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A PROBABILISTIC APPROACH FOR ADEQUACY AND SECURITY ASSESSMENT OF BULK POWER SYSTEMS

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SUMMARY

This paper describes a probabilistic method for assessing adequacy and security of a bulk power system. The method takes into account the random failure of generating units, hourly loads, transmission limitations and the impact of transient disturbances on system performance. It also considers the effect of system control actions that are implemented during times of emergency on system performance indices. System constraints such as energy limitations associated with hydro plants, merit order of thermal plants, must run units, relationship between flows on transmission interfaces can be easily handled by the proposed method. The unserved energy expressed in system minutes is used as a measure of system unreliability. The measure has two components, one reflecting system adequacy and the other reflecting system security. Application of the proposed method to the Ontario Hydro West system is presented.

keywords: Adequacy, Security, Contingency, Transmission Limits.

A PROBABILISTIC APPROACH FOR ADEQUACY AND SECURITY ASSESSMENT OF BULK POWER SYSTEMS

INTRODUCTION

Adequacy and security of a bulk power system have been among the major concerns of system planners for many years. System adequacy is defined as the capability of the system to supply its load taking into account transmission constraints and scheduled and unscheduled outages of generators and transmission facilities. System security is defined as the ability of the system to withstand disturbances arising from faults or unscheduled removal of bulk power supply equipment. Therefore, adequacy encompasses the steady state post outage analysis of the bulk power system while security encompasses the analysis of critical dynamic conditions.

Adequacy assessment of the bulk power system has received considerable interest over the past decade. Well-documented methods for the adequacy assessment have been developed and reported [1-7]. On the other hand, security assessment has received little attention and work is slowly progressing on the use of probability methods in the security assessment. Some attempts have been made to use the Monte Carlo approach [4] in the security assessment of bulk power systems. Both adequacy and security assessments would help system planners to design a more adequate and secure system.

In the adequacy assessment, control actions are implemented in an emergency and they include rescheduling generation, cutting interruptible loads, making emergency purchases from neighbouring utilities, reducing voltage, etc. These actions vary from one utility to another and are usually taken prior to any firm load curtainment. The impact of one or more of these control actions on system reliability could be of valuable interest to system planners.

Special protection systems such as generation rejection and load rejection schemes are installed on the system to increase security limits. Underfrequency load shedding schemes are used to contain or minimize the impact of system disturbances on customers. In the security assessment, it is necessary to model the effect of the protection schemes that cause load to be interrupted. It is also necessary to determine the impact on customers when the system or portions of the system shuts down completely.

This paper describes an approach to assess adequacy and security of a bulk power system taking into account some of the above mentioned concerns. Both system adequacy and security are expressed in system minutes. The description of the method and its application to the Ontario Hydro West System are presented in the next sections.

ONTARIO HYDRO COMPOSITE SYSTEM RELIABILITY PROGRAM

Ontario Hydro has developed a computer program for composite system adequacy evaluation. The program is called PROCOSE, which stands for Probabilistic Composite System Evaluation. This program creates a large number of load flow states which are likely to exist during a predefined period of time. The program, in use since 1980, performs a probabilistic dc load flow based on state enumeration and has a special algorithm to reduce the total number of system states to an equivalent one of manageable size. The generation load pattern contained in these states represents the dispatch of the available generation which minimizes the total fuel costs and unsupplied load while obeying transmission constraints. The PROCOSE program is described in detail in Reference [7]. Duly a brief description of PROCOSE is provided here.

Initially, the program creates load flow states with the available generation scheduled economically without considering transmission limits. If the available generation is not sufficient, load is shed in accordance with a user's defined policy. Subsequently, the load flow states which violate transmission limits are rescheduled, if possible, to eliminate the violations at minimum generation rescheduling cost. If the generation is not sufficient to relieve the violations, these are relieved by applying a load shedding policy that minimizes generation costs and load cuts.

The salient features of PROCOSE are:

1. Energy limitations on the hydraulic plants are recognized and hydraulic generation is used to peak shave the load;
2. Sales and purchases among neighbouring utilities can easily be modelled;
3. Hourly loads during the study period are represented and load forecast uncertainty can be included if required;
4. Thermal generators are loaded in the most economical manner.
5. A rescheduling algorithm is used to keep power transfers within transmission limits and to minimize the amount of unsupplied load and generation costs.
6. Forced as well as scheduled outages of the thermal plants are taken into consideration;
7. Interdependence between flow limits on the transmission circuits can be included if required.
8. Control actions implemented in an emergency can easily be modelled.
9. Transmission limits utilized in PROCOSE are based on an operating policy which may include the anticipation of transmission contingencies.

The output of the program includes expected values and joint probability distributions of unsupplied load due to generation deficiency and transmission limitations, output of each generating unit, flows across monitored interfaces and additional fuel costs due to departure from economic dispatch.

Application of PROCOSE for reliability assessment of bulk power systems is demonstrated in References [7] and [8].

PROPOSED METHOD FOR RELIABILITY EVALUATION

The proposed method for reliability assessment of a bulk power system uses the output of the PROCOSE program together with some contingency data. Reliability indices can be computed for a given merit order of thermal generating units. Control actions (preventive measures) available to the system can be applied in order to minimize the amount of unsupplied load during times of emergency. These control actions include:

(a) reschedule thermal generators;
(b) cut economy sales;
(c) run hydro plants at full output capacity, if water is available;
(d) cut firm export sales;
(e) run combustion turbines;
(f) cut interruptible loads;
(g) make emergency purchases from neighbouring utilities;
(h) reduce voltage.

The above control actions can be implemented in any sequence depending on the system conditions. Having applied the appropriate control actions to the system under consideration, the next step is to perform the reliability analysis. The analysis is performed in two steps:

(1) steady state analysis (adequacy assessment);
(2) transient analysis (security assessment).

Both the steady state and transient analyses use the system minutes index as a measure of system unreliability. The system minutes index is defined as the amount of unsupplied energy caused by system disturbances in MW minutes divided by the system peak in MW. One system minute is equivalent to an interruption of the total system peak for one minute at the time of system peak.

Steady State Analysis

In this analysis, there are two components of load interruptions that are computed by the PROCOSE program. The first component is due to having insufficient system generation to supply the total load without considering transmission limits. The second component is due to having to interrupt load in order to observe transmission limits. The output of the PROCOSE program provides the load interruptions for the steady state analysis directly.

In the steady state analysis, a user specifies an operating policy for his system. The policy includes the loading order of generating units, sequence of control actions if any and limits on transmission circuits (or interfaces). Transmission Limits based on the anticipation of system contingencies can also be used in PROCOSE. The system minutes index is computed for a given policy as follows:

$$\text{System Minutes} = T \times LOLP \times \frac{EUSL}{APL} \times 60 \qquad (1)$$

where:

T = Study period in hours;
LOLP = Loss of Load Probability due to generation and transmission;
EUSL = Expected Unsupplied Load in MW due to generation and transmission;
APL = Annual peak load in MW.

Both LOLP and EUSL are obtained from the PROCOSE output. The system minutes index computed using Equation (1) would give a measure of system inadequacy.

Transient Analysis

The steady state analysis does not provide complete information on reliability of a bulk power system. It ignores transient faults that may cause load disconnections due to problems of stability or of misoperation of protections. The transient analysis captures additional load interruptions that can occur when the system becomes unstable for contingencies that are not covered by the operating policy or when load is rejected as a control action following a contingency in order to preserve the stability of the system. The analysis also considers false operations and operation failures of automatic load shedding schemes. The analysis proceeds as follows:

(a) Identify the contingencies that can result in load interruption;
(b) Estimate the frequency of each contingency;
(c) Estimate the probability that the contingency will result in load loss;
(d) Estimate the amount of load that would be interrupted;
(e) Estimate the duration of load interruption;
(f) Compute the system minutes as follows:

$$\text{system minutes} = \sum_{i=1}^{n} F_i \times P_i \times \frac{USL_i}{APL} \times D_i \qquad (2)$$

where:

F_i = Frequency of contingency i for the study period,
P_i = Probability that contingency i will result in load loss,
USL_i = Unsupplied load due to contingency i,
D_i = Duration of load cut in minutes,
APL = Annual peak load,
n = Number of contingencies that cause load interruption.

The probability, P_i, in Equation (2) is obtained from the probability distributions of flows as computed by PROCOSE. The other quantities in Equation (2) are obtained from actual failure data on these contingencies. It should be noted that only contingencies that have a direct impact on customers are considered in Equation (2). The system minutes index computed by Equation (2) would give a measure of system insecurity.

APPLICATION

The proposed method for the assessment of system reliability (both adequacy and security) was applied to the Ontario Hydro (OH) West System. The objective of this application has been to illustrate the importance of considering both system adequacy and system security during planning stages. A brief description of the OH West System is given in the next section.

Description of the Ontario Hydro West System

The Ontario Hydro West System is relatively small (1300 MW of load in 1997) and is at present interconnected with the Ontario Hydro East System through a 600 km, 230 kV double circuit line and with the Manitoba Hydro System via two single circuit 230 kV lines. The Ontario Hydro East System is large and has a capacity reserve margin much greater than that of the West System. In addition, the East System has strong interconnections with New York and Michigan. Although the Ontario Hydro East and West Systems are electrically interconnected, the limited transfer capability of the interconnection between them provides only limited freedom in operating the two systems as one. The Manitoba Hydro System is larger than the Ontario Hydro West System and also has interconnections with Saskatchewan and the United States.

The Ontario West System generation at present consists of ten hydraulic stations with a total of 38 units ranging from 3 MW to 46 MW, two coal-fired stations with a total of 4 units of size 100 MW to 215 MW and two small combustion turbine units. The Ontario West System load is characterized by a high load factor (greater than 80%) and the future annual rate of load growth is estimated to be within two to three percent.

The interconnection between the Ontario East and West Systems is crucial to the supply of the West System. Although the interconnection has a capacity of 300 MW, it provides a backup for the sudden loss of a thermal unit or for low river flow conditions (dry year). It also provides an opportunity to take advantage of economies in the scheduling of the total system generation. The interconnection also provides some flexibility in arranging power purchases from Manitoba.

The Ontario-Manitoba interconnection enables both Ontario and Manitoba to take advantage of day-to-day operating economy transfers and longer term firm power transfers.

Experience with the operation of the West System demonstrates that the interdependence that exists between flows on the Ontario East-West interconnection and the Manitoba-Ontario interconnection plays an important role in the supply of the West System. Figure 1 shows the relationship between flow limits on the East-West interconnection and the Manitoba-Ontario interconnection for 1997 during fair weather conditions. The maximum transfer limit on the East-West interconnection (west bound) is 400 MW with a transfer limit on the Manitoba-Ontario interconnection up to 50 MW. As the transfer limit on the East-West interconnection decreases, the transfer limit on the Manitoba-Ontario interconnection increases. It can be seen from Figure 1 that the maximum transfer to the West System from the Ontario East and Manitoba systems takes place when the transfer on the East-West interconnection is maximum and the import from Manitoba is 50 MW.

As the West System load grows, new facilities (generation and transmission) will be needed to ensure an adequate level of reliability for the system. The following projects were planned for the West System prior to 1997.

(a) Return of the Thunder Bay generating Unit #1 (100 MW),
(b) Installation of series capacitors on the existing Ontario East-West interconnection (100 MW). The transfer capability is increased from 300 MW to 400 MW,

(c) Building of the Little Jackfish hydraulic station (132 MW).

System Models and Assumptions

The following models and assumptions were used:

Load Model

The West System load was represented in detail with the loads distributed on the various buses. All West System hourly loads during the period of study were considered. The West System and East System loads were assumed to be fully correlated. In order to simplify the study, the East System load was represented by an equivalent with the following characteristics:

1. Peak demand of the East System;
2. Average energy demand of the East System;
3. Load duration curve for the East System.

The study did not include load forecast uncertainty.

Hydraulic Generation Model

All hydraulic plants of the East and West systems were assumed to be perfectly reliable. Energy limitations on the hydro plants were taken into account and the hydraulic stations of the East and West Systems were used to peak shave load in its own system. This was done in order to minimize the thermal demand of each system and hence the cost of generation.

Thermal Generation Model

A two state representation of a generating unit was assumed. Forced and scheduled outages of generating units were considered. The thermal units were dispatched economically to supply the total thermal demand in the East and West Systems.

The following loading order of generating units based on their incremental fuel cost was used:

1. East System nuclear;
2. East System (Nanticoke GS);
3. West System (Atikokan GS);
4. East System (Lambton GS);
5. West System (Thunder Bay Unit 2);
6. East System (Lakeview GS);
7. West System (Thunder Bay Units 1&3);
8. East System (remaining stations and assistance from neighbouring utilities);
9. Control action generators.

Control Actions

The control actions available to the West System were:

1. Reschedule thermal generators;
2. Peak West System hydraulic plants;
3. Run West System combustion turbines;

4. Cut interruptible loads;
5. Make an emergency purchase from Manitoba;
6. Reduce voltage.

These control actions were implemented in the above sequence, whenever there was either a capacity shortage or an overload of a transmission interface. Each of the control actions was represented as a generating unit with an appropriate forced outage rate.

Transmission Model

The transmission model used in the study assumed that all the transmission circuits were in service. However, the transmission limits used were based on anticipating transmission contingencies. The following transmission interfaces were represented:

(a) The Ontario East-West interconnection;
(b) The Manitoba-Ontario interconnection;
(c) Interfaces within the West System.

These interfaces were normally operated to single contingency limits.

In addition, the interdependence between flow limits on the East-West interconnection and the Manitoba-Ontario interconnection was modelled. The limit on one interface depends on the flow on the other interface. Figure 1 shows the relationship between flow limits on the East-West interconnection and the Manitoba-Ontario interconnection under fair weather conditions. These limits were determined by postcontingency voltage decline criteria for the loss of the Manitoba-Ontario interconnection.

Figure 1 also shows the relationship between flow limits on the East-West interconnection and the Manitoba-Ontario interconnection under stormy weather conditions. These limits were based on anticipating the loss of the Ontario East-West interconnection. A load rejection scheme was used to increase security limits on the East-West interconnection. Two cases are shown in Figure 1, one with the load rejection scheme unarmed and the other with the scheme armed with 50 MW. The load rejection scheme would be normally unarmed in stormy weather. However, the scheme could be armed in stormy weather if the West System became deficient in resources. The scheme would also be armed in fair weather whenever the flow on the East-West interconnection exceeded the double circuit outage limit.

Contingencies Studied

The following contingencies were considered in the security assessment of the Ontario Hydro West System:

Loss of East-West Interconnection

This interconnection is operated during fair weather to one circuit outage limit. If the flow exceeds the double circuit outage limit and a double circuit contingency occurs, the West System could become unstable. In order to avoid being in that situation, the load rejection scheme would be armed with up to 150 MW during fair weather. The probability of having to arm the scheme was obtained from the probability distribution of flow on the East-West interconnection.

During stormy weather, it was assumed that the double-circuit contingency limit (no load rejection) was observed. The control actions available to the West System were used to ensure the nonviolation of that limit. The load rejection scheme could be also armed in stormy weather when the West System falls short of resources. In this case, the probability of arming the load rejection scheme was also obtained from the PROCOSE results. A PROCOSE case was run with the no load rejection limits and the loss of load probability computed by PROCOSE in this case gave the probability of arming the scheme during stormy weather.

False Trip of Load Rejection

During times when the load rejection scheme is armed for contingencies on the East-West interconnection, there is a possibility of a false operation. The probability of having load rejection armed was obtained from the probability distribution of flow on the East-West interconnection as calculated by PROCOSE. The amount of load rejection was assumed to be 150 MW.

Failure to Trip Manitoba-Ontario Interconnection

The Ontario West System is normally protected against severe Manitoba contingencies by tripping the Manitoba-Ontario interconnection. If the interconnection for any reason, fails to trip in the appropriate time, the West System would become unstable. The amount of load interruption due to such an event was estimated to be 500 MW. It was assumed that the tripping scheme would be armed at all times.

Others

Contingencies which are internal to the West System and are beyond the design and operating criteria such as the loss of all circuits on a common right-of-way, loss of a transformer station, etc, were examined and were found to have insignificant impacts on the computed reliability indices.

Weather and Contingency Data

The weather and contingency data used in the reliability evaluation of the Ontario Hydro West System are shown in Table 1. The weather figures were based on actual weather data in the area of the East-West interconnection. The weather data in Table 1 was used to weight the reliability indices as shown in Appendix A.

The contingency data in Table 1 were based on actual operating experience with the Ontario Hydro West System for contingencies 1 and 2 and was predicted for contingency 3. The West System was assumed to be unstable for contingency 3.

Table 1 WEATHER AND CONTINGENCY DATA

Weather Data

Season	% of Time Fair	Stormy
Winter	98.5	1.5
Summer	76	24

Contingency Data

	Frequency Per Season				
	Winter		Summer		Duration
Contingency	Fair	Stormy	Fair	Stormy	Minutes
1. Loss of East-West interconnection	.1	.4	.6	4.0	30
2. False Operations of Load Rejection	.5		.5		30
3. Failure to trip Manitoba-Ontario interconnection	.05		.05		60

Note: The duration in minutes in Table 1 indicates the time that would be required to restore the rejected load.

Table 2 WEST SYSTEM UNRELIABILITY IN SYSTEM MINUTES

	System Minutes January	July
Steady State Analysis		
Weather		
Fair	$.697 \times 10^{-2}$	0.0
Stormy	$.106 \times 10^{-3}$	0.0
Transient Analysis		
1. Loss of East-West interconnection		
Fair weather	$.551 \times 10^{-1}$	0.339
Stormy weather	$.662 \times 10^{-4}$	0.193×10^{-3}
2. False Operations of Load Rejection	.276	.282
3. Failure to trip Manitoba-Ontario interconnection	.192	.192
Total for one month	.530	.813
Total for six months	3.180	4.878
Total for year	8.058	

Results and Discussions

The studies were done for the year 1997. The year 1997 was chosen because additional capacity will be required at this time in order to meet the system load. Two months, January and July were studied, where January represents the winter months and July represents the summer months. The system minutes index was computed using the proposed method along with information in Table 1. Calculations were performed assuming fair weather and then repeated for stormy weather.

System minutes for the months of January and July were computed and the results are summarized in Table 2. Detailed calculations of system minutes for the months of January and July are given in Appendix A. The annual index as shown in Table 2 was obtained by adding the winter and summer indices. As can be seen from Table 2 the steady state component of the system minutes index is insignificant compared to the transient component. The transient component dominates the reliability index of the West System.

It can also be seen from Table 2 that the contribution of failure to trip the Manitoba-Ontario interconnection to the system minutes index is the same for both January and July. That is because the tripping scheme was assumed to be armed at all times.

CONCLUSIONS

The paper has presented a probabilistic approach to assess the reliability of a bulk power system. The approach includes assessment of both system adequacy and system security. The adequacy assessment provides system unreliability in terms of system minutes due to generation deficiency and due to observing limits based on design and operating criteria. The security assessment provides system unreliability arising from contingencies beyond these criteria. System control actions implemented in an emergency and special protection systems intended for particular purposes have been taken into account in the reliability assessment. The presented method can be used to study the effect of different operating policies on system reliability. Application of the method to the OH West System with 1997 conditions demonstrates that the reliability of the OH West System is largely governed by the security component of the system minutes index.

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APPENDIX A

Computations of System Minutes for Ontario Hydro West System

Steady State Analysis

(1) January Case

The Loss of Load Probability (LOLP) and Expected Unsupplied Load (EUSL) as computed by PROCOSE are given as follows

LOLP = $.54797 \times 10^{-5}$
EUSL = 37.6 MW

The system minutes index was computed using Eq.(1) with the help of Table 1 as follows:

System Minutes (fair weather)

$$= 744 \times .985 \times .54797 \times 10^{-5} \times \frac{37.6}{1300} \times 60$$

$$= .697 \times 10^{-2} \text{ minutes}$$

System Minutes (stormy weather)

$$= 744 \times .015 \times .54797 \times 10^{-5} \times \frac{37.6}{1300} \times 60$$

$$= .106 \times 10^{-3} \text{ minutes}$$

where .985 and .015 in the above calculations are the probabilities of having fair weather and stormy weather in winter respectively.

(2) July Case

In this case, LOLP and EUSL as given by PROCOSE were found to be zero and therefore, the system minutes index for both fair and stormy weather conditions was zero.

Transient Analysis

Only figures for the January case are derived here. July figures can be derived similarly. The system minutes index was calculated using Eq.(2) with the help of Table 1 and results of the PROCOSE program for the following contingencies:

(1) Loss of East-West Interconnection

Fair Weather

In this case the fair weather limits for the East-West and Manitoba-Ontario interconnections were used in PROCOSE. The probability of arming the load rejection scheme for the loss of the East-West interconnection was obtained from the probability distribution of flow on the East-West interconnection. Figure 2 shows the probability distributions of flows on the East-West interconnection before and after rescheduling of the system generation. The probability distribution of flow before rescheduling was based on the economic dispatch of system generation without considering transmission limits while the rescheduling plot was based on observing transmission limits. The probability distribution of flow after rescheduling as shown in Figure 2 is used to estimate the probability of having to arm the load rejection scheme. Based on Figure 1, the flow limit on the East-West interconnection with no load rejection is 300 MW. The load rejection scheme will be armed with up to 150 MW of load rejection whenever the flow on the East-West interconnection exceeds the 300 MW value. Combining Figure 1 with Figure 2 yields a probability of .9555 for a flow greater than 300 MW on the East-West interconnection. The system minutes index using Eq.(2) is given by

System Minutes

$$= .016667 \times .9555 \times \frac{150}{1300} \times 30$$

$$= .0551 \text{ minutes}$$

with .016667 representing the frequency of losing the East-West interconnection in fair weather in January.

Stormy Weather

The stormy weather limits with no load rejection were used in PROCOSE. The probability of arming the load rejection scheme for the loss of the East-West interconnection was not obtained from the probability distribution of flow on the East-West interconnection, but was given by LOLP in this case. The LOLP value as computed by PROCOSE was $.26965 \times 10^{-3}$ and hence the system minutes index becomes

System Minutes

$$= .06667 \times .26965 \times 10^{-3} \times \frac{150}{1300} \times 30$$

$$= .6223 \times 10^{-4} \text{ minutes}$$

with .0667 representing the frequency of losing the East-West interconnection in stormy weather in January.

(2) False Operations of Load Rejection

Since the load rejection scheme is not normally armed in stormy weather and the probability of arming it in stormy weather as calculated above is small, the calculation of system minutes was only done for fair weather. Using Eq.(2) and Table 1, the system minutes index is given by

$$\text{System Minutes} = .08333 \times .9555 \times \frac{150}{1300} \times 30$$

$$= .2756 \text{ minutes}$$

with .08333 and .95555 representing the frequency of false operations and the probability of arming the load rejection scheme respectively during the month of January.

(3) Failure to Trip Manitoba-Ontario Interconnection

In this case, it was assumed that the tripping scheme was armed at all times and therefore, the probability value as utilized in Eq.(2) was equal to 1.0. The system minutes index is given by

$$\text{System Minutes} = .8333 \times 10^{-2} \times 1.0 \times \frac{500}{1300} \times 60$$

$$= .1923 \text{ minutes}$$

where $.8333 \times 10^{-2}$ represents the frequency of failure to trip the Manitoba-Ontario interconnection for the month of January.

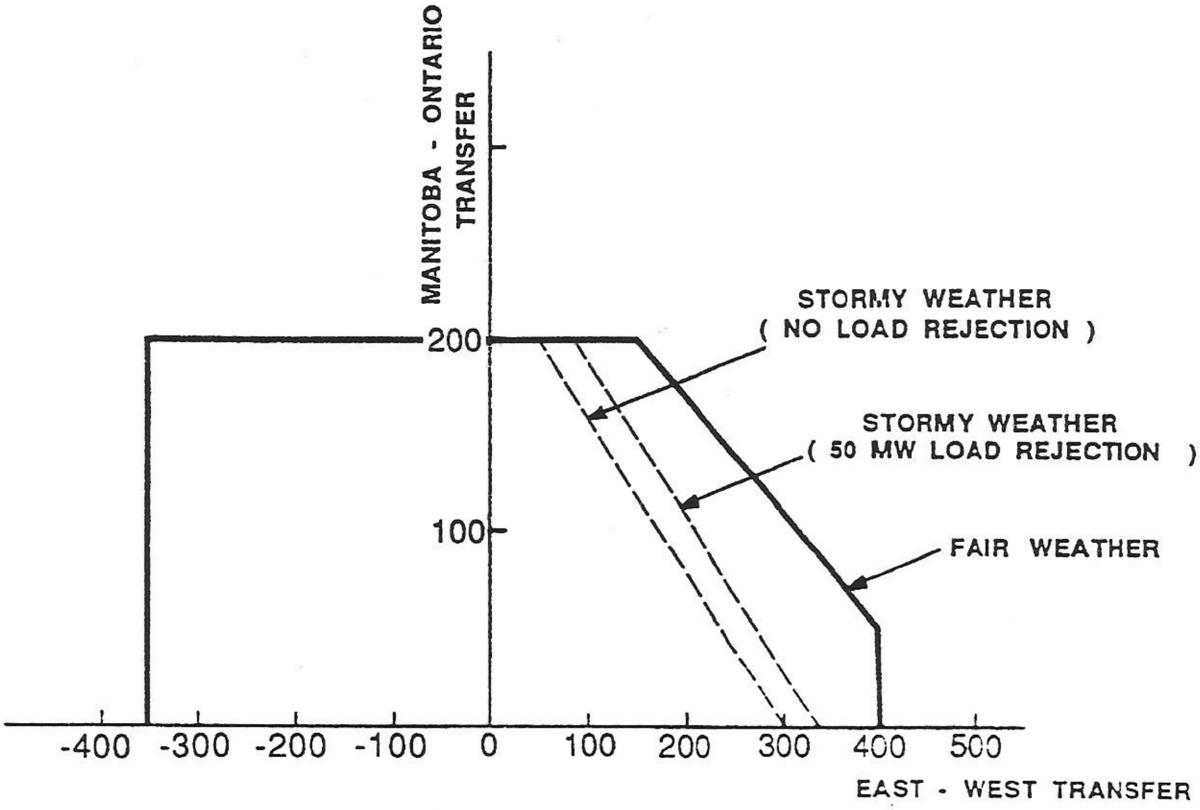

FIGURE 1

RELATIONSHIP BETWEEN FLOWS ON EAST-WEST INTERCONNECTION AND MANITOBA - ONTARIO INTERCONNECTION

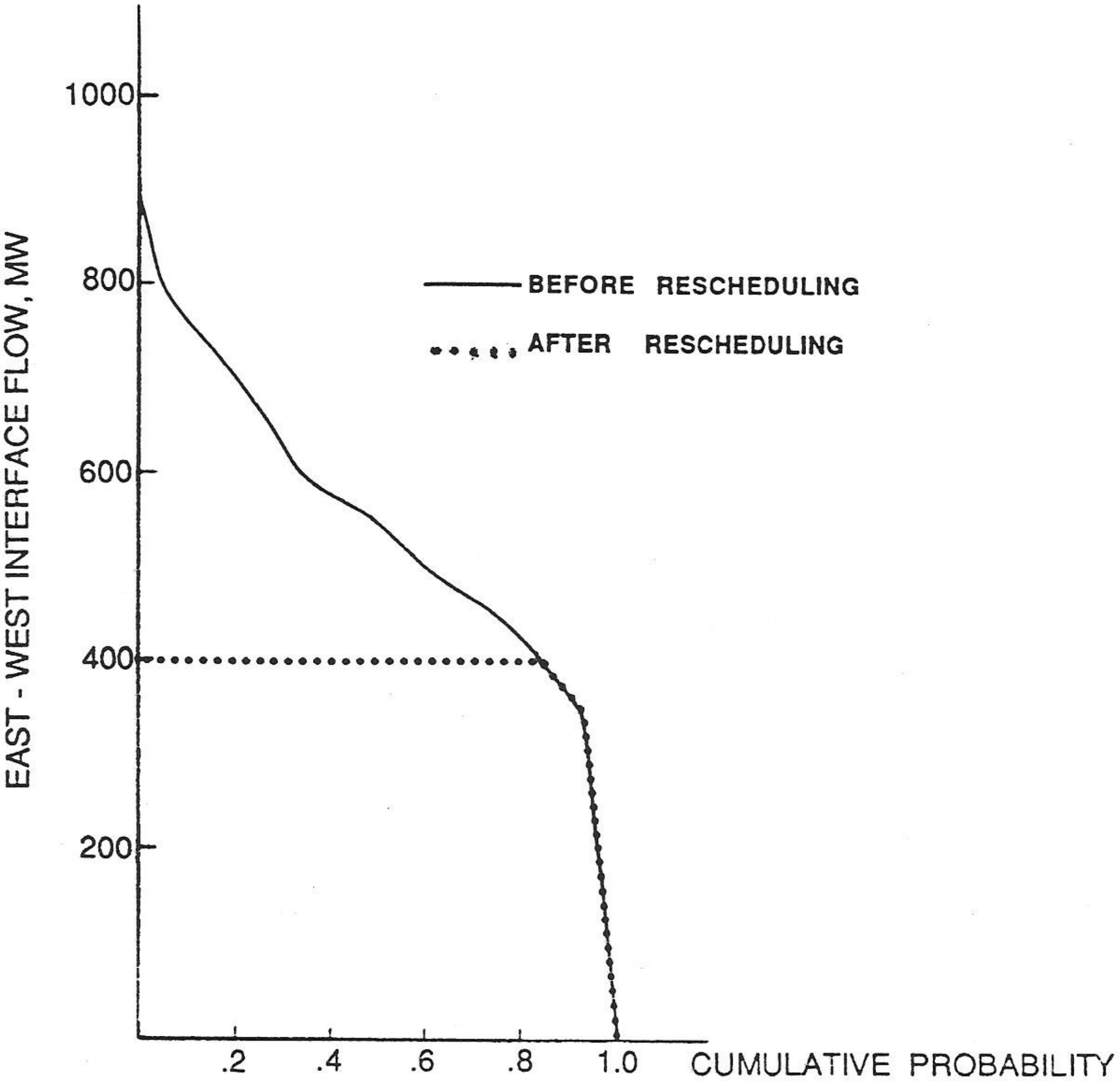

FIGURE 2

PROBABILITY DISTRIBUTION OF FLOW ON EAST - WEST INTERCONNECTION