

POWER SYSTEM RELIABILITY EVALUATION

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by

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ABSTRACT

Reliability considerations are an important aspect of overall power system optimization in both the planning and operating areas. This thesis investigates the application of probability concepts to static and spinning generation reserve problems. The use of confidence levels in the basic component outage statistics are proposed as an additional degree of consistency in system reliability assessment.

Transmission system reliability is studied using published methods and compared with results obtained using a Markov process with a two state fluctuating failure environment covering normal and stormy weather periods. A method of evaluating the composite reliability at any load point and encompassing all the inherent system failure processes is proposed and illustrated. This approach will permit reliability evaluation to become an integral component in the economic appraisal of alternate facilities.

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INTRODUCTION

A basic requisite of a modern power system is the ability to satisfy the constantly changing system load requirement at all times. It is not possible to absolutely guarantee this ability and any attempt to do so is impractical and uneconomical. An important management function is to decide where the limited funds available to improve system security should be used to achieve the best overall result. In most power systems it becomes the responsibility of the System Planning Engineer to analytically determine the cost associated with a particular level of reliability and to provide management with quantitative assistance in making the final decision.

Reliability evaluation can take two distinct forms. It can serve as a prediction of average system performance over a relatively long period of time or it can be considered as a means of obtaining a consistent quantitative assessment of alternate proposals. In a continually changing system it is important to retain the concept that quantitative reliability evaluation is a basic process by which engineering personnel can advise management on the issue of security of customer supply. Reliability constraints should not be considered as separate issues but as an integral part of overall economic evaluation.

Until quite recently, nearly all power system reliability evaluation was limited to the area of total installed generating capacity requirements. Attention is now being given to other system component areas in attempts to optimize supply security to the actual consumer. Complete optimization entails the consideration of all system component areas from generation, trunk transmission and subtransmission facilities

down to the actual customer distribution system. The techniques in use at the present time are divided into the two completely separate areas of generating capacity reliability and subtransmission reliability. Very little emphasis has been placed on the evaluation of composite system reliability encompassing all component areas.

This thesis proposes and illustrates a method by which reliability assessment can become an integral part of system performance evaluation in both the planning and operating areas. A value for steady state adequacy can be obtained for any point within the system by utilizing a quality of service approach rather than an approach involving only continuity of service. A breach of continuity becomes only one form of violation of the service quality standard for the point in question. This approach requires a detailed knowledge of the conditions acceptable to the system in terms of voltage levels, permissible line loadings leading to relay action and stability implications. The ability to incorporate system parameters of this type has increased considerably within the past few years with the continued utilization of high speed digital computers in power system analysis.

Quantitative reliability analysis has not been applied to any great extent in the area of power system operation. This thesis illustrates the application of probability theory to the evaluation of operating capacity reliability and proposes the use of failure rate confidence levels as an additional aspect of consistent evaluation. The thesis also examines the bunching effect of storm associated transmission component failures using Markov processes and compares the results to those obtained by a published approximate method.

Power system reliability evaluation, with the exception of the static generating capacity area, has been generally limited to qualitative assessment. {The techniques proposed in this thesis should provide considerable assistance in developing quantitative incremental reliability costs for any point in a system.} The utilization of high speed digital equipment will permit complex composite systems to be studied in detail and therefore simplify the management problem of optimizing the reliability of customer supply.

2. REVIEW OF THE AVAILABLE METHODS IN POWER SYSTEM RELIABILITY EVALUATION

2.1 Generating Capacity Requirements

A considerable amount of work has been done in this area and some excellent papers published. A comprehensive survey of the available material has resulted in a bibliography⁽¹⁾ containing ninety six publications on the subject. The development of the techniques used at the present time is extremely interesting and although it is rather difficult to determine just when the first published material appeared, it was at least thirty years ago. Interest in the application of probability methods to the evaluation of capacity requirements became evident about 1933. There is, however, very little published material available for the period 1933 to 1947 at which time the first large group of papers appeared. This group of papers by Calabrese⁽¹⁻¹¹⁾, Lyman⁽¹⁻¹²⁾, Seelye⁽¹⁻¹³⁾, Loane and Watchorn⁽¹⁻¹⁴⁾ proposed the basic concepts upon which some of the methods in use at the present time are based. Shortly after this in 1948 the first A.I.E.E. Subcommittee on the Application of Probability Methods was organized. This Subcommittee chaired by Calabrese produced an important report in 1949 containing comprehensive definitions of equipment outage classifications and some statistical data on equipment outage expectancies⁽¹⁻²⁰⁾. Later reports on this subject by this Subcommittee appeared in 1954⁽¹⁻³⁰⁾ and 1957⁽¹⁻³⁶⁾. The 1947 group of papers proposed the methods which with some modifications are now generally known as the "Loss of Load Approach", "Loss of Energy Approach"

The Reference designation (1-11) refers to Paper Number 11 in Reference Number 1 "Bibliography On The Application Of Probability Methods In The Evaluation Of Generating Capacity Requirements". This Bibliography is included in the Appendix.

and the "Frequency and Duration of Outage Approach". They are described in considerable detail in a 1960 A.I.E.E. Committee Report⁽¹⁻⁷²⁾. The "Loss of Load Approach" is sometimes referred to as the "Calabrese Method". The effect of interconnections and the determination and allocation of capacity benefits resulting from interconnections were discussed by Watchorn⁽¹⁻²²⁾ and Calabrese⁽¹⁻²⁶⁾ in 1950 and 1953 respectively. Until 1954 most probability studies had been done either by hand or using conventional desk calculators. The benefits associated with using digital computers to reduce the tedious arithmetic required in these investigations were noted by Watchorn⁽¹⁻³¹⁾ in 1954 and illustrated in 1955 by Kirchmayer and his associates⁽¹⁻³²⁾ in the evaluation of economic unit additions in system expansion studies.

Several excellent papers appeared each year until in 1958 a second large group of papers was published. This group of papers modified and extended the methods proposed by the 1947 group and also introduced a more sophisticated approach to the problem using "Game Theory" or "Simulation" techniques^(1-59 to 70). Additional material in this area appeared in 1961 and 1962 but since that time interest in this approach appears to have declined. A recent Federal Power Commission Report⁽²⁾ stated that former users of the Monte Carlo approach "are currently substituting the loss of load probability type computations for the gaming approach". The A.I.E.E. Subcommittee published in 1961 the previously noted report⁽¹⁻⁷²⁾, which apart from the simulation approach, provided an extremely comprehensive summary of the earlier papers and available methods. The three A.I.E.E. Committee Reports on equipment forced outage experience published in 1949, 1954 and 1957 were generally restricted to

thermal unit equipment information with the exception of a short section on hydraulic equipment in the 1949 report. Brown, Dean and Caprez⁽¹⁻⁷⁴⁾ in 1960 published the results of a statistical study of five years of data on 387 hydro-electric generating units using punched cards for the initial collection and sequential processing of the data. Shortly after this in 1961 the A.I.E.E. Subcommittee produced a manual⁽¹⁻⁷⁹⁾ outlining reporting procedures and methods of analyzing forced outage data using digital equipment. In spite of the many excellent publications available there is still considerable reluctance among many power system engineers to accept the application of probability methods to this problem. This is particularly true in Canada, where out of eleven major companies replying to a questionnaire, only one company stated that its capacity requirement criterion was based upon probability concepts⁽⁷⁾. The remaining ten organizations used relatively inflexible rule of thumb techniques such as fixed percent margins⁽³⁾.

Until 1963 almost all publications on generating capacity requirements were confined to the area of total installed capacity requirements.* An important paper based entirely on the application of probability theory to the area of system spinning requirements was published in 1963 by Anstine and his associates⁽¹⁻⁸⁸⁾. Additional work in this area has since been done in Canada^(4,5,6), and is discussed in Chapter 3.

As previously noted, there are several accepted methods of evaluating the reliability of a given generating capacity condition. Neglect-

*The total installed generating capacity requirement is often designated as the static requirement⁽³⁾ and considered a system planning problem. The spinning capacity requirement⁽³⁾ is a system operating problem and concerns the capacity actually rotating or capable of supplying load within a predetermined minimum time.

ing the simulation approach, the most flexible of these techniques is the "Loss of Load Probability Approach". This method involves the construction of a capacity outage probability table for the available system generating capacity to which the probabilities of coincident load levels can be combined to produce a mathematical expectation or risk level for a specified period. The capacity outage probability table lists the probabilities of having various amounts of capacity on forced outage at any time in the future. The basic statistic is the probability of finding the generating unit on outage at some future time. This probability value is known as the generating unit forced outage rate (F.O.R.). For a particular unit and over some previously defined time period this value is obtained from past performance records.

$$\text{Generating Unit F.O.R.} = \frac{\text{Time on Forced Outage}}{\text{Exposure Time}} \quad (2.1)$$

where: Exposure Time = Operating Time + Forced Outage Time. The best estimate of the probability of the generating unit being on forced outage during future operating periods is obtained by using cumulative values of forced outage and exposure times. It may be necessary to modify the cumulative value due to aging effects or variations in maintenance practices or operating roles. The definitions and classifications⁽²⁴⁾ covering equipment outages must be quite explicit for the resulting statistics to be of use in the prediction of future outage occurrence. System experience has shown that the existence of generating unit forced outages can be considered as random independent events. The probability of existence of simultaneous outages of two or more units is, therefore, the product of the individual unit outage existence probabilities. In a study involving identical units the Binomial Expansion can be used to

obtain the probability of existence for each capacity outage level. For a system containing generating units with different capacities and forced outage rates, the capacity outage probability table is developed by correctly combining the probabilities of the independent events. As the probabilities of having several units on outage at the same time can be quite small, it has been found convenient to curtail the capacity outage probability table by omitting probability values smaller than 10^{-8} .

When many units of different capacities are combined, the table will contain an extremely large number of discrete capacity levels. The number of levels can be reduced by proportionally summing the discrete probability values at selected capacity levels, thus limiting computer storage requirements and facilitating later combination with the load distribution⁽³⁾. A detailed study⁽²⁵⁾ using mathematical models of both the Saskatchewan and Manitoba Systems has shown that there is negligible overall error when a 5MW capacity increment is used. The magnitude of the overall error is dependent upon the capacity increment and the slope of the system load characteristic. The error decreases with increasing slope and is a maximum for a system with one hundred percent load factor.

A failure to carry the system load for any given time occurs when the load for that period exceeds the available generating capacity. A single system capacity outage probability table is required if the assumption can be made that units will not be removed from service for planned or scheduled maintenance. If maintenance is necessary, a theoretically accurate solution involves a continually changing, applicable capacity outage probability table applied to the corresponding system load model. Several approximate methods have been developed to avoid modifying the

capacity outage probability table. They can, however, be quite inaccurate in certain cases.

System loss of load can occur at times other than at the daily system peak. The conventional System Load Duration Curve is a suitable hourly load model and can be used on an annual, monthly, weekly or daily basis depending upon the variation in available system generating capacity. If almost all planned maintenance is performed during the light load months which add relatively small values of loss of load expectancy to the annual total, then the assumption of a constant capacity model may be quite valid and used in conjunction with an annual load distribution.

The system load level expected to occur at some time in the future cannot be forecast exactly. It may be possible, however, to define the load in terms of a probability distribution. This condition can be included in the loss of load probability computations without too much difficulty and the capacity required to satisfy a future uncertain load requirement at a specified risk level evaluated. The inclusion of probability of load forecast uncertainty in reserve generating capacity studies dictates a larger required installed capacity margin to serve the future uncertain peak load than that required to meet an equivalent exact value. These concepts have been applied in detail to mathematical models of the Saskatchewan and Manitoba Systems operating as single systems and as an interconnected system with finite and infinite interconnecting capacity. The results of this study⁽²⁵⁾ are extremely interesting and illustrate the application of probability theory to the determination and allocation of interconnection benefits.

The relative merits of the different methods of evaluating the reliability of generating capacity requirements are not discussed in this thesis. The "Loss of Load Probability Approach" is, however, the basis of several highly automated system expansion programs used by the industry at the present time⁽²⁶⁾. This method is extended in Chapter 5 to the evaluation of composite system reliability encompassing generation and transmission facilities.

2.2 Transmission System Reliability Evaluation

In comparison to the numerous publications in the area of generating capacity reliability there is relatively little published material on the subject of transmission system reliability evaluation. A group of excellent papers were presented at the 1965 Eastern Zone Meeting of the Canadian Electrical Association^(8 to 17) but with a single exception⁽¹⁵⁾ they discussed reliability in a qualitative rather than a quantitative sense. Apart from several earlier papers in the field^(18,19,20), the techniques available at the present time are summed up in two 1964 publications^(21,22). The two methods are considerably different in concept and in the extent to which probability theory is applied.

The first of these methods⁽²¹⁾ deals with the simultaneous conditions that must exist for power flow in series and parallel combinations of system components. The application is quite straightforward and is based upon four relatively simple principles.

- (a) A component operates in only two states, available and unavailable. Maintenance is not considered and the probability of a component being unavailable is given by its forced outage rate "p". If "q" is the availability rate then $p + q = 1.0$.

- (b) Component failures are assumed to be independent and therefore the probability of simultaneous failures is given by the product of the respective probabilities.
- (c) In a series system all components must be available for power flow into a receiving point. The probability of success is the product of the availability probabilities. For a two unit system with outage rates p_1 and p_2 and availability rates q_1 and q_2 .

$$q_s = q_1 q_2$$

$$p_s = 1 - q_1 q_2 = p_1 + p_2 - p_1 p_2$$

If p_1 and p_2 are much less than unity the $p_1 p_2$ product can be neglected. The failure probability of a series system in this case is the sum of the element failure probabilities.

- (d) In a parallel system all paths must fail if no power is to flow into the receiving point. For a two element system the failure probability is the product of the two component failure values.

Forced outage rate is usually defined as the total component outage time divided by the total component exposure time and is the probability of component outage existence. To provide an indication of both outage frequency and outage duration the definition can be modified to indicate the probability of outage occurrence rather than outage existence.

Define the forced outage rate as:

$$p = \frac{\text{Sum of the days upon which an outage of specified minimum duration occurred}}{\text{Sum of unit days}} \quad (2.2)$$

If component forced outage rates for different minimum specified durations are compiled, it is possible to predict the frequency of occurrence of this condition at any particular point in the system. It should be realized that outages can occur on the same day but not simultaneously. This approach assumes that all outages occurring during one day are

simultaneous outages thus giving a pessimistic result. This can be partially reconciled by considering that if two components within an area are forced out of service during the same day the probability of simultaneous occurrence is somewhat higher than implied by absolute outage independence. This method is restricted to the evaluation of continuity at a particular point and cannot be extended to systems that are not fully redundant.

This approach has been applied⁽²⁷⁾ to the small hypothetical system shown in Figure 2.1.

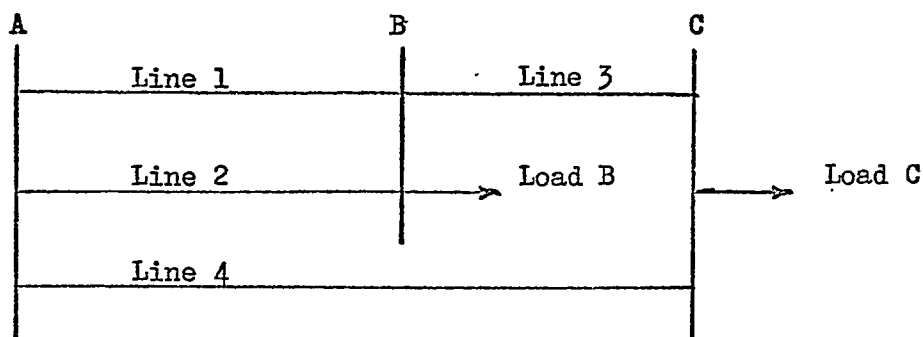


Figure 2.1. Simple Series Parallel System

The failure rates for each line section are:

TABLE 2.1

System Parameters For Method 1

<u>Line Section</u>	<u>Failures/Year</u>
1	0.5
2	0.5
3	0.1
4	0.6

Considering the failures per year as the number of days upon which failures occur within the year, the probability of an outage occurring on lines 1

or 2 is given by

$$p_1 = p_2 = \frac{0.5}{365} = 1.37 \times 10^{-3}$$

Similarly

$$p_3 = 0.274 \times 10^{-3}$$

$$p_4 = 1.644 \times 10^{-3}$$

Define Average Annual Customer Interruption Rate as the expected number of days in a year that the specified outage condition for the load bus will occur. Assuming that the system is first composed of Lines 1, 2 and 3 and then of Lines 1, 2, 3 and 4 the results are shown in Table 2.2.

TABLE 2.2

System Reliability Using Method 1

	<u>Average Annual Customer Interruption Rate</u>
Load B. Lines 1, 2 and 3	6.85×10^{-4}
Load B. Lines 1, 2, 3 and 4	1.31×10^{-6}
Load C. Lines 1, 2 and 3	0.1006
Load C. Lines 1, 2, 3 and 4	0.165×10^{-3}

The reliability indices are based entirely on the continuity of supply to the respective load points therefore assuming a completely redundant system. In an actual system the failure rates for each line section can be obtained by correctly combining the failure rates of the series or parallel equipment configurations within each section.

The second available method^(22,23) again deals with series and parallel systems but predicts both outage duration and outage frequency by making certain specific assumptions regarding the probability distributions of component repair and failure times. An extremely important

aspect of this approach is the introduction of a varying environmental condition associated with the operating component. Two states, normal weather and stormy weather describe the component environment. Each condition has an associated component failure rate in terms of failures per year of operation within that environment. Assuming that component failure times, component repair times, storm durations and normal weather durations are characterized by exponential probability distributions, it is possible to develop outage rates for parallel facilities that include the bunching effect of storm associated failures.

The method⁽²²⁾ uses an approximate expression for the overall outage rate of two parallel facilities under these conditions. A theoretically accurate solution for this system is developed in Chapter 4 using Markov processes. The simple four line system used to illustrate the first method and shown in Figure 2.1 is again considered using the overall annual failure rates and expected repair durations shown in Table 2.3.

TABLE 2.3

System Parameters for Method 2

<u>Line Section</u>	<u>Failure Rate Failures/Year</u>	<u>Expected Repair Time Hours</u>
1	0.5	7.5
2	0.5	7.5
3	0.1	7.5
4	0.6	7.5

Using these values the reliability indices for Loads B and C with and without Line 4 in-service are shown in Table 2.4. These values were obtained using the overall annual failure rates. If the component failure rates during stormy and normal weather conditions are not equal

then the predicted values shown in Table 2.4 may be considerably in error. The magnitude of the error depends upon the expected duration of stormy and normal weather periods and the percentage of component failures that occur under each condition.

TABLE 2.4

System Reliability Using Method 2

	<u>Failures per year</u>	<u>Average Total Outage time, hours</u>
Load B. Lines 1, 2 and 3	0.4281×10^{-3}	0.1605×10^{-2}
Load B. Lines 1, 2, 3 and 4	0.3848×10^{-6}	0.9621×10^{-6}
Load C. Lines 1, 2 and 3	0.1004	0.7515
Load C. Lines 1, 2, 3 and 4	0.1031×10^{-3}	0.3681×10^{-3}

Assume that for the system shown in Figure 2.1 the expected values of stormy weather and normal weather durations are 1.5 hours and 200.0 hours respectively. The predicted failure rate and average outage duration for each load point are shown as a function of the percentage of component failures occurring during the stormy periods in Figures 2.2 and 2.3. As the stormy component percentage failure increases, the differences between the values calculated using overall annual values and those calculated considering stormy periods increase quite rapidly. The magnitude of possible difference in reliability prediction is clearly shown in Figure 2.4 in which the load bus failure rate is shown in per unit of the value calculated using average annual failure rates. Figure 2.4 also shows the effect of longer storm durations occurring less frequently. In each case the error in the predicted value for Load C with line 4 unavailable is quite small as the reliability indices are almost entirely

dependent upon the values for Line 3, the series component. With Line 4 included, the error in the predicted failure rate for Load C again becomes evident due to the bunching effect of storm associated failures on parallel facilities.

It should be quite clear that the reliability indices calculated by the two methods outlined cannot be compared directly. The first method is relatively simple to apply even to a rather complicated system and if component failure is not a function of the environment but occurs purely by chance then this method can give quite useful results.

If the failure rate is a function of the environment then the utilization of overall annual component failure rates in the second method can lead to incorrect reliability predictions for paralleled or networked facilities. In its complete form this method is rather difficult to apply in a complicated system and becomes more of an approximation as additional parallel elements are combined. This is illustrated in Chapter 4 where results obtained by Markov processes are compared with those obtained using this method. The reliability indices calculated for the hypothetical system in the second case were again based only upon the criterion of continuity of supply. The system is assumed to be fully redundant.

At the present time there are very few organizations utilizing probability concepts in the evaluation of transmission system reliability. This is due to a large extent to the absence of comprehensive reporting procedures for transmission facilities. Committees in the United States and Canada are actively engaged in this area and procedures should be available in the near future.