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Modelling Extreme-Weather-Related Transmission Line Outages

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Abstract: One of the primary causes of major transmission line outages are extreme weather conditions particularly lightning, wind and conductor icing (e.g., Quebec, U.S ice storms of 1998). The statistical results of a detailed analysis of Alberta Power Limited's transmission line outage data base and Alberta Environmental Service weather data bases over a 20 year period are investigated in this paper. The analysis will reveal the significance of the geographical location of the transmission lines and their frequency of outages. The paper will also reveal that the number of transmission line outages is not necessarily proportional to the physical length of the line for many transmission lines which contradicts may published methodologies. The paper will present a Monte Carlo simulation reliability model of transmission line network configurations based on the historical Canadian Electricity Association's utility equipment reliability data base and the Environmental Service weather data bases.

Key Words: extreme weather, transmission line outages, Monte Carlo, simulation

1. INTRODUCTION

In todays deregulated power industry, the energy sources to supply a given geographical load can originate anywhere in North America as today's utilities are purchasing economical energy from various geographical energy sources (e.g., out of province and out of country) and transporting the energy over various transmission line networks to load centers. New legislation throughout the world is presently focusing on the reliability of transmission lines during adverse weather conditions. The basic objective of transmission system adequacy assessment is to evaluate the ability of transmission system to transfer energy reliably between sources of generation and distribution load points. Any single or multiple transmission line outage can significantly alter the transmission system operating configuration such that continuity between energy delivery sources to system load points is interrupted. One of the primary causes of major transmission line outages are extreme weather conditions particularly lightning, wind and icing. These weather events are dependent upon the geographical location of the transmission line.

This paper will present some of statistical characteristics of the extreme-weather related Alberta Power Limited's transmission line outages in the Province of Alberta. The transmission line outage data base covers the entire area of the province and defines the primary causes of transmission line outages, e.g., adverse weather, defective equipment, foreign interference, adverse environment, human element and systems conditions. The Alberta Provincial weather data base contains some of the following parameters: daily extreme temperature, daily highest wind speed, monthly lightning records, monthly precipitation records, etc.. Details of this data base are beyond the scope of this paper.

2.0 ADVERSE WEATHER STATISTICS

The weather elements that are considered to be adverse weather conditions are lightning, wind and precipitation. A major concern for utilities is the answer to the question: "are adverse weather conditions a significant cause of transmission lines outages in my electric delivery system"? The answer to this question is clearly shown in Figures 1 and 2 where the frequency of line-related outages are shown for all the Alberta Power Limited transmission lines.

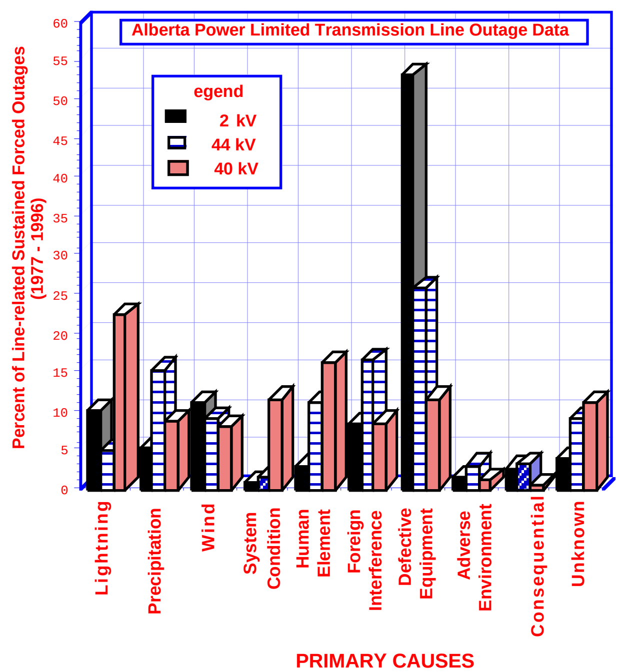

Fig 1. Primary causes of transmission line outage

In comparing the primary causes of outages, adverse weather outages are significant accounting for approximately 33% of all outages as shown in Figure 2.

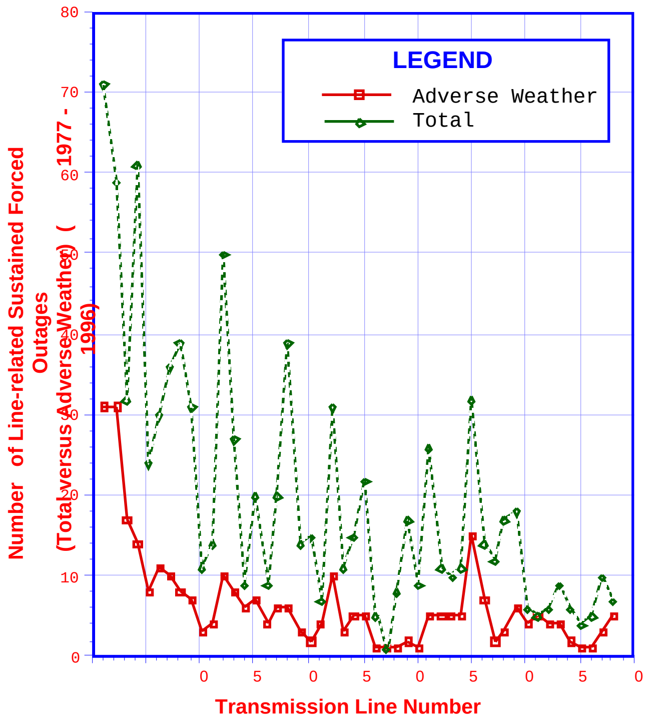

Fig 2. Frequency of adverse weather outages versus total number of outages

The basic framework for a Monte Carlo simulation model of a transmission line network configuration is to have the probability density functions of the frequency and duration of individual transmission lines for the various weather related primary causes. The following probability density functions of the failure rate of transmission line outages expressed as relative frequency histograms are shown in Figures 3, 4 and 5 to illustrate the significant differences in transmission line outage patterns.

1. Primary cause precipitation - Figure 3
2. Primary cause wind - Figure 4
3. Primary cause lightning - Figure 5

The impact of lightning wind and precipitation varies significantly between each transmission line. A correlation analysis of the transmission line outage data revealed that wind and precipitation outages were not proportional to the physical length of the transmission line. However, lightning outages were strongly correlated with the physical length of the transmission line.

A summary of the transmission line-related: sustained forced outage statistics expressed in the Canadian Electricity Association's utility format is shown in Table II.

Statistic	72 kV	144 kV	240 kV
Frequency per 100 km.a	1.521699	0.830133	0.882908
Mean duration (hours)	5.03	6.15	10.40
Median duration (hours)	2.35	1.93	2.36

Note the significant difference in statistics between the voltage classes.

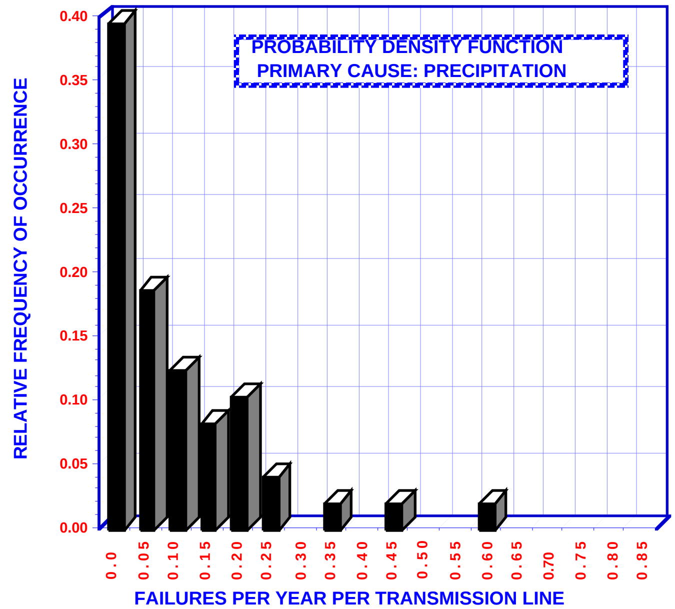

Fig 3. Relative frequency of transmission line outages - Primary cause precipitation

The mean and median duration of transmission line outages cased by precipitation is shown in Table II.

Table II
Duration of Transmission Line "Line-Related" Forced Outage Statistics Primary Cause - **Precipitation**

Statistic	72 kV	144 kV	240 kV
Mean duration (hours)	10.54	8.29	40.91
Median duration (hours)	2.64	1.62	6.77

The mean and median duration of transmission line outages caused by wind is shown in Table III. It is important to note that the median and mean duration of outages are significantly different revealing that the underlying distribution of the duration of transmission lines are skewed and not symmetrical.

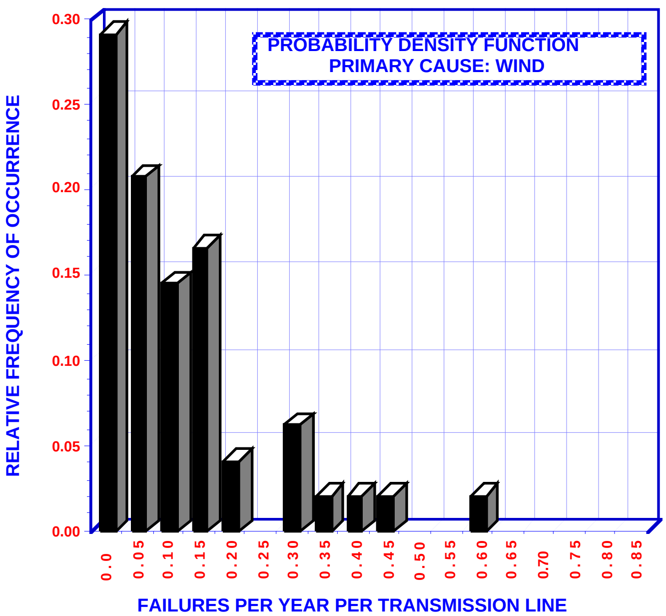

Fig 4. Relative frequency of transmission line outages - Primary cause wind

Table III :Duration of Transmission Line “Line-Related” Forced Outage Statistics
Primary Cause - Wind

Statistic	72 kV	144 kV	240 kV
Mean duration (hours)	5.79	7.03	23.04
Median duration (hours)	4.42	2.19	1.29

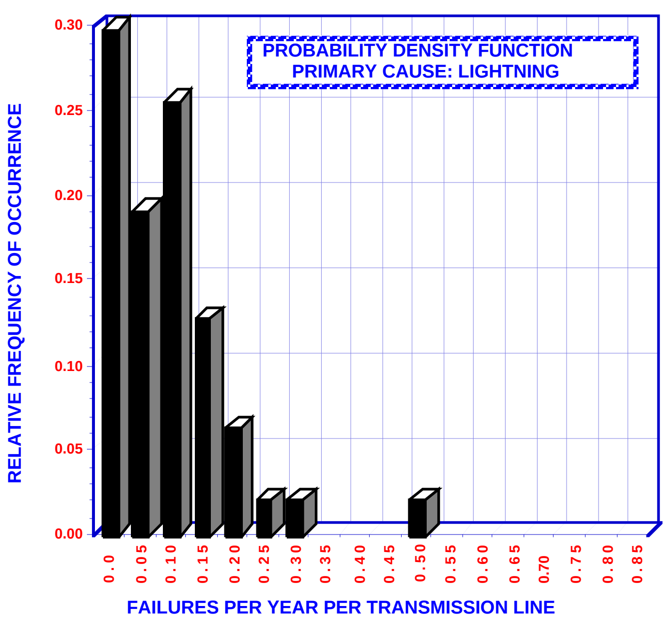

Fig 5. Relative frequency of transmission line outages - Primary cause lightning

The mean and median duration of transmission line outages cased by lightning is shown in Table IV and for defective equipment in Table V.

Table IV
Duration of Transmission Line “Line-Related” Forced Outage Statistics
Primary Cause - **Lightning**

Statistic	72 kV	144 kV	240 kV
Mean duration (hours)	7.12	104.21	1.45
Median duration (hours)	1.83	1.26	0.39

Table V
Duration of Transmission Line “Line-Related” Forced Outage Statistics
Primary Cause - Defective Equipment

Statistic	72 kV	144 kV	240 kV
Mean duration (hours)	5.42	40.20	11.16
Median duration (hours)	2.57	6.28	5.11

The province of Alberta was divided into four distinctive geographical regions. The percentage of transmission line outages by geographical region is shown in Figure 6.

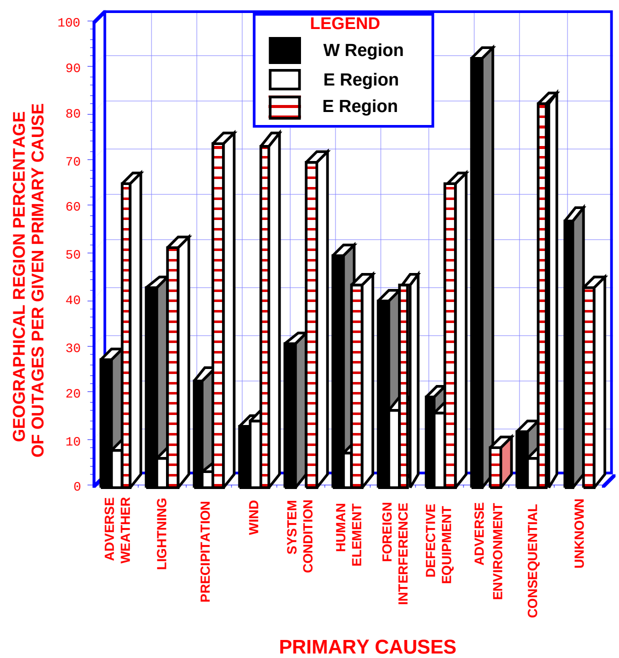

Fig 6. Percentage of transmission line outages by geographical region for a given primary cause

It is clear from Figure 6 that the majority of transmission line outages occurred in the SE Region of the province (i.e., 56.2 %) while the NW Region accounted for 36.9 % of the transmission line outages and the NE Region only 6.9%. The SW Region of the province has very few major transmission lines in its territory and was not considered in this paper.

It is important to note that for all the primary causes of adverse weather, the duration of transmission line outage statistics varied significantly. The mean value and the median value were significantly different implying the the underlying statistical distributions for the duration of outages are not symmetrical and are skewed significantly. This skewness significantly impacts the mean value which is often used in reliability modeling of transmission lines. The underlying distributions will be modeled as discrete distributions based on 20 years of field data.

It is also important to note that the duration of outages for the various primary causes associated with adverse weather varied significantly with the operating voltage level of the transmission line emphasizing the need to categorize transmission lines by voltage levels instead of grouping them into a single category.

3.0 Monte Carlo Simulation Model

The Monte Carlo simulation model will be applied to a portion of a transmission network configuration shown in Figure 7. The transmission line network shown is only a small portion of the total transmission system and will be used to illustrate the application of the Monte Carlo simulation model. The cumulative up and down time distributions for the various adverse weather elements for transmission line#1 are illustrated in Figures 8 and 9, respectively.

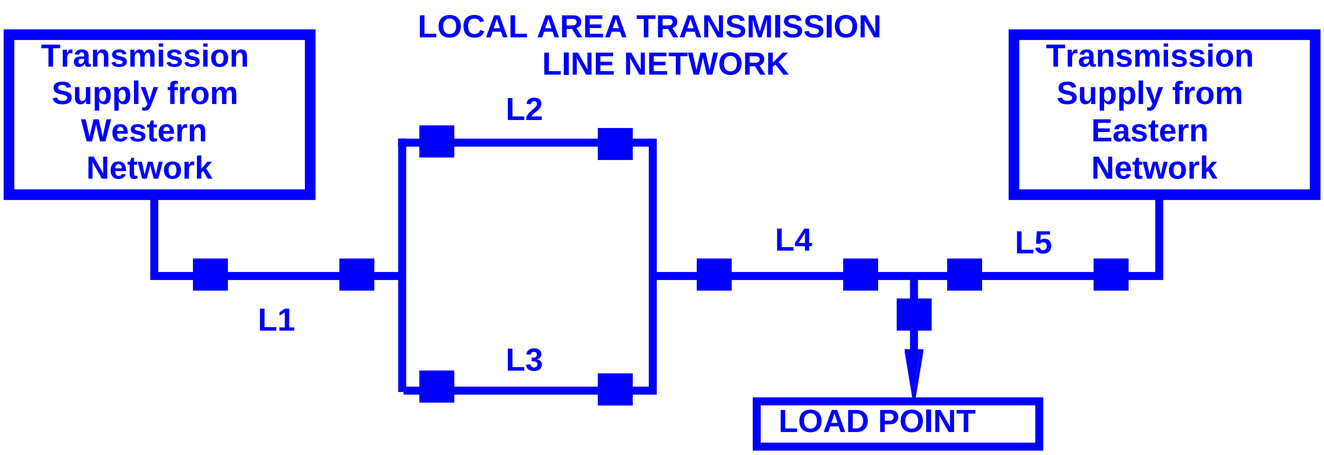

Figure 7 Partial transmission network serving a single load point.

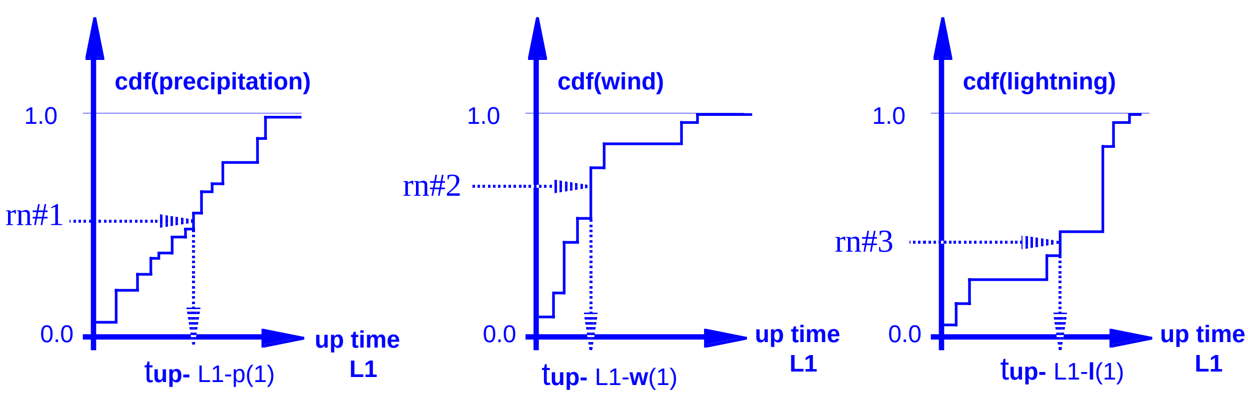

Figure 7 Cumulative distribution of adverse weather up or operational time for transmission line #1

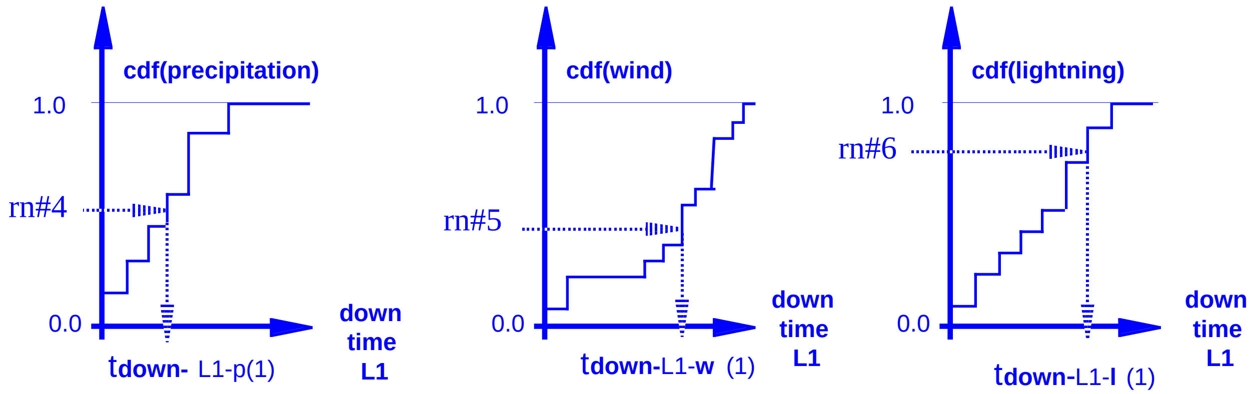

Figure 8 Cumulative distribution of adverse weather variables down time for transmission line #1

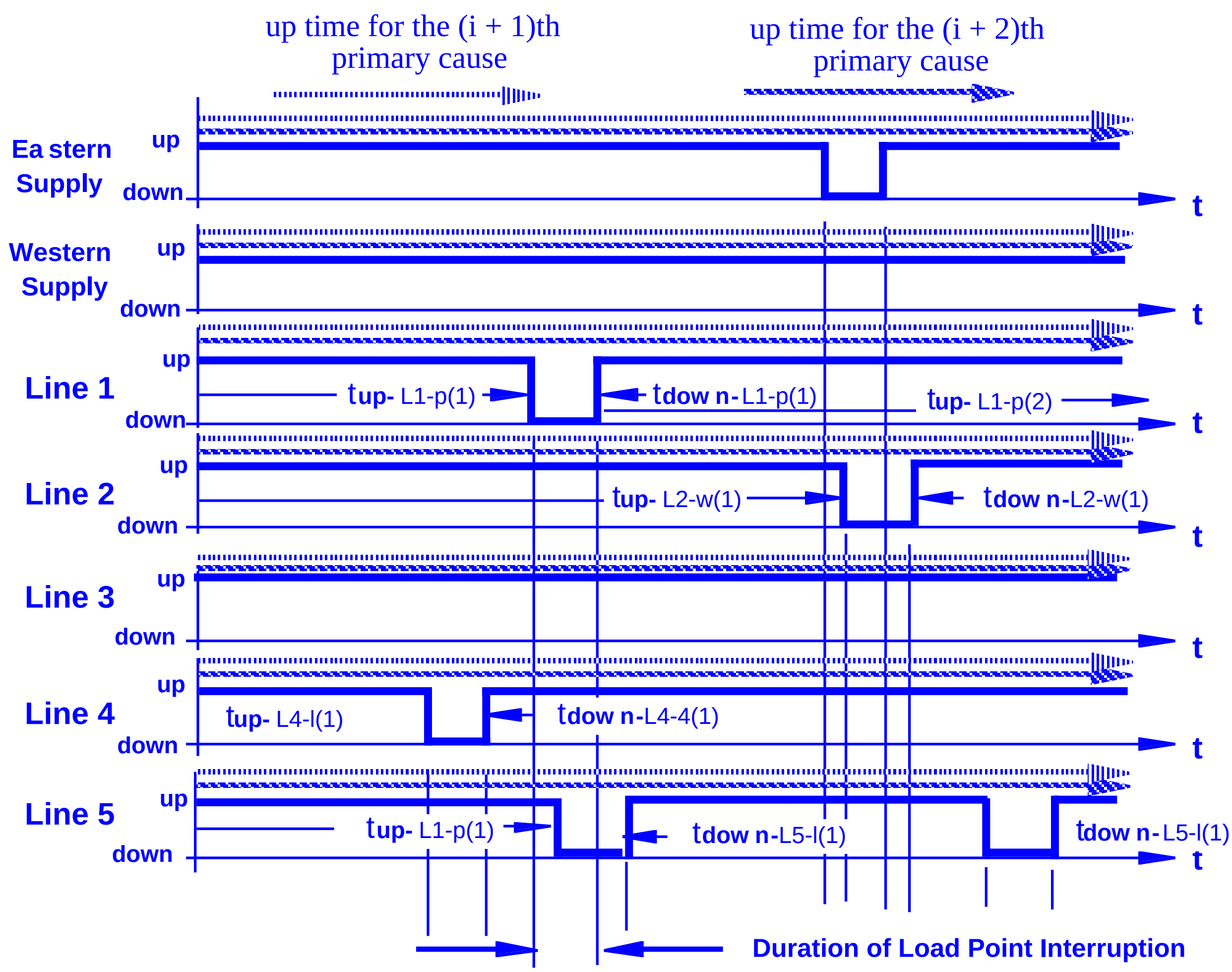

Figure 9 Illustrative simulation time lines for the system lines and interconnections

The cumulative distribution function (cdf) for up and down time durations for each primary cause for the western and eastern transmission line supplies to the local transmission line area network are defined. In this case study only the adverse weather elements were selected. Random numbers (rn#i, ith random number) are continuously generated. Each pair of random numbers generates both an up and down time a a transmission line from its cdf's for a particular primary cause. For example:

rn#1 generates a corresponding "up" time for transmission line #1 - tup-L1-p(1) for the primary cause precipitation(p).

rn#2 generates a corresponding "down" time for transmission line #1 - tup-L1-p(1) for the primary cause precipitation(p).

The corresponding "up" and "down" times for each primary cause are plotted on a time line as shown in Figure 9. For each down state or combination of down states, the local transmission line network is evaluated if a single or multiple transmission line outage causes an interruption to the load point. If the load is interrupted, then the appropriate duration of the load point interruption is determined and summed over the entire length of the simulation study. The frequency of occurrence of these down states are counted. At the end of the simulation study, the average frequency and duration of load point interruptions is determined. The time line is continued in the Monte Carlo study for a minimum of 1000 years to obtain stable estimate of the frequency and duration of load point interruptions. Depending upon the size of the local area transmission network, convergence constraints may limit the number of years, however, each network configuration is unique.

The following simulation results considering only adverse weather were obtained:

1. λ(load point) = 2.7 interruptions per year
   - western network supply only
   r(load point) = 2.225 hour /interruption - western network
2. λ(load point) = 3.55 interruptions per year
   - eastern network supply only
   r(load point) = 1.45 hours/ interruption - eastern network
2. λ(load point) = 0.004 interruptions per year
   - both eastern and western supply
   r(load point) = 0.878 hours/ interruption
   - both eastern and western supply

Note when the supply to the local area transmission line is independent the frequency and duration of load point interruptions is low in this particular geographical area. Studies of other geographical areas revealed significantly higher frequency of load point interruptions.

4.0 CONCLUSIONS

This paper has attempted to present the extreme (i.e., adverse) - weather related transmission line outage statistics for a 20 year data bases of Alberta Power Limit's and Environment Services. The objective of the paper was to reveal the unique failure pattern and characteristics of transmission lines in the Province of Alberta. These statistics and the patterns of failure provide the framework for the Monte carlo simulation methodology presented in this paper.

There is often the belief that extreme or adverse weather-related transmission line outages are an infrequent occurring event. This paper has clearly shown that adverse weather transmission line outages account for approximately one third of all transmission line outages in the Province of Alberta. When adverse weather patterns affect a large geographical area and/or a concentrated number of transmission lines (e.g., 1998 Quebec Ice Storm), then part or all of the transmission line network can be interrupted. In other cases, similar weather patterns may only interrupt a portion of the network but due to redundancy the transmission line network continuity of service to it load points can be maintained.

The paper revealed that the underlying statistical distributions of the duration of adverse weather outages were skewed (i.e., the mean and median values of the duration of the various primary causes of adverse weather were significantly different). This conclusion limits the application of many existing reliability methodologies based on assumed statistical distributions(e.g., normal, exponential, etc.). This paper illustrated a Monte Carlo simulation methodology that was applied to a local area transmission network. Detailed cumulative distribution functions of all the primary causes is beyond the scope of this paper.

5.0 ACKNOWLEDGEMENTS

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