do not satisfy current seismic standards. Equipment of the other 9 substations was manufactured between 1976- and 1986. This equipment is very vulnerable to earthquakes. On average, "year of manufacture of substation equipment" account for 14% of the vulnerability of substations.

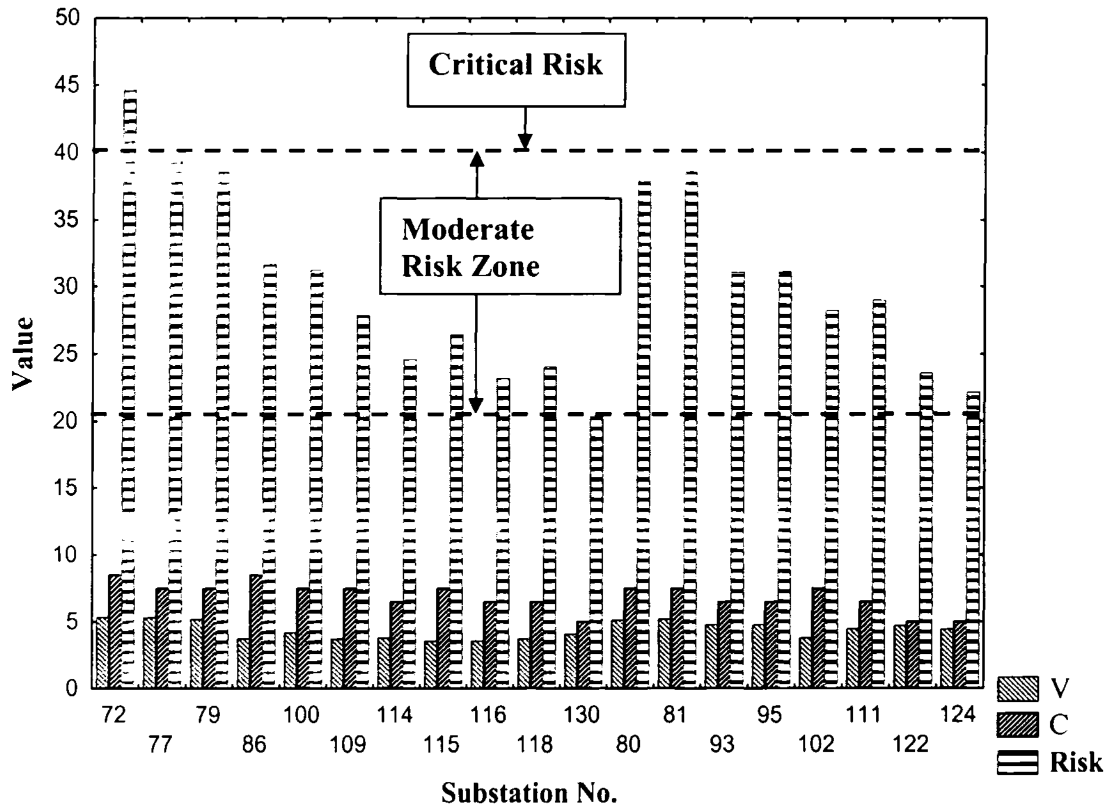


Figure 4.28: Bar Chart of Vulnerability, Consequences and Risk for 18 Substations in Montreal

4.10 Conclusion

Statistical analysis of seismic risk on substations of Hydro-Quebec was performed using STATISTICA^R. The Analysis identified the four most critical parameters responsible for high-risk index of substations: year of manufacture of equipment, anchoring of heavy equipment, load-bearing structure of the building and control systems. The mean value of vulnerability is 4.26, which is more than the critical vulnerability level 4.0. Study shows equipment in 42% substations of Hydro-Quebec was manufactured between1957 and 1975. Only 13 % of substations equipment was manufactured after 1987. Data also show that 90% of substations lack proper anchoring of equipment. More than half of substation control buildings are masonry structures. This type of structure is very vulnerable to earthquakes and increases the overall risk level of substations. Only 10% of the buildings are steel structures with adequate bracing and anchoring to their foundations. Analysis shows vulnerability has a correlation of 0.6 with the risk index and consequences has a correlation of 0.8 with the risk index. The sensitivity study shows that the seismic risk index of substations is very sensible to the seismic exposure level. The number of high-risk substations increases significantly when seismic exposure level is set to 1.0.

Chapter 5

Seismic Fragility of Circuit Breakers

5.1 Seismic Fragility Curves Derived From Nominal Resistance Data

Nominal resistance data for different types of circuit breakers were supplied to Hydro-Quebec by various manufacturers. Hydro-Quebec has supplied nominal resistance data for this research. These resistances are expressed as a fraction of g or in m/s^2 (acceleration associated with gravity). These ratings are usually very conservative and correspond to a value in the lower tail of the distribution for the resistance of the circuit breaker. In the following we assume that the ratings correspond to values equal to the mean resistance minus three standard deviations. Typical coefficients of variation for the resistance of circuit breakers are assumed to be approximately equal to 15%. Under these assumptions, the mean and standard deviation in Table 5.1 for each type of circuit breaker were derived.

Using this data, a fragility curve can be derived using the following equation,

$$P_f(PGA) = \Phi(-\beta \mid PGA) = \Phi\left(-\frac{\mu_R - PGA}{\sqrt{\sigma_R^2}}\right) \qquad \ldots\ldots\ldots\ldots\ldots 5.1$$

As an example, the reliability index and probability of failure for the ATB 330 kV GE circuit breaker for different PGA are presented in Table 5.2. The fragility curve is obtained by plotting the probability of failure as a function of PGA.

Figure 5.1 shows the fragility curves obtained for various ATB circuit breakers manufactured by General Electric (GE). These curves indicate that 735kV and 120kV circuit breakers have low reliabilities under the current code and that the 230 and 320 kV have high reliabilities under NBCC 1995 code but will be barely acceptable under NBCC

2005. None of the circuit breakers are adequate for seismic zone 6 (Charlevoix region) under NBCC 1995.

CB Type	Resistance (g) (Hydro-Quebec, 1990)	Mean (g)	Standard Dev. (g)
ATB 120KV, GE	0.14	0.25	0.04
ATB 230KV, GE	0.30	0.55	0.08
ATB 330KV, GE	0.26	0.47	0.07
ATB 735KV, GE	0.10	0.18	0.03
DLVF 230KV, BBC	0.30	0.55	0.08
DCVF 230KV, BBC	0.12	0.22	0.03
DLVF 315KV, BBC	0.20	0.36	0.06
DLVF 735KV, BBC	0.15	0.27	0.04
PK8B 735KV, Delle	0.22	0.40	0.06
PK8C 735KV, Delle	0.20	0.36	0.06
PK8VC 735KV, Delle	0.25	0.45	0.07
PK10 735KV, Delle	0.22	0.40	0.06
PK12 735KV, Delle	0.30	0.55	0.08
OR2M 120KV, Delle	0.15	0.27	0.04
Merlin Gerin 230KV	0.25	0.45	0.07
PVH 161KV S&S	0.10	0.18	0.03
PVH 230KV PK4	0.12	0.22	0.03
PVH 315KV PK4	0.12	0.22	0.03
Brown Boveri SF6 230KV	0.26	0.47	0.07
Brown Boveri SF6 300KV	0.24	0.44	0.07
800KV GL-318 4LM SF6/CF4	0.28	0.51	0.08

Table 5.1: Nominal Resistance, Mean Resistance and Standard Deviation for Different Types of Circuit Breakers.

Fragility curves were similarly obtained for the remaining circuit breakers listed in Table 5.1. Figure 5.2 shows the fragility curves for the various circuit breakers of BBC. The DCVF230KV circuit breaker is very vulnerable and does not satisfy current code specifications. Similarly, the DLVF735KV and DLVF315KV circuit breakers will be unsatisfactory under NBCC 2005 specifications for the Montreal area. None of the BBC circuit breakers are currently acceptable for use in seismic zone 6.

PGA in (g)	Reliability Index, β	$\phi(\beta)$	Probability of Failure, $P_f=1-\phi(\beta)$
0.1	5.256	0.999999942	5.8E-08
0.15	4.551	0.99999732	2.68E-06
0.2	3.846	0.99994	6E-05
0.25	3.141	0.99916	0.00084
0.3	2.435	0.99266	0.00734
0.35	1.730	0.95818	0.04182
0.4	1.026	0.84849	0.15151
0.5	-0.385	0.35197	0.64803
0.6	-1.795	0.03673	0.96327
0.7	-3.205	0.00069	0.99931
0.8	-4.615	2.11E-06	0.999998

Table 5.2: Reliability Index and Probability of Failure of ATB 330 KV GE Circuit Breaker for Different PGA

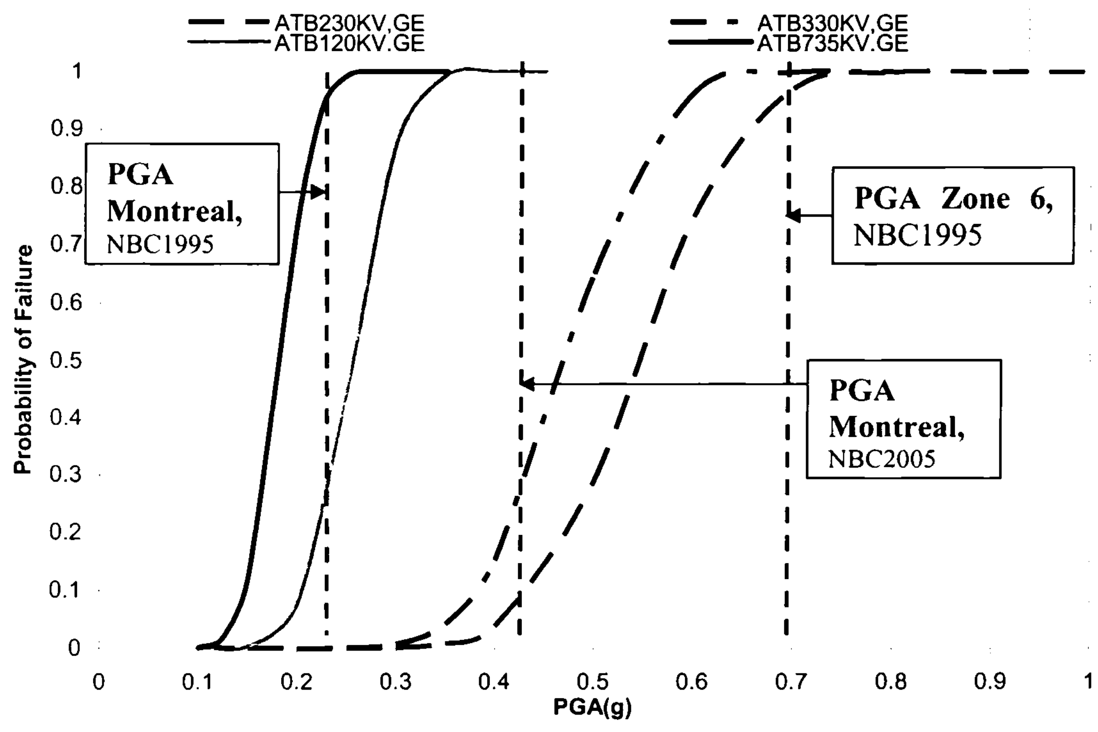


Figure 5.1: Fragility Curves of GE Circuit Breakers

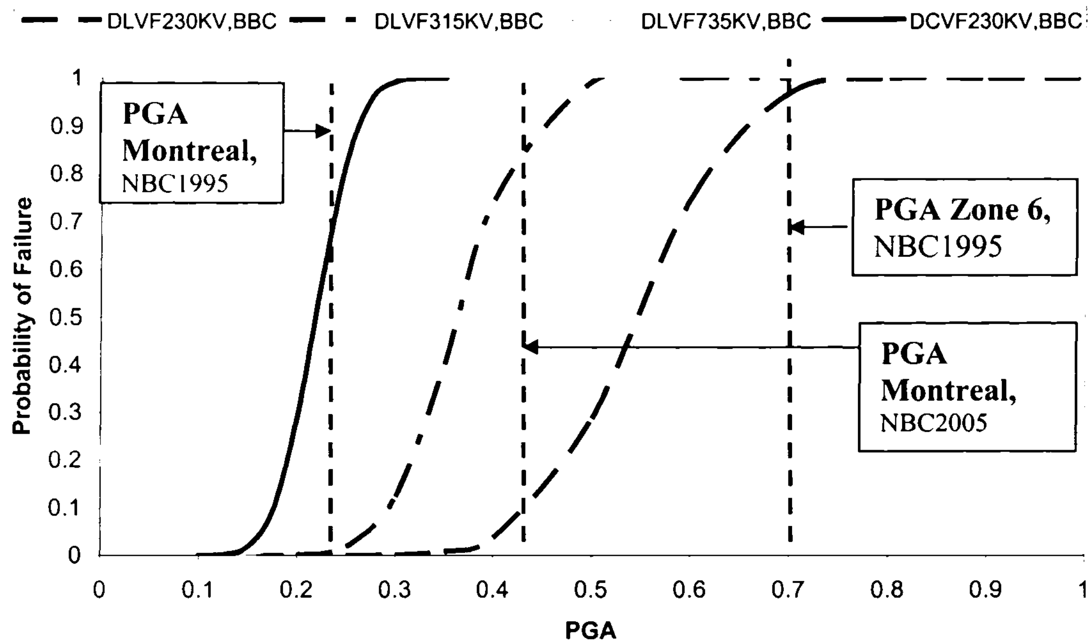


Figure 5.2: Fragility Curves of BBC Circuit Breakers

Figure 5.3 shows the fragility curves for various types of Delle circuit breakers. OR2M, the120 KV circuit breaker is not acceptable under the current code for zone 4 (Montreal and Quebec City). PK8B 735KV, PK8C 735KV, PK8VC 735KV, and PK10 735KV circuit breakers have high reliabilities according to the specification of NBCC 1995 for Montreal and Quebec City region. PK8B 735KV, PK8C 735KV, PK8VC 735KV, and PK10 735KV circuit breakers have low reliabilities and not acceptable under NBCC 2005 for zone 4. None of the Delle circuit breakers are acceptable for zone 6 under the current code.

Figure 5.4 illustrates the fragility curve of 230KV Merlin Gerin Circuit Breaker. This type of circuit breaker has high reliability for zone 4 under the current code but is not acceptable under the specifications of NBCC 2005 for Montreal and Quebec City regions.

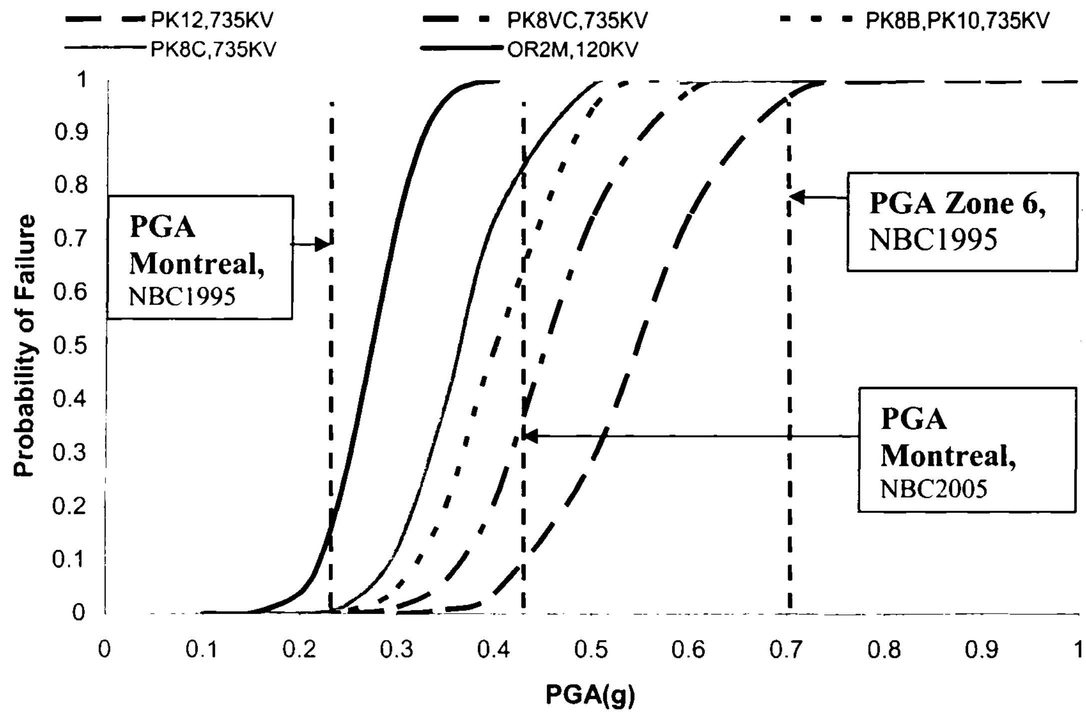


Figure 5.3: Fragility Curves of Delle Circuit Breakers

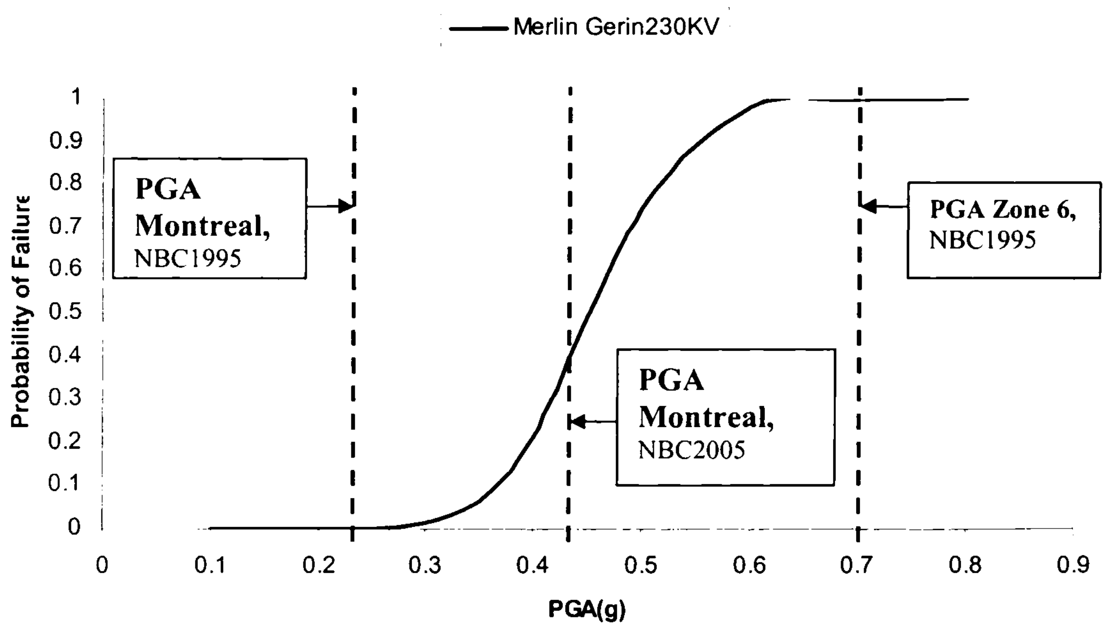


Figure 5.4: Fragility Curve of 230KV Merlin Gerin Circuit Breaker

Figure 5.5 represents the fragility curves of S & S circuit breakers used by Hydro-Quebec in different substations. This type of circuit breaker is very vulnerable. Reliabilities of PVH 230KV and PVH315KV circuit breakers are very low for maximum PGA value of zone 4 under NBCC1995. PVH161KV circuit breaker is not acceptable under the specification of current code for zone 4. None of the circuit breakers are acceptable under the proposed NBCC 2005 for Montreal and Quebec City regions.

Figure 5.6 shows the fragility curves for Brown Boveri circuit breakers. These types of circuit breakers have high seismic resistant capacity and are safe in zone 4 during earthquake according to NBCC1995. SF6, 230KV and SF6, 300 KV circuit breakers have low reliabilities and are barely acceptable under the specification of NBCC 2005 for zone 4 areas.

Figure 5.7 represents the fragility curve for GL-318 4LM SF6 circuit breaker. Reliability of this type of circuit breaker is very high for zone 4 under the current code. This type of circuit breaker is acceptable for zone 4 under the specifications of proposed NBCC 2005 but not acceptable for zone 6 under the current code.

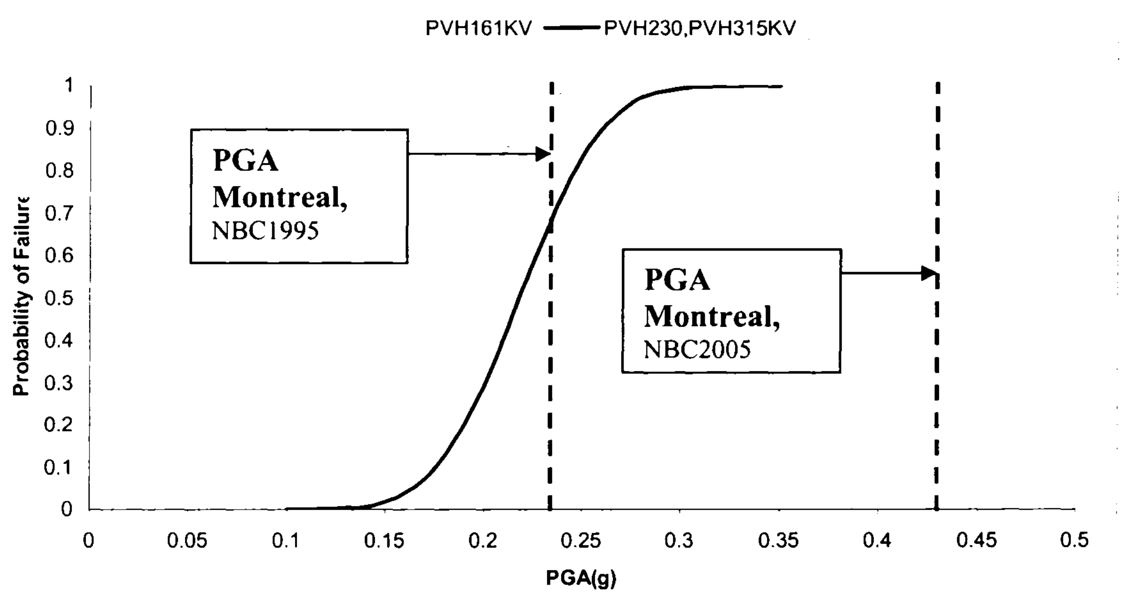


Figure 5.5: Fragility Curves of PK4 and S&S Circuit Breakers

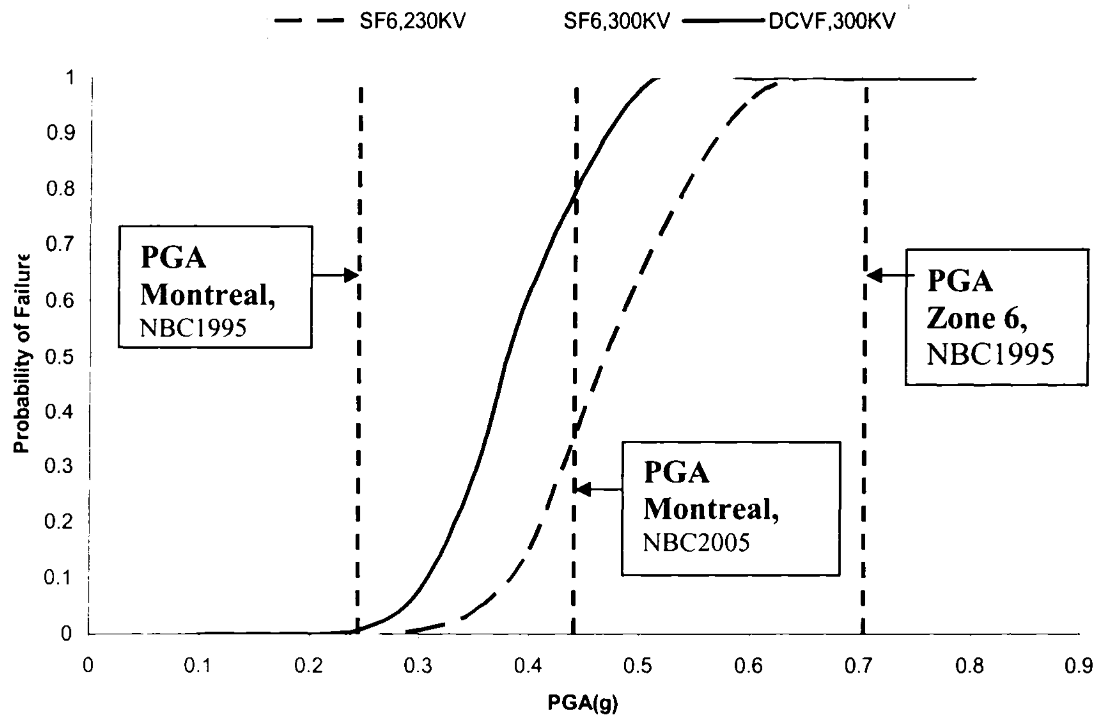


Figure 5.6: Fragility Curves of Brown Boveri Circuit Breakers

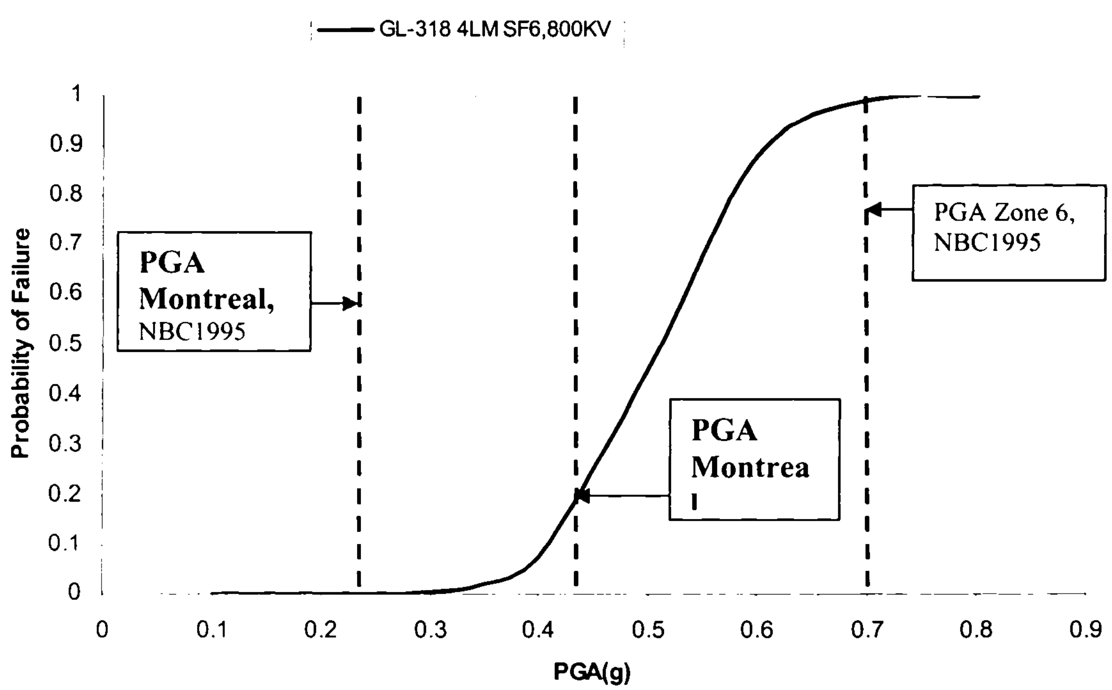


Figure 5.7: Fragility Curve of GL-318 4LM SF6/ CF4 Circuit Breaker

5.2 Fragility Curve of New Types of Circuit Breakers Using Applied Moments

Magnusson (2003), produced a report on seismic loads on circuit breakers. He analysed various load combinations in accordance with SN 29.1a, IEC 60056, IEC 60694, IEC 61166 and IEC 61264.

Load Calculation on Circuit Breaker Type: LTB1/245/800E2 ABB

Center of gravities

Height to center of gravity of pole unit, h_1	=	10.4 m
Height to center of gravity of top post insulator, h_2	=	8.7 m
Height to center of gravity of bottom post insulator, h_3	=	5.6 m
Height to center of gravity of link gear, h_4	=	3.6 m
Height to center of gravity of operating mechanism, h_5	=	3.0 m
Height to center of gravity of support structure, h_6	=	1.9 m

Dead weight

Breaking unit, m_1	=	572 kgs
Top post insulator, m_2	=	300 kgs
Middle and bottom post insulator, m_3	=	505 kgs
Link gear, m_4	=	135 kgs
Operating mechanism, m_5	=	465 kgs
Support structure, m_6	=	250 kgs

Height of critical locations for circuit breakers

Height to upper terminal, L_o	=	10.7 m
Height to top of upper post insulator, L_1	=	9.9 m
Height to bottom of upper post insulator, L_2	=	7.5 m
Height to bottom of lower post insulator, L_3	=	3.8 m

Earthquake Load on Circuit Breaker:

Frequency,	f	=	2 Hz
Critical damping,	ξ	=	0.03
Horizontal acceleration, ah = 0.39g		=	3.8259 m/s^2
Vertical acceleration, av		=	0.66ah

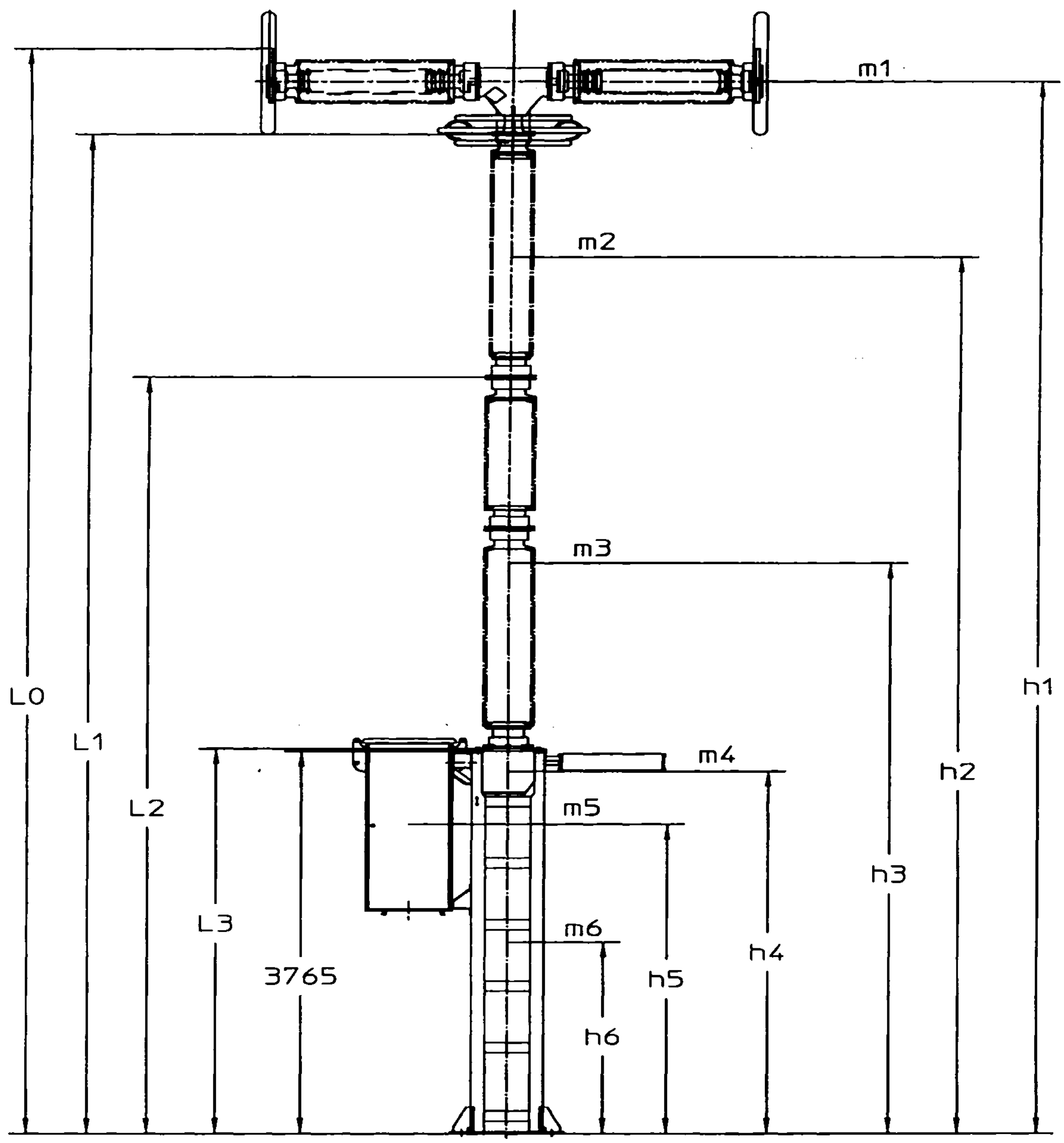


Figure 5.8: Different Parts of Circuit Breaker, LTB1/245/800E2 ABB
(Magnusson, 2003)

Horizontal acceleration response, ahr = 0.39g × Amplification factor × Soil factor

= 0.39g × 1.97 × 1.3

= 9.798 m/s^2

Vertical acceleration response, avr = 0.66.ahr = 6.467 m/s^2

Load on each mass due to horizontal earthquake acceleration, Feh_i = ahr.m_i

Load on each mass due to vertical earthquake acceleration, FeV_i = avr.m_i

Bending moment due to earthquake acceleration,

$Meh_1 = Feh_1 (h_1-L_1)$ = 2802.265 Nm

$Meh_2 = Feh_1 (h_1-L_2) + Feh_2 (h_2-L_2)$ = 19780.465 Nm

$Meh_3 = Feh_1 (h_1-L_3) + Feh_2 (h_2-L_3) + Feh_3 (h_3-L_3)$ = 60299.651 Nm

$Meh_4 = \sum_{i=1}^{6} Feh_i.h_i$ = 134653.739Nm

Normal wind load on equipment

Normal wind, v = 31 m/s

Drag factor, cylindrical surface, cc = 1.0 m^2

Drag factor, flat surface, cp = 2.0 m^2

Frontal area of breaking unit, A_1 = 1.3 m^2

Frontal area of top post insulator, A_2 = 0.8 m^2

Frontal area of bottom post insulator, A_3 = 1.3 m^2

Frontal area of link gear, A_4 = 0.1 m^2

Frontal area of operating mechanism, A_5 = 1.1 m^2

Frontal area of support structure, A_6 = 2.0 m^2

Transverse load due to normal wind

Normal wind load on breaking unit, Qv_1 = $0.625v^2A_1.cc$ = 780.81 N

Normal wind load on top post insulator, Qv_2 = $0.625v^2A_2.cc$ = 480.5 N

Normal wind load on bottom post insulator, Qv_3 $= 0.625v^2A_3.cc$ $= 780.81$ N

Normal wind load on link gear, Qv_4 $= 0.625v^2A_4.cp$ $= 120.13$ N

Normal wind load on operating mechanism, Qv_5 $= 0.625v^2A_5.cp$ $= 1321.38$ N

Normal wind load on support structure, Qv_6 $= 0.625v^2A_6.cp$ $= 2402.5$ N

Bending load due to normal wind

Bending load on top of post insulator due to normal wind, Mv_1,

$$= Qv_1 (h_1-L_1) = 390.41 \text{ Nm}$$

Bending load on upper post insulator due to normal wind, Mv_2,

$$= Qv_1 (h_1-L_2) + Qv_2 (h_2-L_2) = 2840.95 \text{ Nm}$$

Bending load on bottom post insulator due to normal wind, Mv_3,

$$= Qv_1 (h_1-L_3) + Qv_2 (h_2-L_3) + Qv_3 (h_3-L_3) = 8913.27 \text{ Nm}$$

Bending load on support structure due to normal wind, Mv_4,

$$= \sum_{i=1}^{6} Qv_i.h_i = 25634.67 \text{ Nm}$$

Static terminal load according to IEC 60056

Horizontal load transversal to line, Fthx = 1000N

Horizontal load transversal to line, Fthy = 1300 N

Horizontal load transversal to line, Fthz = 1300 N

Bending load along line due to static terminal load

Bending load on top of post insulator, $MFthx_1 = Fthx (L_0-L_1) + Ftz.Lb$ $= 3099.7$ Nm

Bending load on upper post insulator, $MFthx_2 = Fthx (L_0-L_2) + Ftz.Lb$ $= 5499.7$ Nm

Bending load on bottom post insulator, $MFthx_3 = Fthx (L_0-L_3) + Ftz.Lb$ $= 9199.7$ Nm

Bending load on support structure, $MFthx_4 = Fthx.L_0 + Ftz.Lb$ $= 12999.7$ Nm

Impact load due to operation

Bending moment on structure at the stand and bottom of post insulator, Mimp =1500 Nm

Load combinations

Earthquake + Normal wind + Static terminal + Impact at operation

Bending moment in X direction,

$Mx_1 = Mv_1.0.1 + Meh_1 + MFthx_1.0.7$ = 5011.09 Nm 5.2.1

$Mx_2 = Mv_2.0.1 + Meh_2 + MFthx_2.0.7$ = 23914.35 Nm.........5.2.2

$Mx_3 = Mv_3.0.1 + Meh_3 + MFthx_3.0.7 + Mimp$ = 69130.76 Nm.........5.2.3

$Mx_4 = Mv_4.0.1 + Meh_4 + MFthx_4.0.7 + Mimp$ = 147816.99 Nm.......5.2.4

Minimum failure loads for insulator and support structure

M_1 = 40000 Nm

M_2 = 45000 Nm

M_3 = 100000 Nm

M_4 = 150000 Nm

Fragility Curves:

Minimum failure loads are calculated based on mean resistance minus three standard deviations. Typical coefficients of variation for the resistance of circuit breakers are assumed to be approximately equal to 15%. Under these assumptions, the mean resistance and standard deviation for each part of the circuit breaker were derived. Applied load on different parts were determined by equations 5.2.1 to 5.2.4 for different ground accelerations. Using these equations, the reliability index and probability of failure of each part was determined as,

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

$$p_f = 1 - \phi(\beta)$$

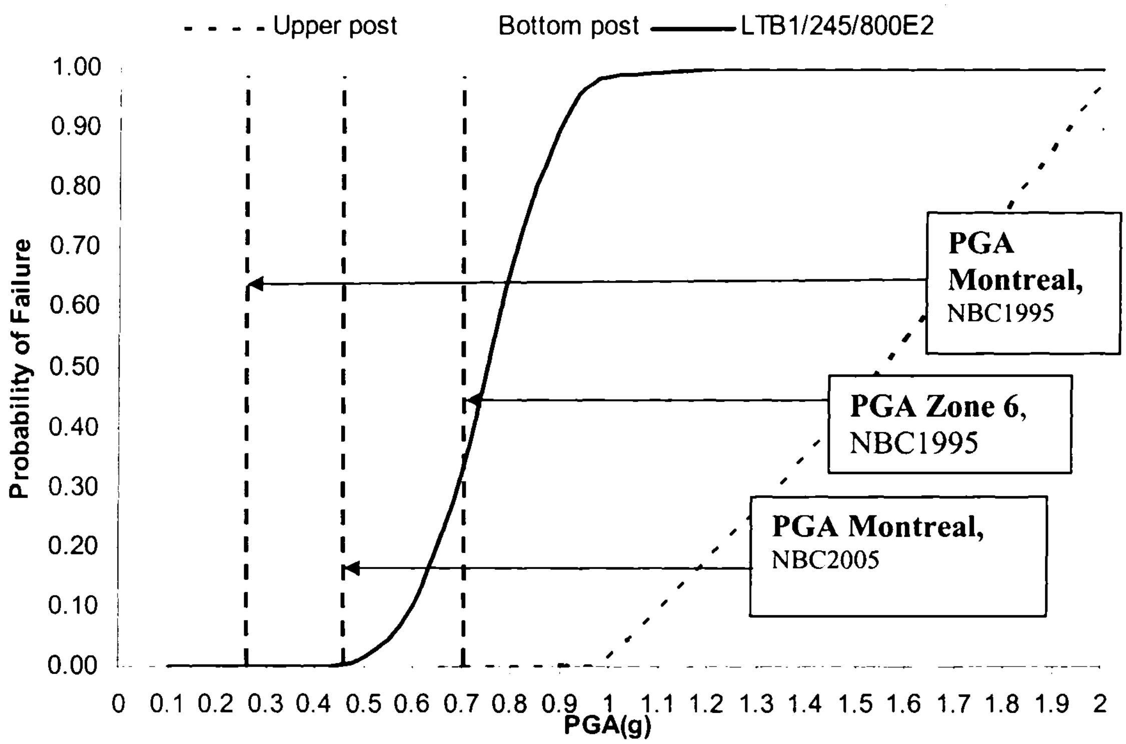


Figure 5.9: Fragility Curve of ABB, LTB Circuit Breaker

The probability of failure of each part of the circuit breaker is plotted as a function PGA in Figure 5.9. The resulting reliability of the total circuit breaker is assessed by using the equation of system reliability for a series system (Figure 5.9).

$$1 - p_S = \prod_{i=1}^{n} (1 - p_i)$$

Using the same procedure, fragility curves for the HPL170B1 ABB circuit breaker were derived (Figure 5.10). It is observed that ABB circuit breakers have high reliabilities for zone 4 under the specifications of current code and proposed NBCC 2005. This type of circuit breaker is also acceptable for zone 6 under the current code.

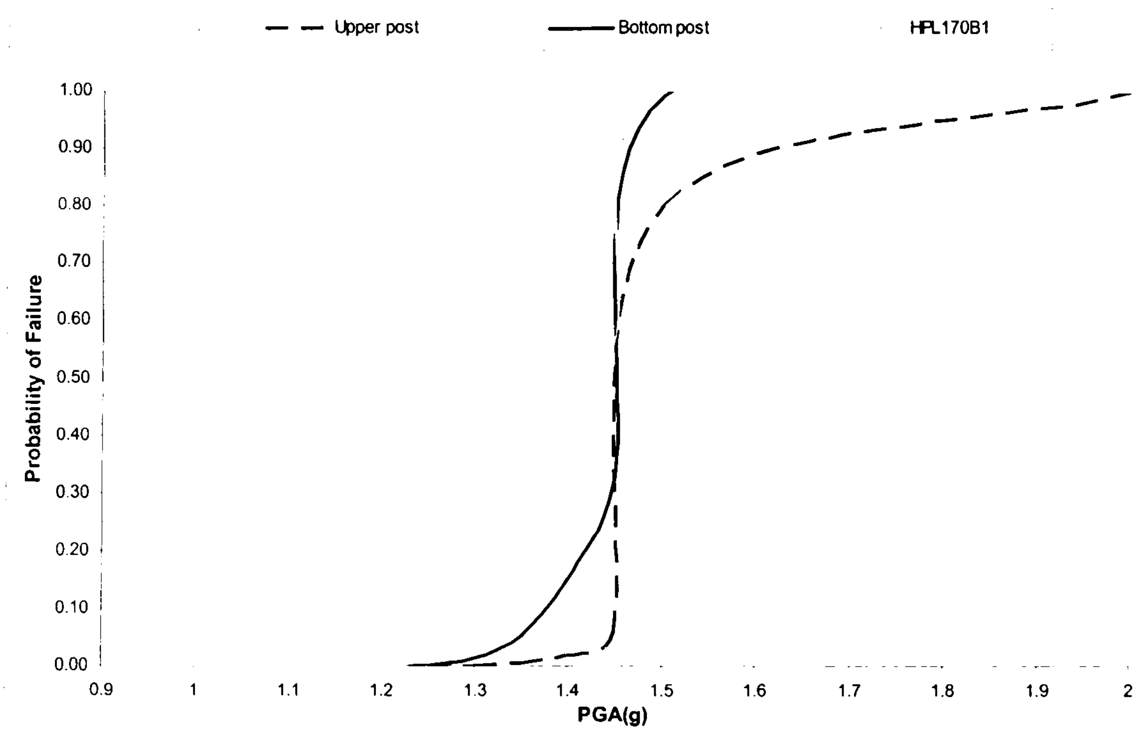


Figure 5.10: Fragility Curve of ABB, HPL Circuit Breaker

5.3 Comparison of Fragility Curves with Other Studies

According to Hydro-Quebec specification SN-29.1a, maximum stresses to porcelain elements resulting from seismic loads and other applicable loads, must not exceed the statistical average resistance minus three standard deviations for a safety coefficient of 1.2, or the average resistance minus two standard deviations for a safety coefficient 1.5. The later criterion is considered for developing the fragility curve of ATB230KV, GE circuit breaker of Hydro-Quebec.

Figure5.11 compares the fragility curve of Hydro-Quebec ATB230KV, GE circuit breaker With Utility Working Group (UWG) fragility curve and Field Data. Der Kureghian (2002) has developed the fragility curve of ATB230KV, GE circuit breaker by using the damage data of circuit breakers from past earthquakes. It is observed that fragility curve developed by analysis and UWG fragility curves underestimated the failure probability of ATB230KV, GE circuit breaker during earthquakes. The damage data was very inconsistent. Damage data of few substations were considered for fragility estimates. So, the fragility curve of field data may not represent the overall performance of circuit breakers during earthquakes.

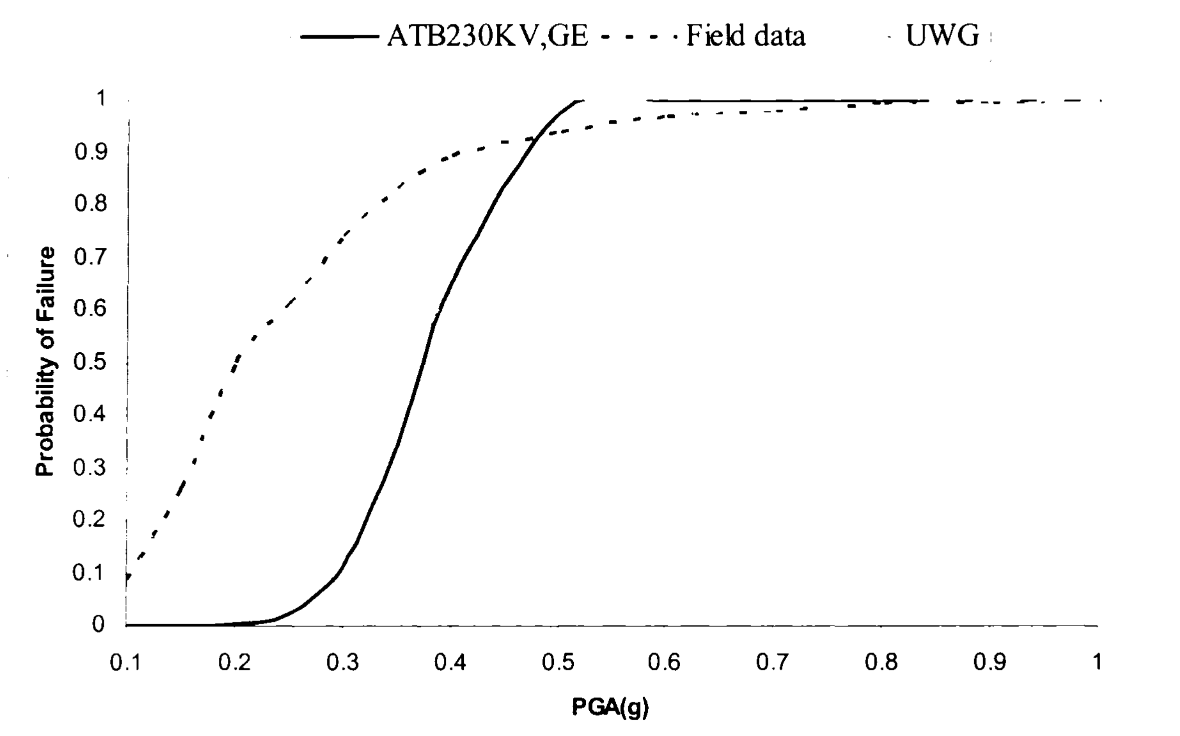


Figure 5.11: Comparison of Fragility Curve of Hydro-Quebec ATB230KV, GE Circuit Breaker with UWG Fragility Curve and Field Data

5.4 Average Risk of Different Types of Circuit Breakers Used by Hydro-Quebec

Hydro-Quebec has developed a risk index for of different types of circuit breakers by using the following equation:

Risk = Vulnerability (V) X Consequences (C)

Table 5.3 gives the values (c) and weighting factors (W.F) for different parameters used to calculate vulnerability by using the following equation

$$\text{Vulnerability} = \text{Seismic Exposure} \times \frac{\sum c \times W.F}{\sum W.F}$$

Figure 5.14 shows the average risk of different types of circuit breakers used in some important substations of Quebec. BBC circuit breakers are at highest risk level and the average risk for this type of circuit breakers is more than 50. Merlin Gerin, Delle and ATB circuit breakers are also at high-risk. Performance of GFX and ABB circuit breakers are at moderate risk levels. Photographs of some of the high-risk circuit breakers are shown in Figures 5.13 to 5.17. Vulnerable supports and anchoring of some of circuit breakers are presented in Figures 5.18 to 5.20

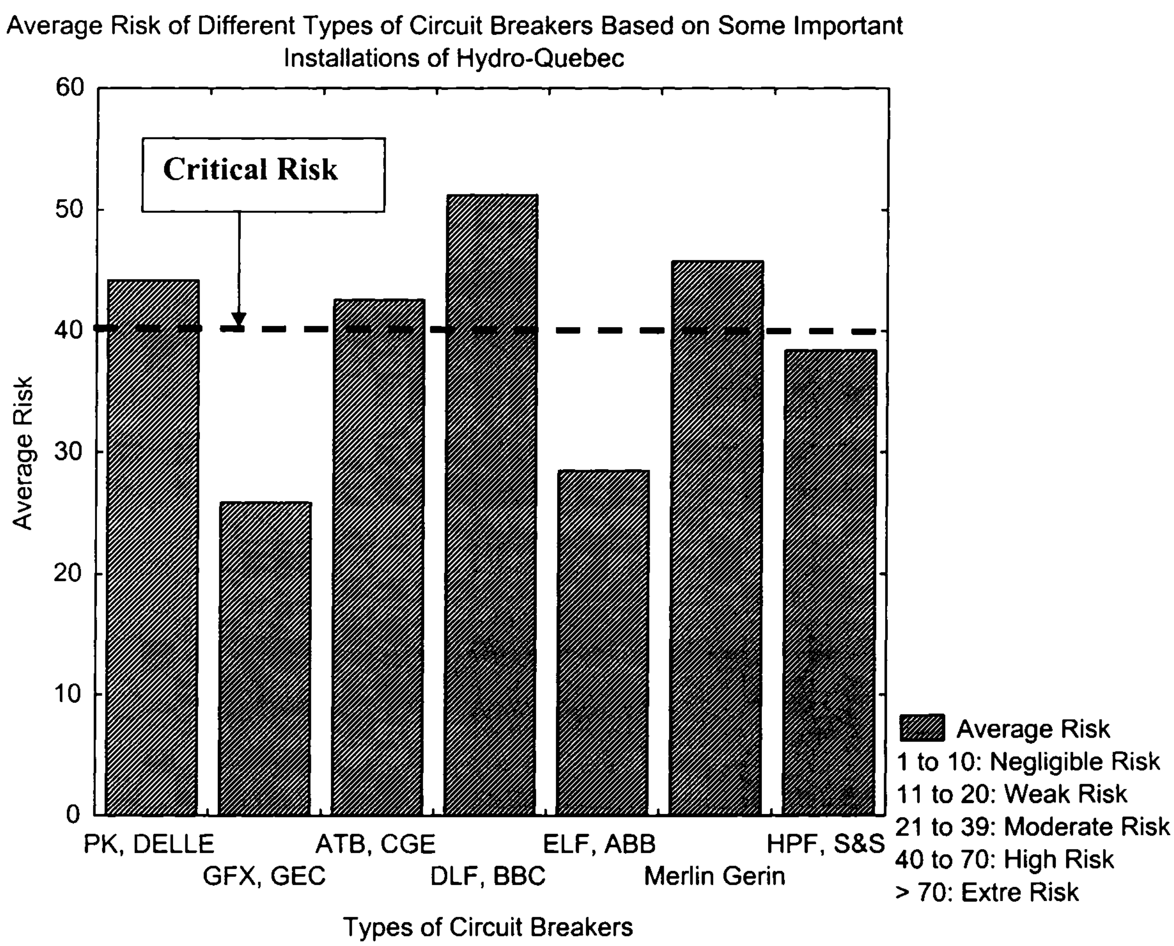


Figure 5.12: Average Risk of Different Type of Circuit Breakers

Parameters	Different Condition	c	W.F
Geology of the site	rock/dense or compact ground with coarse grains; firm and consistent ground with fine grains, of depth = < 15 m	1	4
	Not very deep ground of characteristic intermediary	2.5	
	Compact soils with large particles thicker than 15 meter, or on semi-compact soils with large particles or soft soil with fine particles or soft clay less than 15-meter thick	5	
	Semi-compact soils with large particles on soft soil with fine particles thicker than 15 meter	7.5	
	Loose to very loose soils with fine particles thicker than 15 meter	10	
Sensitivity of electric equipment to voltage	Equipment 69 KV	1	3
	120- 161 KV	2.5	
	230 KV/or equipment 315 KV braced	5	
	315 KV/or equipment 735 KV braced	7.5	
	735kV	10	
Year of design of the apparatus	1986-2000	1	8
	1976-1985	5	
	1957-1975	10	
Influence of support	Rigid support metal (lattice)/or squat tubular support (single column or gantry)/or standardized support/or if rehabilitated	1	3
	Intermediate support metal/Capacitor battery with insulators of support low height	5	
	Preceding supports of quality or doubtful resistance or not adequately braced	7.5	
	Flexible support or flexible support with rings or circles of support (gantry kind) with column and beam hurled compared to the conventional/Battery of condensers with insulators of slim supports	10	
Influence of the center of gravity of mass	Low mass uniformly distributed with center of gravity in the medium height of the apparatus	1	3
	Average mass with the center of gravity above the base of the apparatus	2.5	
	Mass with the center of gravity at middle height of equip.	5	
	Mass concentrated at the top of the apparatus	7.5	
	Mass very heavy concentrated at the top of the apparatus	10	
Flexible conductor between apparatus	Adequate sag (69 to 735KV)	1	2
	Sag is doubtful (69 to 315KV) or without sag (69 to 161KV)	5	
	Doubtful sag (735KV) or without sag (230, 315KV)	7.5	
	No sag (735KV)	10	
Dynamic interaction of rigid connection	If span less than or equal to 6 meter	1	1.5
	Span 6-10 meter	5	
	Span greater than 10 meter (upto 315 KV)	7.5	
	Span greater than 10 meter (735 KV)	10	

Table 5.3: c and W.F of Different Parameters for Risk Study (Hydro-Quebec, 2001)

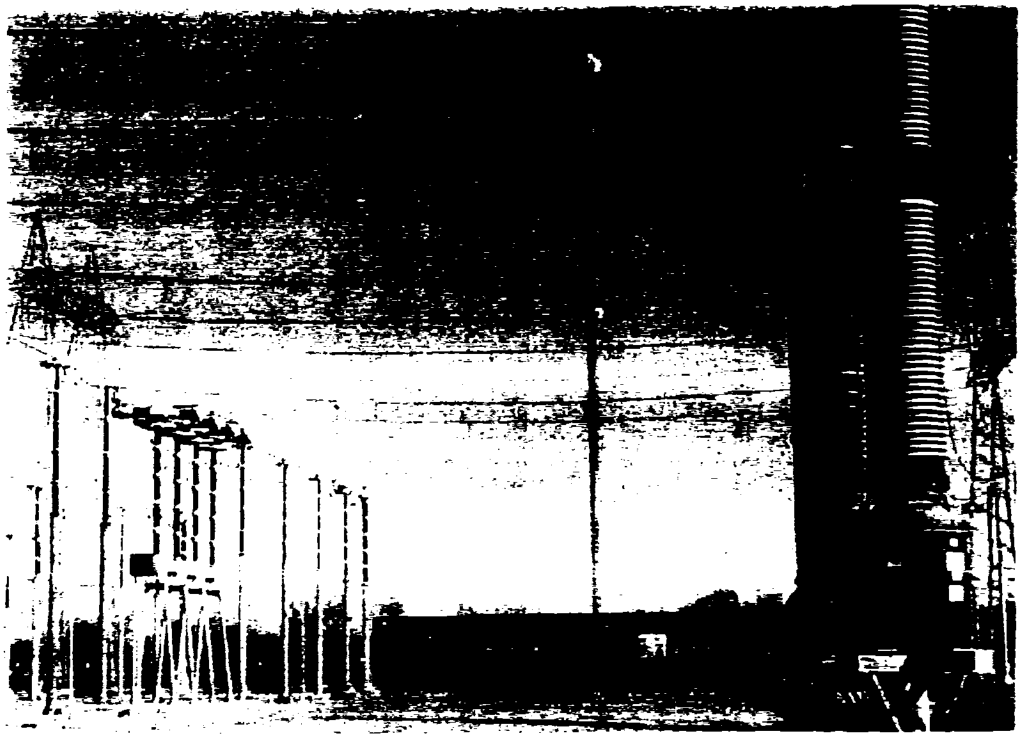


Figure 5.13: PK8C Circuit Breaker with Ceramic and Steel Support
(Hydro-Quebec, 2001)

Figure 5.14: Circuit Breaker DLF 735 KV
(Hydro-Quebec, 2001)

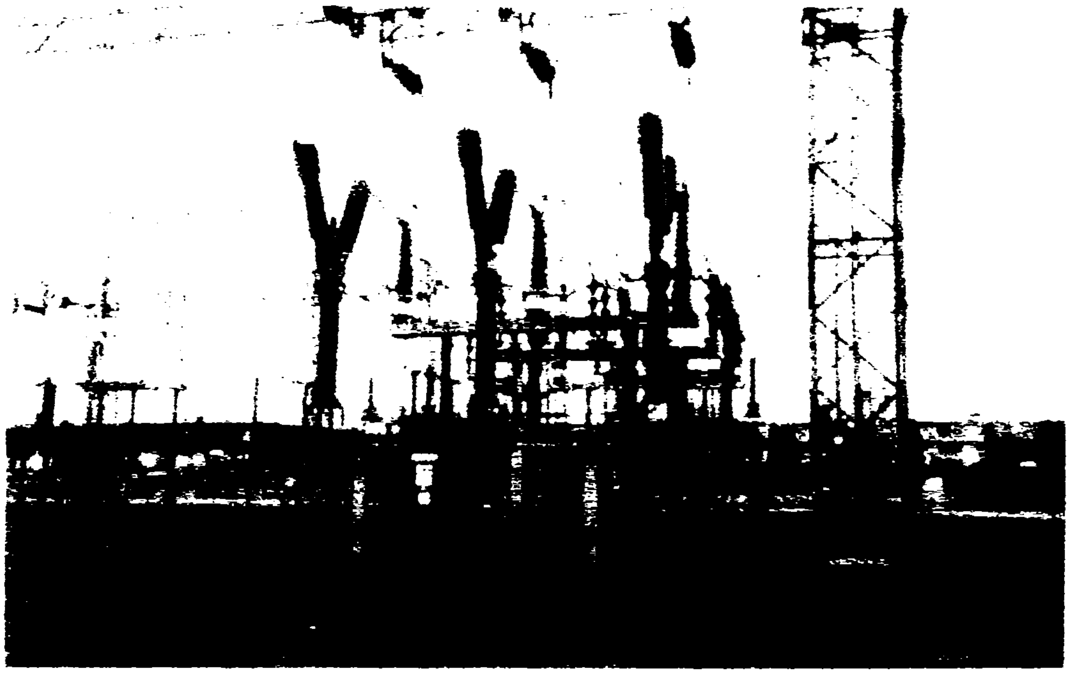


Figure 5.15: Circuit Breaker OR2M Very Heavy Installed On Hollow Support Insulation, Un Braced Metal Frame and Lightly Anchored (Hydro-Quebec, 2001)

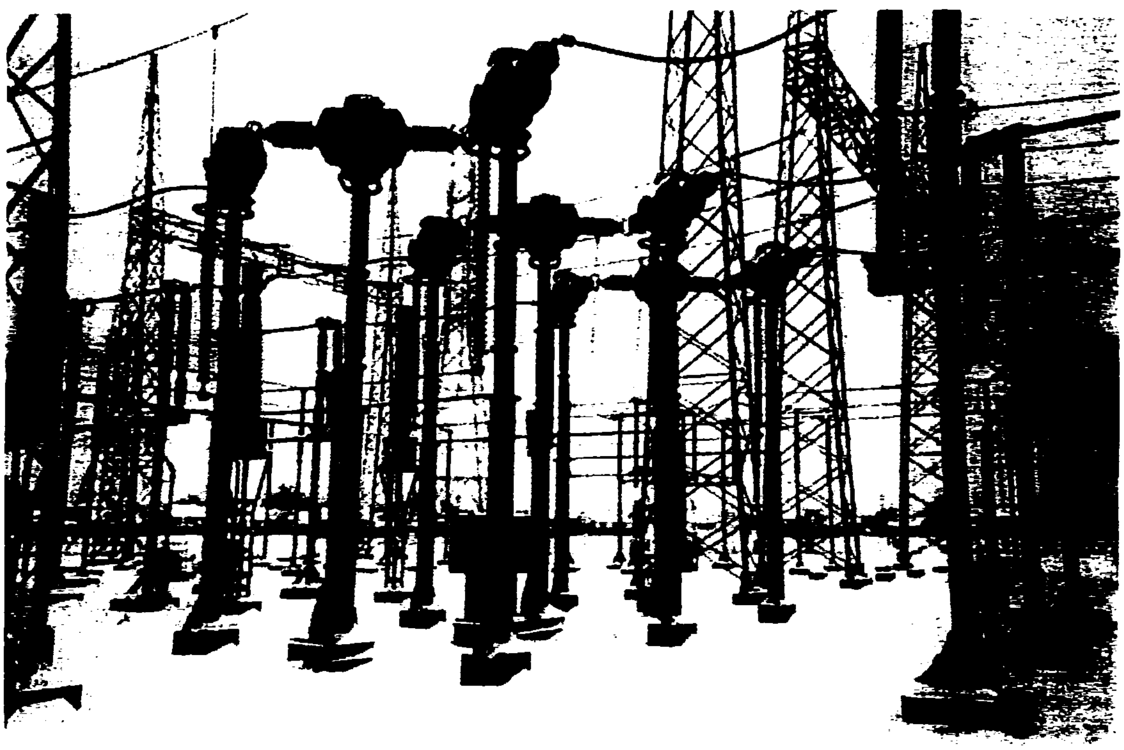


Figure 5.16: Very Heavy Circuit Breaker AT 315 KV, Mass Concentrated at Top, Behaves Like a Reversed Pendulum (Hydro-Quebec, 2001)

Figure 5.17: Circuit Breaker Delle PK4A with Vulnerable Insulation Supports
(Hydro-Quebec, 1999)

Figure 5.18: Vulnerable Support of Circuit Breaker (Hydro-Quebec, 1999)

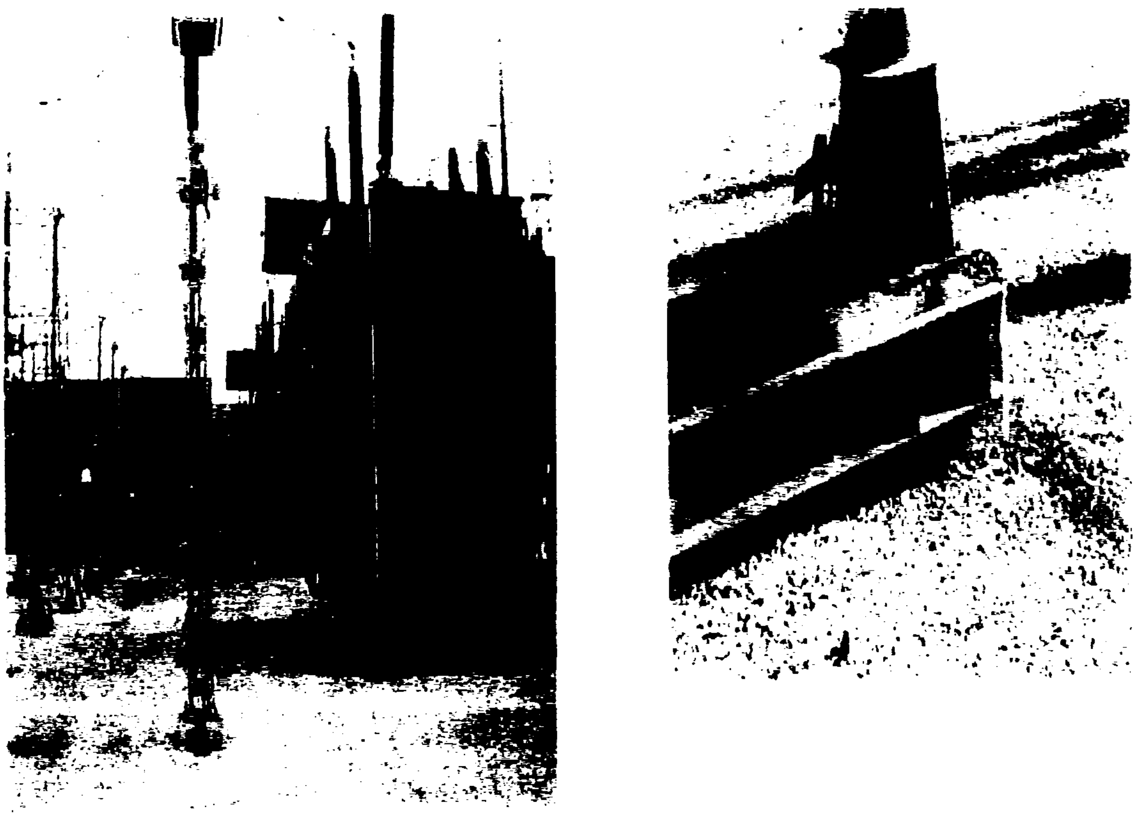
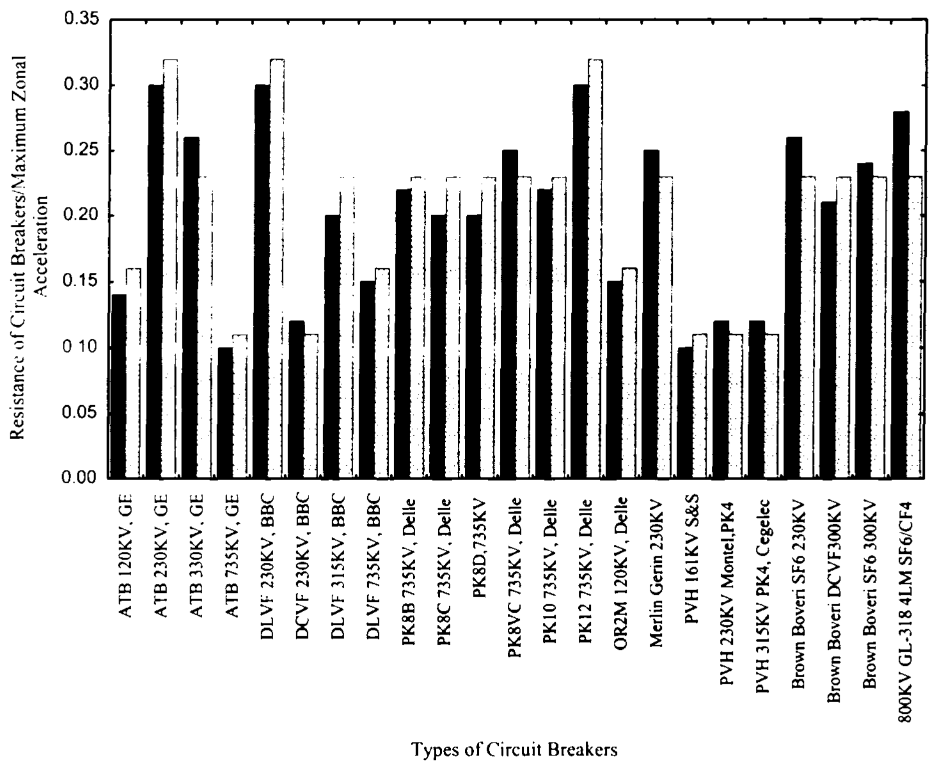


Figure 5.19: Defective Anchoring of the Support of PK4 Circuit Breaker
(Hydro-Quebec, 2001)

Figure 5.20: Circuit Breakers SF6 of GEC with Adequate Para seismic Criteria.
(Hydro-Quebec, 1999)

5.5 Adequacy of Different Types of Circuit Breakers of Hydro-Quebec

Different types of circuit breakers have limited applicability in different seismic zones. Zonal application limits depend on the resistance of circuit breaker (Figure 5.21). Probability of failures of circuit breakers in different seismic zones are presented in Table 5.4.



PGA on Rock Circuit Breaker Resistance

Figure 5.21: Zone Limit Application of Different Types of Circuit Breakers

Circuit Breaker Type	Circuit Breaker Resistance in(g)	Zone	Probability of Failure Range (%)	Zone	Probability of Failure Range (%)
ATB 120KV, GE	0.14	3	0.01 - 1	4	1 - 30
ATB 230KV, GE	0.3	5	0.01 - 1	6	1 - 95
ATB 330KV, GE	0.26	5	0.01 - 2	6	2 - 100
ATB 735KV, GE	0.1	2	0.01 - 1	3	1 - 20
DLVF 230KV, BBC	0.3	5	0.01 - 1	6	1 - 95
DCVF 230KV, BBC	0.12	2	0.01 - 0.1	3	0.1 - 4
DLVF 315KV, BBC	0.2	4	0.01 - 1	5	1 - 20
DLVF 735KV, BBC	0.15	3	0.01 - 1	4	1 - 20
PK8B 735KV, Delle	0.22	4	0.01 - 1	5	1 - 10
PK8C 735KV, Delle	0.2	4	0.01 -1	5	1 - 20
PK8D,735KV	0.2	4	0.01 - 1	5	1 - 20
PK8VC 735KV, Delle	0.25	4	0.001 - 0.1	5	0.1 - 4
PK10 735KV, Delle	0.22	4	0.01 - 1	5	1 - 10
PK12 735KV, Delle	0.3	5	0.01 - 1	6	1 - 95
OR2M 120KV, Delle	0.15	3	0.01 - 1	4	1 - 10
Merlin Gerin 230KV	0.25	4	0.01 - 0.1	5	0.1 - 3
PVH 161KV S&S	0.1	2	0.01 - 1	3	1 - 20
PVH 230KV Montel,PK4	0.12	2	0.01 - 1	3	1 - 20
PVH 315KV PK4, Cegelec	0.12	2	0.001 - 0.1	3	0.1 - 4
Brown Boveri SF6 230KV	0.26	5	0.01 - 2	6	2 -99
Brown Boveri DCVF300KV	0.21	4	0.01 - 1	5	1 - 12
Brown Boveri SF6 300KV	0.24	4	0.001 - 0.1	5	0.1 - 5
800KV GL-318 4LM SF6/CF4	0.28	5	0.01 - 1	6	1 - 98

Table 5.4: Resistance and Probability of Failure Range in Different seismic Zones of Different Types of Circuit Breakers

5.6 Conclusion

In this study fragility curves of circuit breakers are obtained using the nominal resistance of circuit breakers. The fragility curves are established from the probabilities of failure corresponding to various levels of peak ground acceleration. These curves represent the expected performance of circuit breakers in the event of an earthquake. From the analysis we find that ATB 120KV GE, ATB 735KV GE, DCVF 230KV BBC, DLVF 735KV BBC, OR2M 120KV Delle, PVH 161KV S&S, PVH 230KV PK4, PVH 315KV PK4 circuit breakers are very vulnerable. These types of circuit breakers are not acceptable for zone 4 (Montreal and Quebec City) under the current code. ATB 230KV GE, ATB 330KV GE, DLVF 230KV BBC, DLVF 315KV BBC, PK8B 735KV, PK8C 735KV, PK8D 735KV, PK8VC 735KV, PK10 735KV, PK12 735KV, Merlin Gerin 230KV, GL-318 4LM, and Brown Boveri circuit breakers are acceptable in zone 4 under the current code but not acceptable in zone 6 (Center of Charlevoix, Kamouraska, La Malbaie, Riviere-du-Loup). Fragility curves of ABB circuit breakers are obtained using an analysis of applied moment and are found to be highly reliable. The fragility analysis indicates that high voltage circuit breakers are more vulnerable than low voltage circuit breakers. Fragility curve of ATB 230KV GE circuit breaker developed by this study is compared with the fragility curve from field damage data of past earthquakes of CB9 circuit breaker. The study shows fragility curve of ATB 230KV GE circuit breakers underestimate failure probability when PGA value is less than 0.45g. The reason might be that, peak ground accelerations used to plot the data are based on attenuation relationships rather than actual recordings. Also, spectral acceleration may be a better predictor of equipment performance rather than peak ground acceleration.

Chapter 6

Seismic Risk of Substations Control Buildings

6.1 Introduction

Electric substations control buildings are vulnerable to earthquake ground motion. Control equipment is located inside control buildings and building damage results in severe damage to control equipment. During past earthquakes, many substation control buildings were damaged and resulted in significant service disruptions. Considering their importance, Hydro-Quebec performed vulnerability studies of some of the important substations control buildings. In this chapter, the critical parameters of the vulnerability of substation control buildings and the seismic base shear resistance capacity calculated according to the National Building Code are described.

6.2 Hydro-Quebec Study

The following parameters are used for the vulnerability assessment of substations control buildings: Geology of the site, Year of design of the building, Load bearing structure of the building, Geometrical irregularity, Mass and anchoring of roof and floor, and Condition of building. Hydro-Quebec developed equations 3.1 and 3.2 and Tables 6.1 to 6.3 to determine the seismic vulnerability of substation control buildings.

Parameters	Different Conditions	c	W.F
Geology of the site	Rock/dense or compact ground with coarse grains; firm and consistent ground with fine grains, of depth =< 15 m	1	4
	Not very deep ground of characteristic intermediary	2.5	
	Compact soils with large particles thicker than 15 meter, or on semi-compact soils with large particles or soft soil with fine particles or soft clay less than 15-meter thick	5	
	Semi-compact soils with large particles on soft soil with fine particles thicker than 15 meter	7.5	
	Loose to very loose soils with fine particles thicker than 15 meter	10	
Year of design of the building	1986 - 2000 (3rd generation: conform to the earthquake standards)	1	5
	1971 - 1985 (2nd generation)	5	
	1957 - 1970 (1st generation)	10	
Load bearing structure of the building	Metal structure adequately braced/ structure meet resistant to the moment/ prefabricated building conformity with the standards, anchored positively on adequate foundations or low walls/ the roof is heavy compared to the conventional	1	6
	Reinforced concrete frame resistant to the moment/combined structure of precast and prestressed concrete with anchoring and detail of adequate assembly/simple metal framework with wall of filling in masonry not armed, and braced with rigid elements/ roof or the floor is heavy compared to a conventional	2.5	
	Metallic framework braced by ties/masonry armed in the two directions/metal building with 1st flexible level/prefabricated building anchoring with friction/the roof or the floor is heavy compared to the conventional	5	
	Prefabricated concrete framework of non-adequate assembly, joint or anchoring (or not resistant to the moment)/badly anchored on non-adequate low walls / metal framework (simple, articulated) with not armed masonry wall filling/framework metal resistant with weakness or deficiencies in the joints/ or anchoring the roof or floor is defective	7.5	
	Load-bearing wall in not armed masonry/prefabricated building simply deposited on low walls	10	

Table 6.1: c and WF of geology of the site, year of design of the building, and load bearing structure of the building (Hydro-Quebec, 2001)

Parameters	Different Conditions	c	W.F
Geometrical irregularity	Absence of irregularity	1	1.5
	Not very marked irregularity	2.5	
	Horizontal irregularity	5	
	Both horizontal and vertical irregularity	10	
Mass and anchoring of roof and floor	Roof and light floor anchored properly on framework or load-bearing walls and concrete slab anchored well on the support	1	4
	Roof and intermediate floor of weights anchored on framework or load- bearing walls and prefabricated reinforced concrete slab anchored well on the supports	2.5	
	Load bearing walls and roof or floor anchored partially	5	
	Simply supported light roof and floor not anchored properly or heavy roof partially anchored and braced with light floor adequately fixed and braced	7.5	
	Roof and heavy floor or load-bearing walls or roof and pre-stressed and prefabricated concrete not anchored between them	10	
Condition of building	Materials and structural elements not degraded and not damaged	1	1
	Somewhat faded materials and structural elements damaged	5	
	Critical state: concrete or masonry seriously damaged, corroded steel etc	10	

Table 6.2: c and WF of geometrical irregularity, mass and anchoring of roof and floor, and condition of building (Hydro-Quebec, 2001)

Consequences (C): The scale of consequences varies from 1 to 10. The value of consequences depends on the strategic importance of the substation building. Strategic importance depends on:

1. Impact of the loss
2. The continuity of service of buildings and
3. Loss of income

Table 6.3 present the value of consequences for different value of strategic dimension.

Strategic Importance	Value of Consequence
Strategic importance: 0.1	1
Strategic importance: 0.2 to 0.3	2.5
Strategic importance: 0.4 to 0.5 or small occupation of number less than 4 and duration less than 7hour/week	5
Strategic importance: 0.6 to 0.7 or average occupation	7.5
Strategic importance: 0.8 or very frequent occupation of number less than or equal to 4 continuously	8.5
Strategic importance: 0.9 to 1 or very frequent occupation of long duration of number greater than 4 continuously	10

Table 6.3: Value of Consequences According to Strategic Dimension of Substations Buildings (Hydro-Quebec, 2001)

6.3 Critical Parameters

Substation buildings are classified into six categories of structures

1. Terra cotta or hollow clay brick
2. Steel braced with concrete block
3. Reinforced Cement Concrete (R.C.C.) column and beam not rigid connections
4. R.C.C. and masonry wall

5a. Two level with braced steel frame

5b. Two level with R.C.C.

6. Trailer / mobile structure

The substations control buildings of Table 6.4 are considered for the analysis. The type of structure for each of building is presented in Table 6.4. The database of risk study of buildings is analysed by STATISTICA ^{R}. The analysis shows that the critical parameters of vulnerability are Geology of the site, Year of design of the building, Load bearing Structure of building, and Mass and anchoring of roof and floor.

Control Building	Type of Structure
Duvernay (Building 4)	Load bearing wall
Duvernay (Building 3)	Load bearing wall
Duvernay (Building 8)	Load bearing wall
Levis (Building 1)	Terra cotta / hollow brick
La Prairie (315KV)	Terra cotta / hollow brick
Chateaugay (Building 1)	Unreinforced masonry with steel frame
Notre-Dame (315KV)	Load bearing wall
Jacq-Cartier (Building 1)	Unreinforced masonry with steel frame
Jacq-Cartier (Building 2)	Unreinforced masonry with concrete frame
Charlevoix (315-69KV)	Load bearing wall
Rivdu-Loup (315-230KV)	Unreinforced masonry with steel frame

Table 6.4: Type of Structures of Substations Control Buildings
(Hydro-Quebec)

Figure 6.1 shows the value of each critical parameter for the substation control buildings considered in the analysis. It is observed that most of the buildings were designed before 1970 without considering earthquake design standards and are very vulnerable. Most of the structures are load-bearing walls that are very fragile to seismic ground motion. Table 6.5 shows the percent contribution of different parameters to the vulnerability index. From the analysis it is shown that the parameter 'load bearing structure of building' has the highest contribution to the vulnerability index. Vulnerability also depends significantly on Year of design of building, Anchoring of roof and floor, and Geology of the site. Figure 6.2 provides the mean, maximum and minimum percent contributions of different parameters to the vulnerability index.

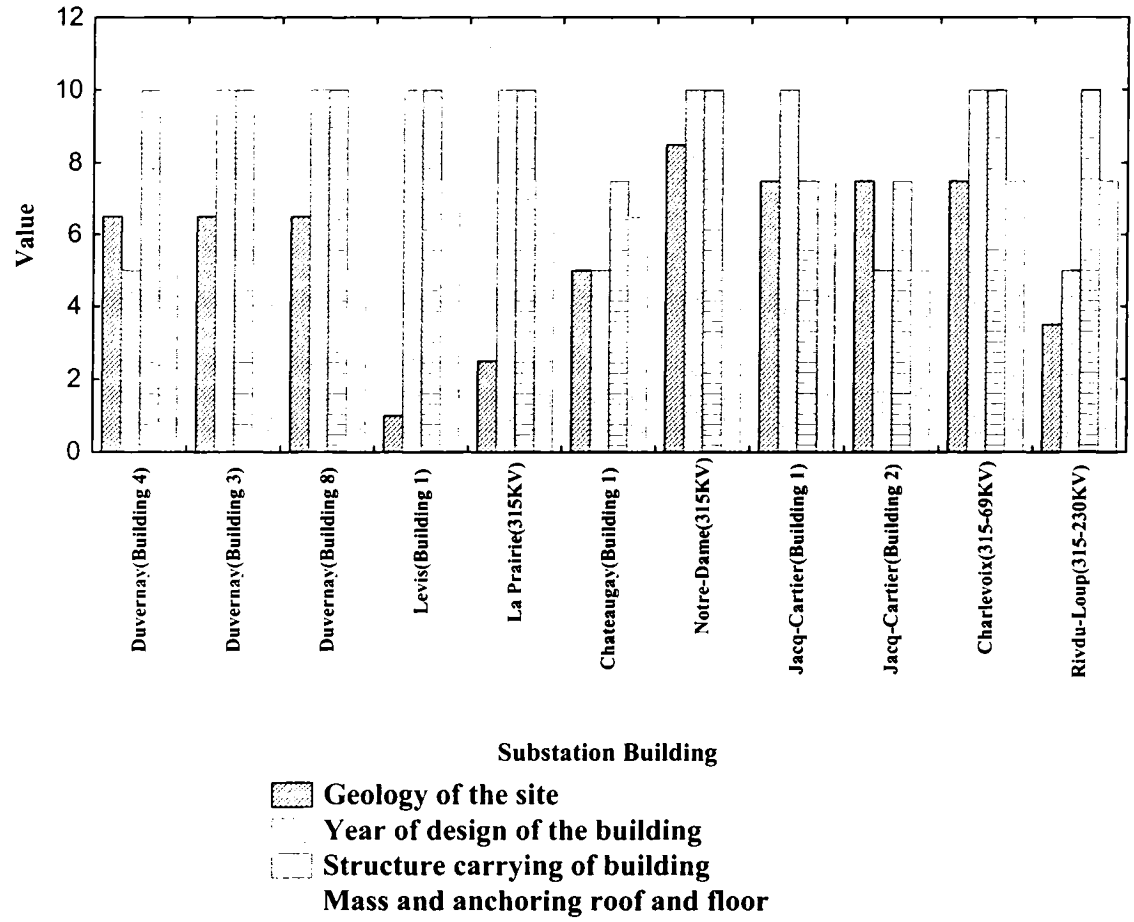


Figure 6.1: Value of Geology of the site, Year of design of the building, Load bearing Structure of building, and Mass and anchoring of roof and floor

Parameters	Mean	Minimum	Maximum	St.Dev.
Geology of the site	15.28	2.69	24.49	6.44
Year of design of building	26.84	17.83	33.61	6.21
Load bearing structure of building	37.50	28.57	44.19	4.15
Geometrical irregularity	2.24	0.87	6.02	1.58
Anchoring of roof and floor	16.90	12.01	21.39	3.50
Condition of building	1.23	0.58	4.28	1.25

Table 6.5: Statistics on Contribution (%) of Different Parameters to Vulnerability Index of Building

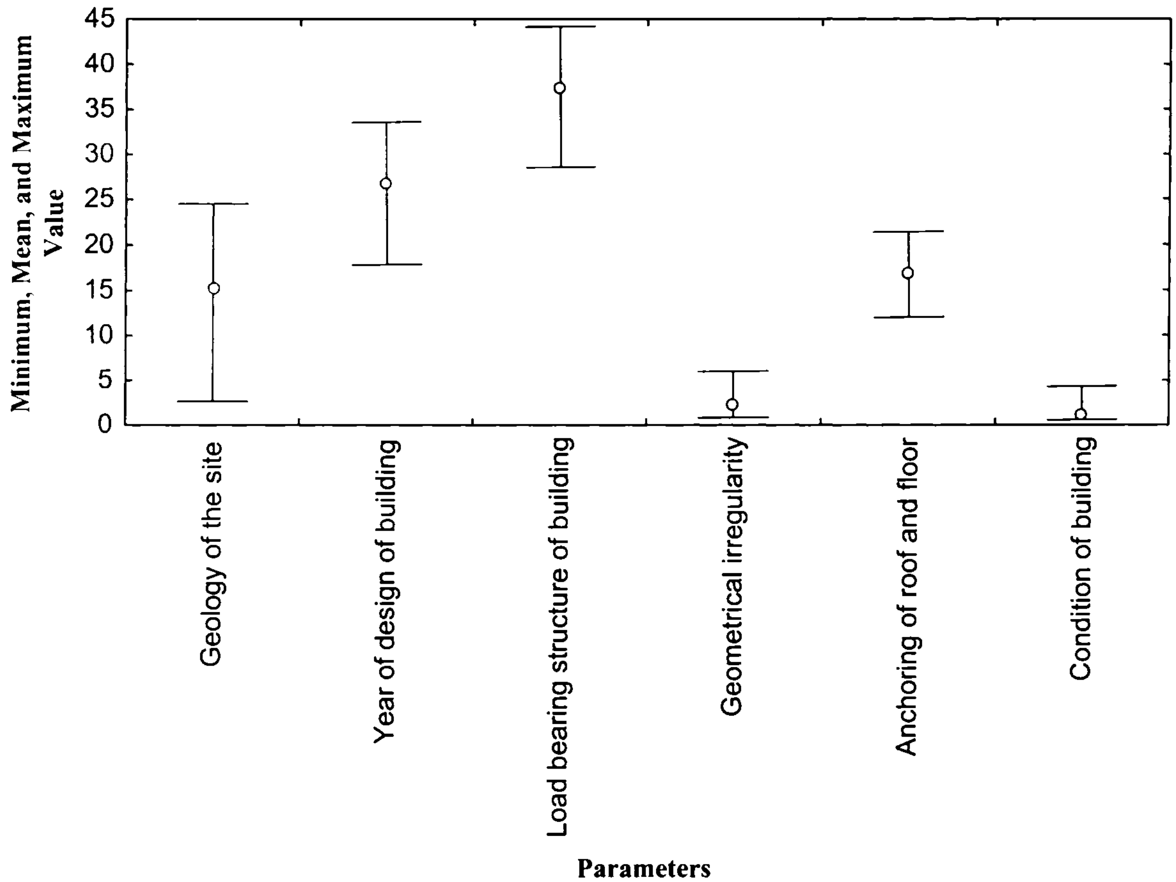


Figure 6.2: Contribution (%) of Parameters to Vulnerability Index of Buildings

6.4 Vulnerability, Risk and Correlation

Figure 6.3 shows the vulnerability of each building. It is observed that the vulnerability of all the control buildings exceeds the critical vulnerability level 4. Substation control buildings in Charlevoix are very vulnerable to earthquakes. The vulnerability index for this building is more than 8. The Charlevoix substation is located in zone 6 where the earthquake threat is very significant and seismic exposure level is high. Figure 6.4 shows the correlation between vulnerability and risk. It is observed that vulnerability and risk are perfectly correlated indicating that consequence of failure is the same for all the substations.

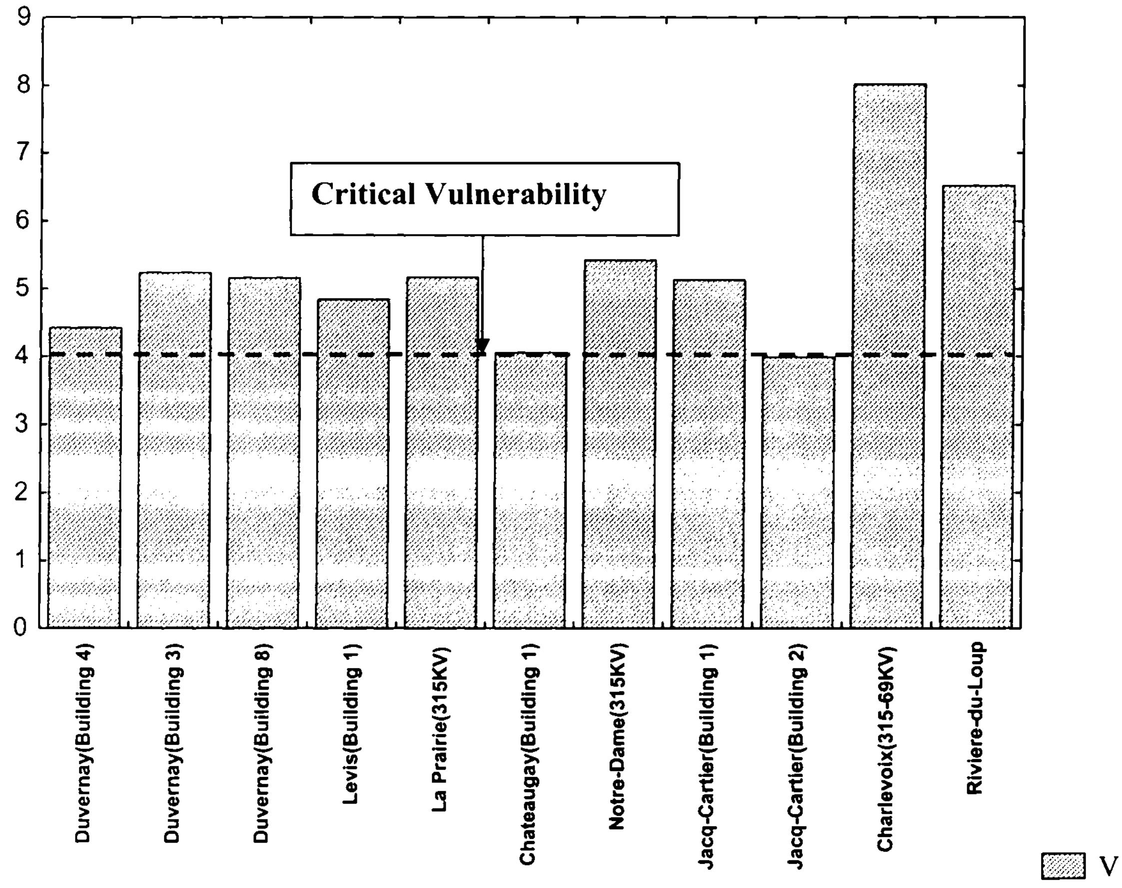


Figure 6.3: Vulnerability Level of Different Control Buildings

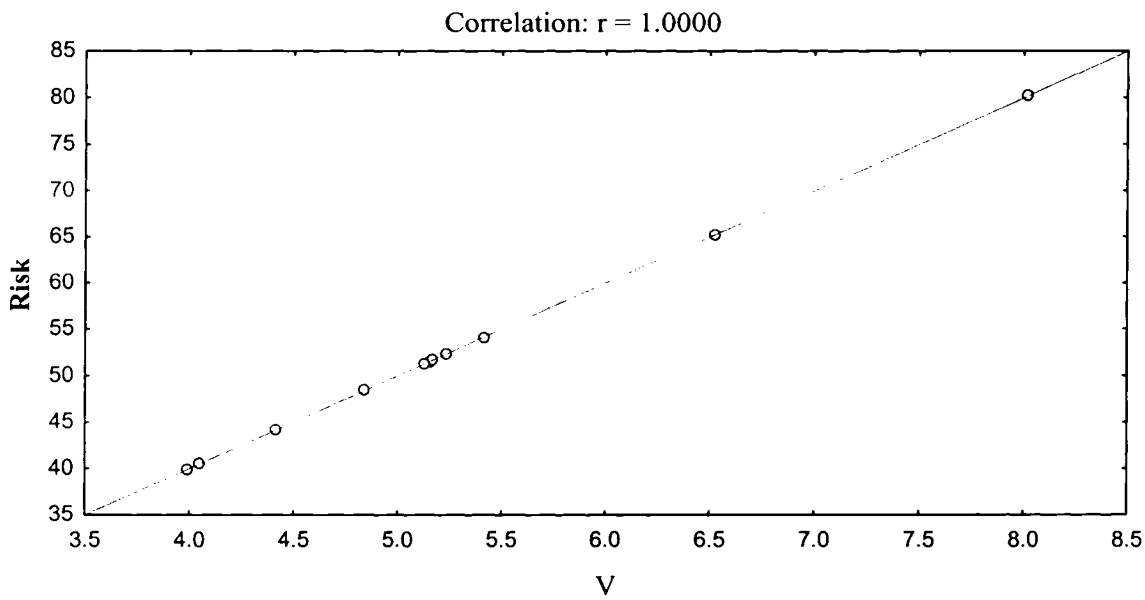


Figure 6.4: Correlation of Vulnerability with Risk

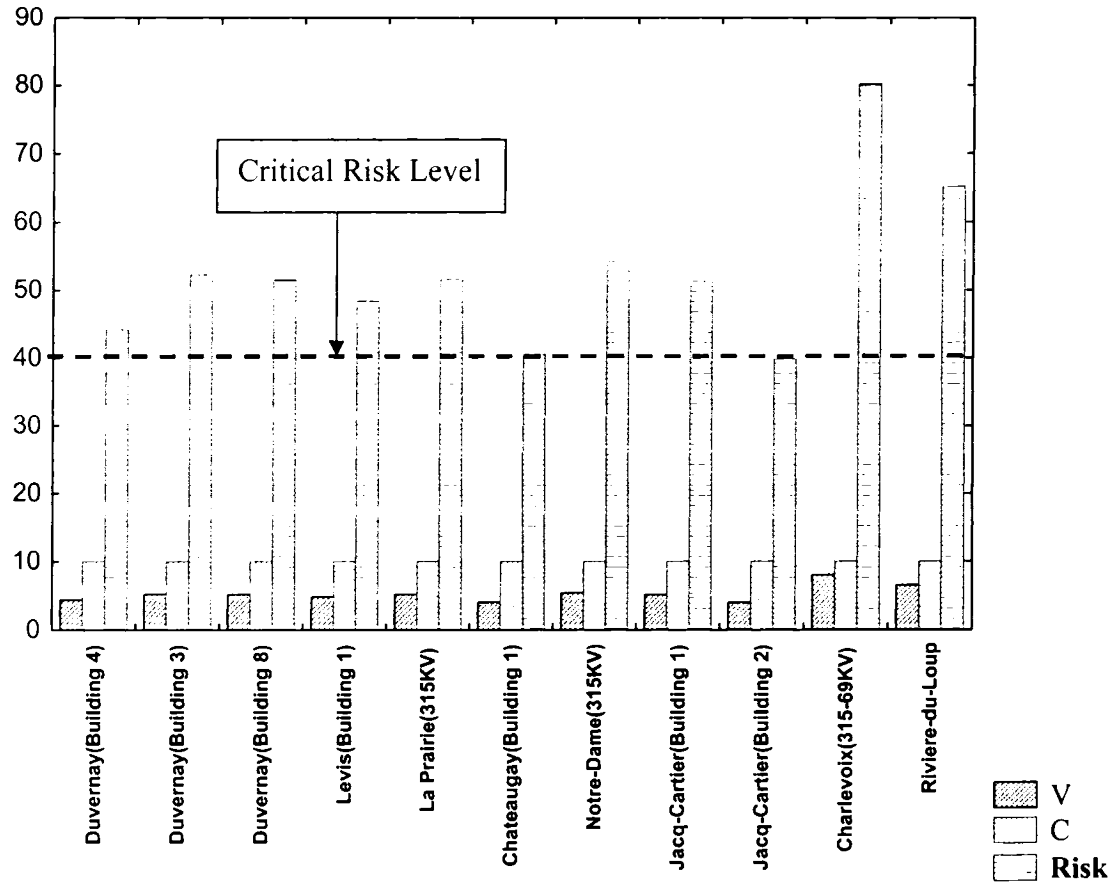


Figure 6.5: Vulnerability, Consequences, and Risk of Different Control Buildings

Figure 6.5 shows the vulnerability, consequences and risk for the different substation control buildings. It is observed that all the control buildings exceed the critical risk level 40. The control building of Charlevoix is at the most extreme risk level followed by Riviere-du-Loup.

6.5 Base Shear Coefficient (V/W) of Duvernay

Lateral earthquake design forces at the base of the Duvernay substation control building is determined by using the NBCC 1995 and the proposed NBCC 2005

6.5.1 Base Shear Using NBCC 1995

The base shear is the equivalent lateral seismic force representing the elastic response, V_e calculated in accordance with the following formula:

$$V_e = v\ S\ I\ F\ W$$

Where,

Zonal velocity ratio, $v = 0.1$

Velocity related seismic zone, $Z_v = 2.0$

Acceleration related seismic zone, $Z_a = 4.0$

Seismic zonal ratio, $Z_a/Z_v = 2.0$

Seismic response factor, S depends on fundamental period of vibration of the building T and Z_a/Z_v. For Duvernay substation building the fundamental period is estimated as;

$$T = .09h_n/(D_s)^{1/2}$$

$$= 0.095 \text{ sec}$$

Where, h_n = the height of the building above the base = 3.35m

D_s = dimension of wall which constitutes the main lateral load resisting system in a direction parallel to the applied forces

= 12.75m

Now for T = .095 sec and $Z_a/Z_v = 2.0$ we get the value of seismic response factor, S = 4.2 from Table 4.1.9.A of NBCC 1995

Seismic importance factor, I = 1.5 for post-disaster building

Foundation factor, F = 1.0 according to Table 4.1.9.1.C of NBCC 1995 for soil condition of Duvernay

$$\text{Now, } V_e = v\ S\ I\ F\ W$$

$$= (0.1)\ (4.2)\ (1.5)\ (1.0)\ W$$

$$= 0.63\ W$$

The minimum lateral seismic force, V, is calculated in accordance with the following formula:

$$V = (V_e/R)\ U$$

R = force modification factor, from Table 4.1.9.1.B of NBCC 1995 the value of R for unreinforced masonry of Duvernay substation control building is 1.0

U = level of protection factor based on experience = 0.6

$$\text{Now, } V = (0.63W)/1.0 \cdot 0.6$$
$$= 0.378\ W$$
$$= 0.378 \times 1262$$
$$= 477\ KN$$

For ordinary steel plate shear wall we get, R_d = 2 from Table 4.1.9.1.B.

$$\text{So, } V = (0.63W)/2 \cdot 0.6$$
$$= 0.252\ W$$
$$= 0.252 \times 1262$$
$$= 238.52\ KN$$

Considering torsion,

$$V_f\ \text{wall} = 55\%\ V = 0.55 \times 238.52$$
$$= 131\ KN$$

6.5.2 Resistance and Reliability of the Building

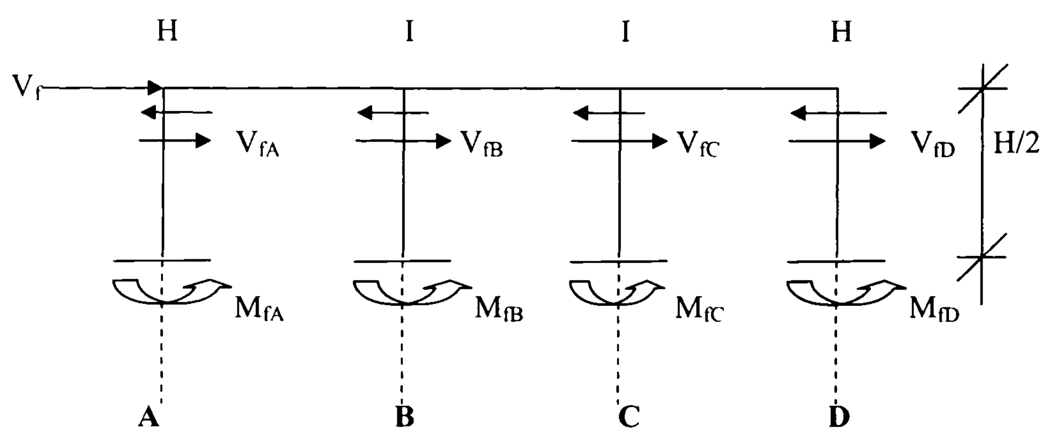


Figure 6.6: Seismic Base Shear and Moment to the Structural System of Duvernay
(Moffet, 2002)

$$V_f = V_{fA} + V_{fB} + V_{fC} + V_{fD} = 131 \text{ KN}$$

$$V_{fA} = V_{fD} \quad \text{and} \quad V_{fB} = V_{fC}$$

W 150 × 22 steel section is used

$$I_A = I_D = I_{XXW150\times 22} = 12.1 \times 10^6 \text{ mm}^4$$

$$I_B = I_C = I_{YYW150\times 22} = 3.87 \times 10^6 \text{ mm}^4$$

$$I_A / I_B = 3.13 \quad \text{and} \quad V_{fA} = I_A / I_B\, V_{fB} = 3.13\, V_{fB}$$

Now, $V_f = 3.13V_{fB} + V_{fB} + V_{fB} + 3.13V_{fB} = 8.26\, V_{fB} = 131$ KN

$$V_{fB} = V_{fC} = 15.86 \text{ KN}$$

$$V_{fA} = V_{fD} = 3.13V_{fB} = 3.13 \times 15.86 = 49.64 \text{ KN}$$

$$M_{fA} = M_{fD} = V_{fA} \times H/2 = 49.64 \times 4.5/2 = 111.69 \text{ KN.m}$$

$$M_{fB} = M_{fC} = V_{fB} \times H/2 = 15.86 \times 4.5/2 = 35.68 \text{ KN.m}$$

For W 150 × 22 steel section,

$$M_{RX} = 42.9 \text{ KN.m and } M_{RY} = 13.7 \text{ KN.m}$$

Now, $M_{RX} / M_{fA} = 42.9/111.69 = 0.38$ $\quad$ $M_{RY} / M_{fB} = 13.7/35.68 = 0.38$

To calculate the probability of failure of the building we considered the nominal seismic base shear to be two standard deviations above the mean value and the nominal resistance of the steel section to be two standard deviations below the mean value. It is further assumed that the uncertainty on the lateral load has a COV of 0.40. The uncertainty on the resistance of the steel section, considering the uncertainties in material properties, fabrication, and modeling is 0.20. Also, all the variables are considered as normal random variables. The applied moment caused by the nominal load is 111.69 KN.m. The plastic moment capacity of the steel section can be considered to be the nominal moment capacity of the steel section, which is 42.9 KN.m. Using the above assumptions, we get the mean value of applied moment and resistance as 62.05 KN.m and 71.5 KN.m respectively. The reliability index, β is 0.33 and the corresponding probability of failure is equal to 0.37,

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

$$p_f = 1 - \phi\left[\frac{(\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right]$$

From the analysis it is seen that the building is very vulnerable.

6.5.3 Base Shear Using Proposed NBCC 2005

The minimum lateral earthquake force, V, is calculated in accordance with the following formula:

$$V = S(T_a)M_vI_EW/(R_dR_o)$$

The design spectral acceleration values of S(T) is determined as follows:

$$\begin{aligned} S(T) &= F_aS_a(0.2) \text{ for } T \leq 0.2 \text{ sec} \\ &= F_vS_a(0.5) \text{ or } F_aS_a(0.2) \text{ whichever is smaller for } T = 0.5 \text{ sec} \\ &= F_vS_a(1.0) \text{ for } T = 1.0 \text{ sec} \\ &= F_vS_a(2.0) \text{ for } T = 2.0 \text{ sec} \\ &= F_vS_a(2.0)/2 \text{ for } T \geq 4.0 \text{ sec} \end{aligned}$$

The fundamental lateral period of vibration, T_a of the building is calculated according to article 4.1.8.11.3. of NBCC 2005,

$$\begin{aligned} T &= 0.05\,(h_n)^{3/4} \\ &= 0.05 \times 5.26^{3/4} \\ &= 0.17 \text{ sec} \end{aligned}$$

The site class of the Duvernay substation is 'C' which is determined by using Table 4.1.8.4.A. of NBCC 2005. Acceleration- based site coefficient, $F_a = 1$, which is a function of site class and $S_a(0.2)$ as determined by Table 4.1.8.4.B. of NBCC 2005. The 5% damped spectral response acceleration values $S_a(T)$ for site class 'C' for periods 0.2 sec for the region is 0.69. This value is determined in accordance with subsection2.2.1 of NBCC 2005 and is based on 2 % probability of exceedance in 50 years.

$$S\,(T) = 1.0 \times 0.69 = 0.69$$

The seismic importance factor is, $I_E = 1.5$ for post-disaster buildings (Table 4.1.8.5. of NBCC 2005). The higher mode factor is, $M_v = 1.0$, from Table 4.1.8.11. The force modification factor of the Seismic Force Resisting Systems (SFRS) is, $R_d = 1$ and the over strength factor $R_o = 1$, are determined from Table 4.1.8.9 of NBCC 2005 for unreinforced masonry structures.

$$\text{Now, } V = (0.69)\,(1)\,(1.5)\,(W)/\,(1.0 \times 1.0)$$
$$= 1.035\ W$$

For a conventional steel structure of moment resisting frames we get, $R_d = 1.5$ and $R_o =$ 1.3 from Table 4.1.8.9.

$$\text{Then, } V = (0.69)\,(1)\,(1.5)\,(W)/\,(1.5 \times 1.3)$$
$$= 0.531\ W$$

According to NBCC 2005 for an SFRS with an R_d equal to or greater than 1.5, V need not to take more than 2/3 of V.

$$\text{So, } V = 0.354\ W$$
$$= 0.354 \times 1262$$
$$= 446.75\ \text{KN}$$

Comparing NBCC 1995 with NBCC 2005, we get a seismic base shear increase for the new code for short duration. As the base shear increases the applied moment to the structure will be increased. The corresponding probability of failure is equal to 0.90. So, the probability of failure of the Duvernay substation control building will be higher for NBCC 2005 than NBCC 1995.

6.6 Conclusion

Substation control buildings are one of the most seismically vulnerable components of an electric distribution network. Their damage resulting from their collapse also damages the interior control equipment that causes power outage. In this study, the seismic risk level on some of the important substation control buildings of Hydro-Quebec was analyzed. It is observed that the vulnerability and risk index of all the control buildings exceed the critical vulnerability level of 4.0 and the critical risk level of 40.0. Geology of the site, year of design of the building, load bearing structure of the building, and mass and anchoring of roof and floor are identified as the most critical parameters responsible for high vulnerability index. Among the parameters "load bearing structure of building" is considered as the most critical parameter. Substation control buildings made of unreinforced masonry are very vulnerable to earthquakes. Seismic base shear were calculated using NBCC 1995 and the proposed NBCC 2005 and confirm the extreme vulnerability of these types of buildings.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Statistical analysis of seismic vulnerability and risk index of electric power substations of Hydro-Quebec was performed using STATISTICA^R. From the analysis, the main causes of high seismic risk for substations and ways of reducing the risk level are identified. The analysis identified the four most critical parameters responsible for high-risk index of substations: year of manufacture of equipment, anchoring of heavy equipment, load-bearing structure of the building and control systems. By acting on the above parameters, quantitative seismic risk level of substations can be significantly reduced and large-scale losses due to earthquakes can be avoided. Data analysis indicates that half of the substation equipment was made before 1975 without considering earthquake standards. Up to 90 percent of substation equipment lacks proper anchoring. More than half of substations control buildings are unreinforced masonry structures. These types of structures are very vulnerable to earthquakes and increase the risk level of the substations. This study also suggests that risk levels are very sensible to seismic exposure levels. Risk levels rise significantly when the seismic exposure level is 1.0.

Nominal resistances of different types of circuit breakers were used to assess the fragility of equipment with an analytical approach. The fragility curve was developed from the probabilities of failure corresponding to various levels of peak ground acceleration. The fragility analysis quantifies the performance of circuit breakers in the event of an earthquake. Analysis indicates that ATB735KV GE, ATB120KV GE, DCVF230KV BBC, PVH161KV S&S, PVH230KV S&S, PVH315KV S&S circuit breakers are vulnerable to earthquakes at low levels of PGA and are not acceptable under the current code and proposed NBCC 2005 specifications for zone 4 (Montreal and Quebec city).

This study also shows that different types of Delle, Merlin Gerin, and Brown Boveri circuit breakers have low reliabilities under the specifications of NBCC 2005. ABB LTB and ABB HPL circuit breakers have high reliabilities and are suitable for high seismic exposure level areas. The fragility curves determined by analytical methods are compared with earthquake damage data and Utility Working Group fragility curves. The fragility curve developed by the analytical procedure underestimates damage probabilities for ATB 230KV circuit breaker up to a PGA level 0.45g above that level damage probabilities are similar to field data. One explanation for the difference may be that: peak ground accelerations used to plot the data are based on attenuation relationships rather than the actual records. In addition, PGA is not probably the best indicator of equipment seismic performance; spectral accelerations may be a better predictor of performance.

The seismic risk level of important substation control buildings of Hydro-Quebec was analyzed. Most of the substation control buildings are unreinforced masonry and are very vulnerable to earthquakes. The seismic base shear coefficient (V/W) is determined by using NBCC 1995 and NBCC 2005. Seismic base shear forces increase significantly for NBCC 2005. The reliability of masonry substation buildings is very low. The reliability level can be improved by providing ductile steel or concrete structures designed in accordance with the Canadian Standards Association codes.

7.2 Recommendations

The seismic performance of existing substations can be greatly improved by providing the following upgrades:

- Anchorage of heavy equipment.
- Replacement of Masonry structures with steel structures or concrete structures designed according to Canadian Standards Association (CSA) codes.
- Reinforced masonry, designed for ductility, may offer a practical solution for the substations.

- The equipment designed before 1975 should be replaced by new equipment designed according to modern earthquake specifications.
- Special measures should be taken for the substations of zone 6 where the seismic exposure levels are very high.

7.3 Recommendations for Future Research

- Electric substations consist of many types of inter connected equipment and failure events are often not independent of each other. This study did not estimate the joint probability of failure of equipment in substations. Reliability of an entire electric substation and transmission system by determining joint component fragilities are not available currently but could be the subject of future research.

- Seismic fragility curves for the substation control buildings could be developed in future research

- Improved fragility curves could be develop by considering the uncertainties regarding PGA, site conditions, equipment types, models, and deterioration. In this context, all prevailing aleatory and epistemic uncertainties can be included in the development of fragility curves.

- Damage states can be included in the development of fragility curves. Damage states describe the level of damage to each of the electric power system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Functionality of each component of the electric power system would have to be considered for this fragility curve.

- Seismic vulnerability of substations should also be combined with the vulnerabilities of other lifelines to measure overall seismic hazards for an urban community.

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