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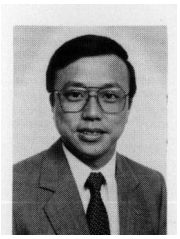
Discrete-event simulation of load point interruptions



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ABSTRACT

A discrete-event simulation system has been created for obtaining probability distributions of load point reliability indices in an electricity supply system. The modeled behavior of transmission components includes temporary and permanent faults, common mode faults, maintenance, switching after permanent fault, breaker failure to open, closing of normally opened breakers, and fluctuating weather environment. Also, the simulation system can study the effect of parameter uncertainty when there is limited component outage data or weather data.

1. INTRODUCTION

In an electricity supply system, transmission facilities are required to move the energy generated by power plants to various points in the system. These points may represent direct industrial customers or, alternatively, points of delivery to local distribution systems. They will be referred to as load points in the following. A common way in which a load point interruption can occur is through the outage of transmission components such as circuits, transformers, breakers and bus bars, thus cutting off the paths of supply to the load point.

When monitoring the actual reliability performance of load points, the following information is frequently recorded and assessed for each load point:

(1) Number of interruptions in a period
(2) Duration of each interruption in a period
(3) Total duration of all interruptions in a period.

To appreciate the possible range of the actual behaviour, it is necessary to obtain probability distributions corresponding to (1), (2), and (3) above, based on reliability modeling. A discrete-event simulation system can generate these probability distributions. The unique feature of this particular simulation system is that it incorporates a very detailed model of transmission component outage phenomena. The model includes temporary and permanent faults, common mode faults, maintenance events, operation of protection zone, switching after permanent fault, cancellation of maintenance, breaker failure to open, closing of normally opened breakers, and fluctuating weather environment. Model application is not restricted to specific component types. Further explanation of the model behavior is given in Sections 2-4.

Several aspects differentiate this simulation system from prior work. There is the concern with load point reliability over a specified period of time and obtaining probability distributions of reliability indices. It is distinct from prior work[5,8] which calculates the mean values of reliability indices for the case when time approaches infinity. One use of the distributions of reliability indices lies in the area of performance monitoring. An idea is obtained about how good the actual performance has been by comparing actual performance with the distribution of predicted performance. For example, if the actual performance is worse than the 90th percentile of the distribution of predicted performance, then it may be desirable to investigate the cause of the actual performance and to consider the need for improvement. Other applications of the probability distributions of reliability indices are described in References 4 and 17.

Studying the effects of parameter uncertainty on the probability distributions of load point reliability indices has, heretofore, not been undertaken by other analysis programs, either through the use of discrete-event simulation or mathematical modeling. Further details are provided in Section 5 on this system's ability to incorporate the effects of uncertainty in the parameters concerning the component outages or weather environment.

A simulation model was created for the study of n-section electricity distribution systems. The distribution configurations are radial in nature (i.e., the components are connected in series), as opposed to nonradial configurations where the component outage phenomena modeled are those for the transmission system, containing many phenomena not usually required for the analysis of distribution systems.[4] Examples of some of the phenomena are common mode faults, distinction between temporary and permanent faults, maintenance, breaker failure to open, cancellation of maintenance, and fluctuating weather environment. A simulation program has also been developed for a general repairable system.[14] Its component outage model does not include the details required for transmission components.

A mathematical approach for obtaining the probability distributions for (1) and (2) above was also proposed.[17] Exponentially distributed time-to-outage and outage duration were assumed and also a single weather environment and one kind of component outage. While, the simulation system in this paper can handle additional types of probability distribution that describe component outages, as well as provide the capability of modeling a fluctuating weather environment and different kinds of component outages.

2. COMPONENT OUTAGE MODEL

A transmission component is subjected to different kinds of outages. It may sustain an outage due to an independent fault or maintenance work. In addition, it may be one of the components sustaining a common mode fault.[2,3] Common mode faults are simultaneous faults on multiple components due to a common cause.

Upon the occurrence of a fault, the breakers surrounding the faulted component would open. These breakers define a protection zone for the faulted component. If the fault is self-clearing, the zone can be automatically or manually reclosed. This type of fault is referred to as temporary and the component is on temporary outage. If the fault causes actual damage, then the damaged component will be isolated by opening switches which form the switching zone for the faulted component. Unfaulted components in the same protection zone can then be returned to service.[6] This type of fault is referred to as a permanent fault and the component is on permanent outage. If the component is a circuit breaker, it may exhibit the additional mode of failing to open for a fault, i.e., the stuck breaker mode.[7] In such a case, the adjacent protection zones must be opened. Problem circuit breakers may be isolated by switching and then repaired.

All of the above phenomena have been incorporated into the component outage model (see Figure 1).

Since transmission components are usually situated outdoors, the effects of adverse and normal weather[11] have also been modeled. During adverse weather, the component outage rates are significantly higher. Chance is increased for the outage durations of different components to overlap in time; this phenomenon is referred to as "bunching." A common way for "bunching" to occur is during severe windstorms when transmission circuits are repeatedly on outage due to the galloping of conductors. The provision of two weather environments in the model does not mean that all storm types should be classified as adverse weather. It only means that those storm types that can significantly increase the chance of overlapping outages due to "bunching" need be considered as adverse weather. The rest of the storm types are then treated as "normal" weather. An analyst's experience and judgment with the specific system under study can play a part in this choice.

If outage data analysis strongly supports the need to model additional types of adverse weather, the simulation system can be easily modified to effect this change. It is worth mentioning, however, that there are many other contributors to load point unreliability in addition to "bunching." Examples of these other contributors are common mode fault, breaker failure to open, and single component outage that directly interrupts the load point. Including a particular storm type's impact as adverse weather should therefore be measured against the contribution of these other kinds of component outages. If the impact is relatively small, then there is no need to consider the storm type as adverse weather.

Assumed in the model is that repair, but not maintenance, can be initiated during adverse weather. Although once initiated maintenance may continue into an adverse weather period.

3. OUTAGE EFFECT ANALYSIS

Load point interruption may be the result of single or multiple component outages. Upon the occurrence of a component outage, it is necessary to determine if the outage results in load point interruption. Furthermore, it is necessary to determine if the load point interruption will end upon the completion of reclosing, switching, or repair action. This type of analysis is referred to as outage effect analysis.

Network representation allows multiple supply sources and a single load point. Load point interruption is defined as the interruption of all paths from the sources to the load point. To achieve the efficient determination of load point interruptions, the method of Reference 1 has been chosen. Initially, this method involves the determination of all paths from the sources to the load point. The paths are then used to determine the

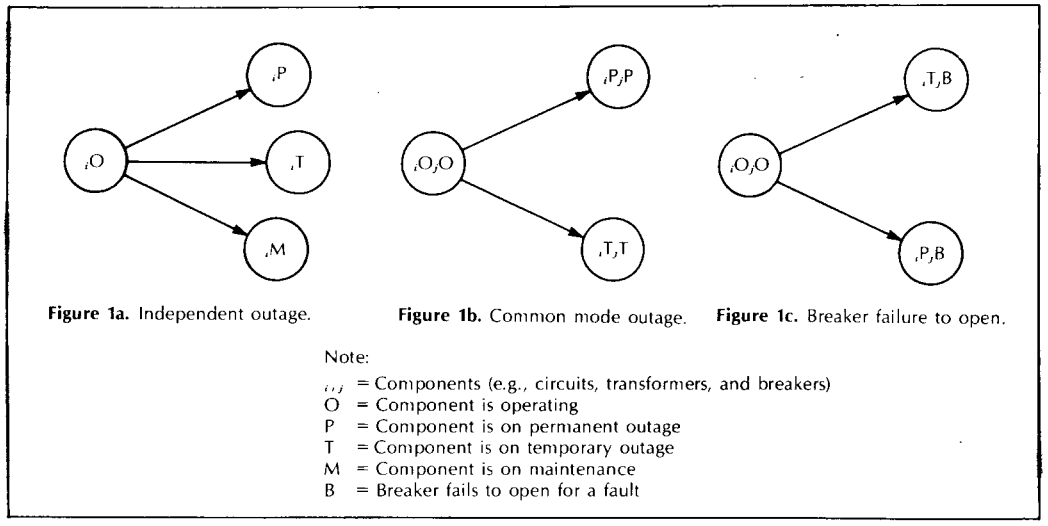

Figure 1. Component outage model. (For simplicity, the aspects of adverse/normal weather and switching/repair operations are not depicted.)

path information of each component, which is a string of bits with the bit positions representing the path numbers. A bit is set to '1' if the component is on the corresponding path. Having accomplished the above, the effect of component outages can be determined by performing a logical 'OR' operation on the bit patterns. If the result consists of '1's for all bit positions, then load point interruption has occurred.

Owing to the complexity of the component outage phenomena and the load point restoration process, adaptation has been made to the above method in this simulation system. Adaptation consists of the creation of three bit-strings, representing:

(1) The protection zone of a component, with normally opened breakers opened

(2) The switching zone of a component, with normally opened breakers opened

(3) A normally opened breaker itself.

Bit-strings (1) and (2) are used to determine if load point interruption results from the outage of components under the normal system (i.e., when the normally opened breakers are opened). If load point interruption persists after the restoration of temporarily faulted components and the isolation (for repair) of permanently faulted components, then the normally opened breakers will be closed, one at a time, in a predetermined order. Bit-string (3) is used to determine the success of this operation in terminating the load point interruption.

4. DISCRETE-EVENT SIMULATION

Simulation begins by the generation of a normal weather period and assumes that no component is on outage initially. Within this period, the appropriate time-to-outage for each component is generated. Further discussion regarding the probability models for the time-to-outage and outage duration is given in Section 5. The time-to-outage defines the occurrence of an event and is stored in an event array. If the time-to-outage exceeds the weather period, then the component is considered to have survived the period. If not, then the appropriate outage durations are generated. In the case of a component being individually faulted, each breaker belonging to the component's protection zone is tested for the stuck breaker condition by sampling from the Bernoulli distribution, where:

$$X = \begin{cases} 1 \text{ with probability } p \\ 0 \text{ with probability } 1 - p \end{cases}$$

$X = 1$ denotes a stuck breaker and p its probability of occurrence.

All events that result in component outages are duplicated into a separate array (called overlap) for conducting the outage effect analysis and the accumulation of load point interruption data. When the analysis of a component outage is finished, another time-to-outage is generated for the component and the above process repeats.

Upon the ending of a weather period, an opposite weather period is generated and the simulation progresses in a similar manner. If the consideration of only one weather environment is called for, then the simulation system assigns the largest number in the computer to the first normal weather period. This, in effect, prevents the generation of further weather periods.

The simulation system is designed to handle complexities introduced by the existence of switching duration and repair duration, the straddling of an outage duration on the transition between two weather periods, the cancellation of a maintenance outage if it initiates a load point interruption, and common mode outages. In addition, exclusivity is maintained between the different outage types, i.e., temporary, permanent, and maintenance. For instance, a temporary independent component outage is not allowed to occur when that component is already on a permanent independent outage.

Event and overlap arrays also contain other information associated with each outage, such as the identity of the component, the type of the outage (e.g., maintenance), and the relevant bit-strings. These arrays are processed using linked list processing.[10,15] Simulation is based on the variable (next event) time advance approach.[10,15] An overview of the process of simulation is presented in Figure 2. Note that the ending of a weather period and the ending of a study period are both represented as artificial outages, with the time-to-outage being the length of the period and the outage durations being zero. These artificial outages are included in the event array and subjected to linked list processing, along with the other outages.

5. PARAMETER UNCERTAINTY

It is general practice in reliability analysis of electricity supply systems to compute statistics based on collected component outage and weather data. These statistics are governed by the probability model assumed for the component or the weather environment. For example, if time-to-outage and outage duration are assumed to be exponentially distributed for a component, then the mean time-to-outage and mean outage duration are the statistics calculated from actual outage data. The probability model is based on statistical tests (e.g., goodness of fit tests) or probability plots of the data collected.

Transmission components are not on outage very often. The sample sizes are, therefore, small, for the collected time-to-outage and outage duration data. In addition, there are several other considerations that can limit the sample size. For example, it may not be desirable to pool data from components situated in different areas because of differences in weather, operating practice, and procedure in analyzing and interpreting outage data. Weather data may also be limited owing to insufficient years of record or the unsuitability of pooling data from different areas.

Given a small sample size, the value of the statistics calculated may be far from the true behavior of the component outage or weather environment. Since these calculated statistics are required as input parameters for the reliability model, they introduce uncertainty in the final results from the model – this problem is referred to as parameter uncertainty. Methods do exist to obtain the probability distributions of the statistics or parameters.[16] These distributions can be incorporated into the simulation as described below.

The effect of parameter uncertainty on the probability distributions of load point reliability indices is assessed by an alternate version of the discrete-event simulation system. In this version, additional input data describe the probability distribution of each parameter. A sample is drawn from each of these distributions, thus forming a set of parameter values. This set is then used in one replication of the simulation. Each additional replication is based on a new set of sampled parameter values. Assume that the random variables representing the parameters are independent. Examples of using this version of the simulation system are given in Reference 9.

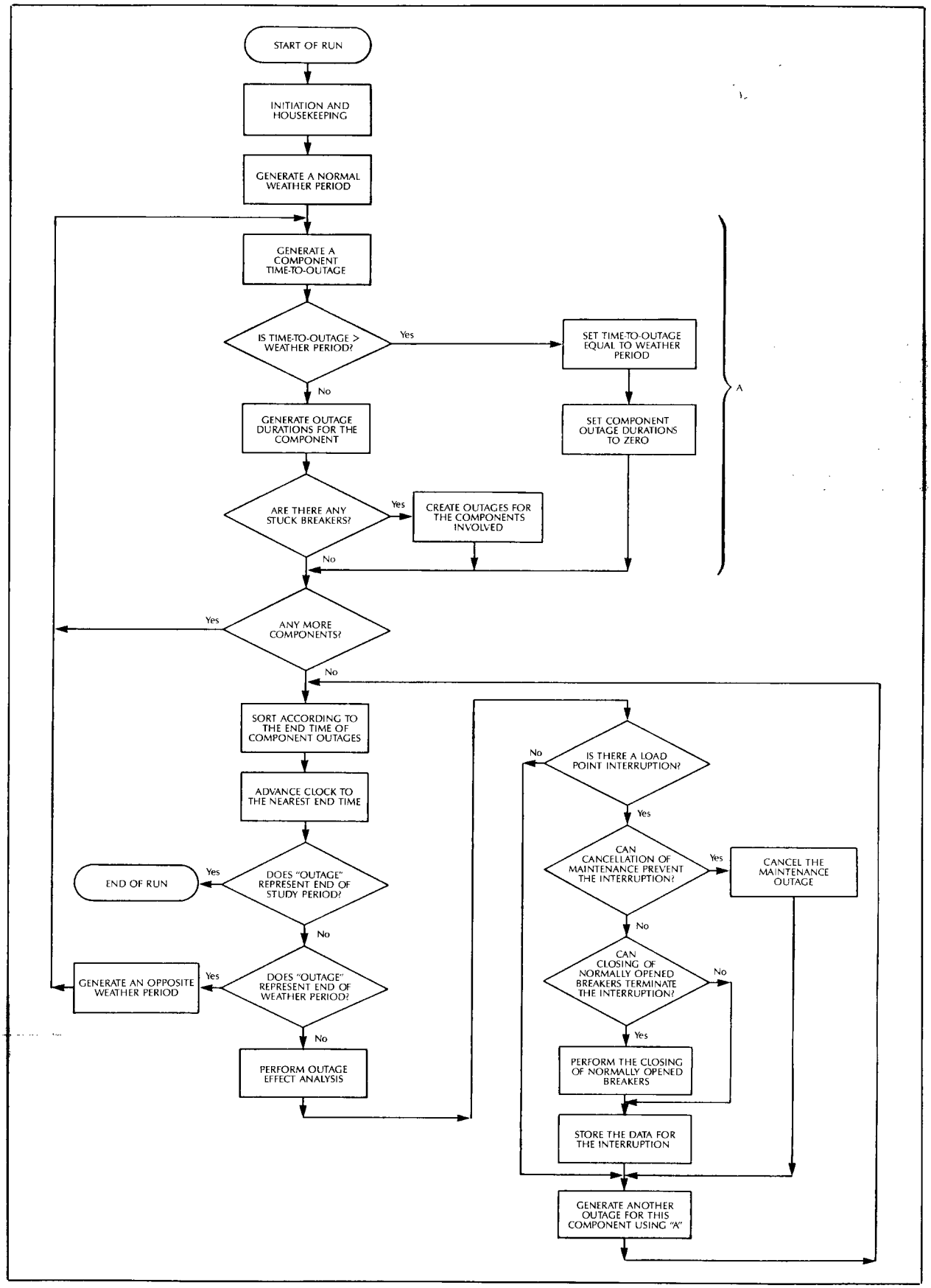

Figure 2. Flowchart of the simulation.

6. COMPUTER PROGRAM

The computer program written for this simulation system has about 2500 lines of FORTRAN code. It performs the tasks of initialization, reading of network information, derivation of paths, derivation of the bit-strings of each component, reading of outage statistics, execution of discrete-event simulation, and output of results. FORTRAN 77 was chosen because of its availability.

Memory requirements are 40K words on a Sperry UNIVAC 1182 computer. The program can handle up to 30 components, 6 sources and 72 paths. For each outage type, the probability distributions can be either exponential or a piecewise linear approximation of any distribution. The latter approach is similar to the GPSS system.[12] A total of 100 piecewise linearly approximated distributions can be accommodated.

7. EXAMPLE

A load point is supplied through the assumed substation configuration in Figure 3. It may represent a point of delivery to a local distribution system. The configuration consists of two supply sources (main terminals A, E); two circuits (B, D); two transformers (F, J); four breakers (C, G, I, K); and two bus bars (H, L).

The statistics used are given in Table 1. Weather periods and component time-to-outage are taken to be exponentially distributed. It is assumed that the substation is unattended. The time to perform switching operations is largely governed by the operator's travel time to the substation and is assumed to be uniformly distributed. The repair durations are represented by gamma distributions with shape parameters of 0.5. This is because of the frequently observed "J shaped" histograms based on collected outage data.

The exponential distribution is used for temporary outage duration and the uniform distribution is used for maintenance duration. When a breaker is called upon to open for a fault, the probability of it failing to do so (i.e., stuck breaker) is assumed to be 0.008.

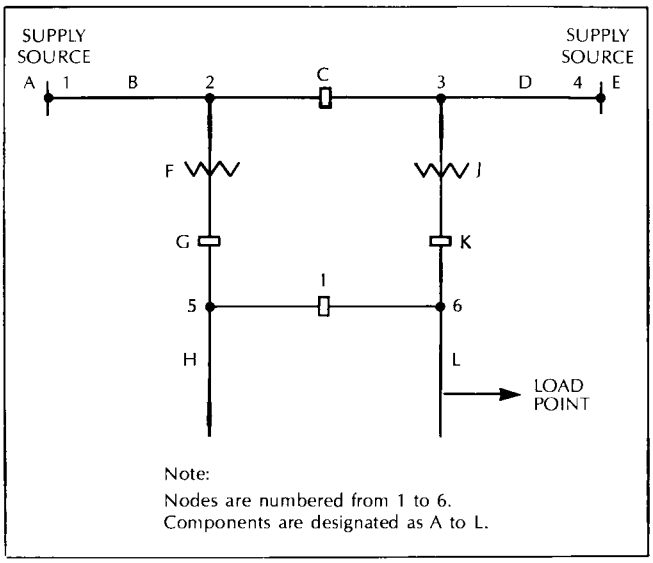

Figure 3. A sample supply system.

The assumed statistics for the adverse/normal weather model pertain to severe winter storms which occur once every few years but result in very high outage rates for the components during the storm. Thus, the mean normal weather duration and the mean adverse weather duration are set at 3.5 yrs. and 3 h, respectively.

There are four protection zones in the sample system:

A, B, C, F, G
G, H, I
C, D, E, J, K
K, L, I

The components in this study are assumed to be self-switching (i.e., the switching zone is the component itself).

Table 1. Component outage statistics.

Component outage type	Component designation	Normal weather outage rate*	Adverse weather outage rate†	Duration‡
Main terminal permanent fault	A, E	0.05	4.86	S = 8 ± 2 min R = 13.5 h
Circuit permanent fault	B, D	0.06	544.00	S = 8 ± 2 min R = 18 h
Circuit temporary fault	B, D	0.23	6333.00	T = 0.15 h
Transformer permanent fault	F, J	0.05	3.22	S = 41 ± 7 min R = 22.8 h
Breaker permanent fault	C, G, I, K	0.10	2.83	S = 41 ± 7 min R = 20.6 h
Bus bar permanent fault	H, L	0.08	4.92	S = 41 ± 7 min R = 6.1 h
Circuit maintenance	B, D	2.00	–	10 ± 2 h
Stuck breaker	C, G, I, K	p = 0.008 irrespective of weather		S = 41 ± 7 min R = 19.9 h

Note:

* Expressed as number of outages per year of normal weather.
† Expressed as number of outages per year of adverse weather.
‡ S Denotes switching, R denotes repair, and T denotes temporary. The repair and temporary outage durations represent mean values.

The simulation experiment consists of 1000 replications of a five-year period. The following paths are derived from sources to load point:

4 – 3 – 6
4 – 3 – 2 – 5 – 6
1 – 2 – 5 – 6
1 – 2 – 3 – 6

For the distribution of the number of interruptions in five years, see Figure 4. The results (mean and standard deviation) indicate that it is not a Poisson distribution; this is attributable to the inclusion of severe storms in the model. These storms may or may not occur in a five-year period. However, if one does occur, it could result in multiple interruptions in quick succession. Figure 5 shows the distribution of interruption durations experienced over five years, plotted on a logarithmic scale. The interruption durations up to about 30 min. are primarily (but not solely) due to temporary outages in adverse weather occurring on one circuit and overlapping with the outages of the other circuit. The sharp rise starting at about 34 min. is primarily the result of the uniformly distributed switching durations; whereas, long durations starting at around 50 min. are attributable to component repair. Figure 6 shows the distribution of the total duration of interruptions in a five-year period, also on a logarithmic scale. The "steps" evident in the figure are due to the presence of interruptions restored through switching, with uniformly distributed switching durations. This simulation experiment requires 58 s of CPU time on a Sperry UNIVAC 1182 computer.

8. CONCLUSIONS

A discrete-event simulation system has been created to obtain probability distributions of load point reliability indices based on a very detailed model of transmission components outages. The modeled phenomena include switching operations, adverse/normal weather, closing of normally opened breakers, etc., etc.

Alternate applications include the calculation of just the mean and standard deviation of the reliability indices, or, if appropriate, the calculation of moments in order to fit a Pearson distribution.[13] Both of these will require less CPU time.

A possible extension to this system is the modeling of component outage rates that can change with time. Complex operating policies may also be included in the model. For example, a circuit may be removed from service once it has faulted a predetermined number of times in a severe storm.

ACKNOWLEDGMENTS

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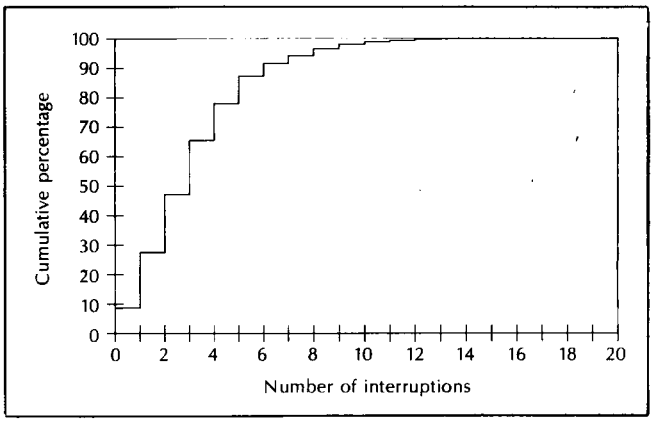

Figure 4. Number of interruptions in five years (mean = 3.09; S.D. = 2.39).

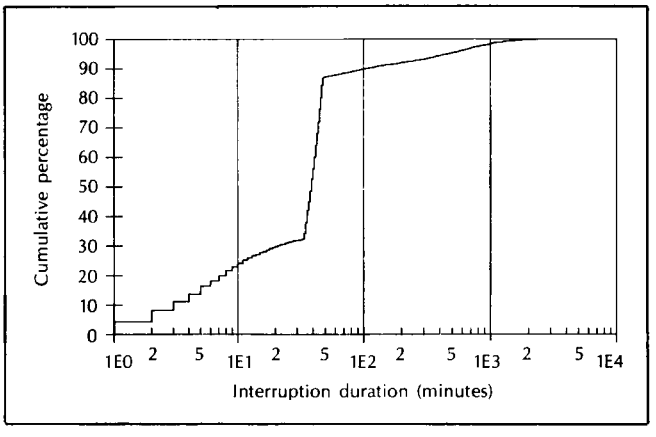

Figure 5. Interruption duration (mean = 88.5 min; S.D. = 244.7 min).

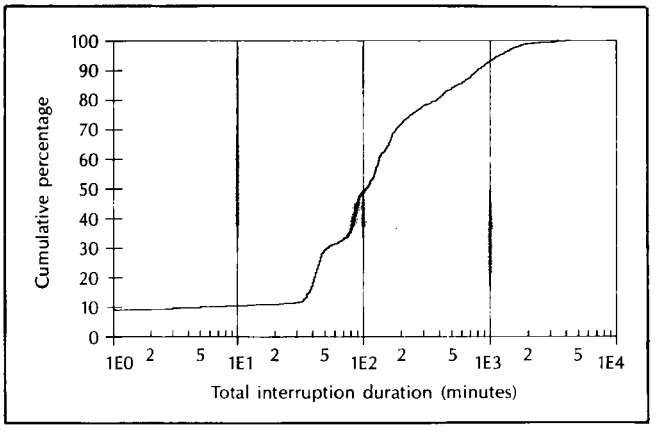

Figure 6. Total interruption duration in five years (mean = 273.4 min; S.D. = 456.6 min).

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