ADEQUACY EVALUATION OF COMPOSITE POWER SYSTEMS INCLUDING VARYING WEATHER CONDITIONS

A Thesis

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"ADEQUACY EVALUATION OF COMPOSITE POWER SYSTEMS
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ABSTRACT

The application of probabilistic techniques in the area of composite generation and transmission system reliability evaluation is now receiving considerable attention. This thesis attempts to further the state of the art in composite system reliability evaluation by including the effect of varying weather conditions. The thesis illustrates the development and analysis of several models which can be used to represent a fluctuating environment. Models presented in this thesis are used to examine the sensitivity of selected reliability indices to individual parameter variation in a composite test system. A previously developed composite computer program based on simulation and load flow analysis of "credible" outage conditions has been extended by including the weather effects.

During stormy weather periods, the failure rate of a component can increase sharply and the probability of overlapping failures can be much greater than that existing in normal weather periods. This phenomenon is called "failure bunching" due to the fact that components are fully or partially exposed to a common weather condition. Component failures, therefore, are not randomly distributed throughout the year but are more probable in constrained short periods in the year. Evaluation techniques for composite system reliability assessment are presented in this thesis which include varying weather conditions. Several methods, designated as the approximate equation technique, the full Markov state process, the approximate four-state approach and the line or area addition method are presented and discussed. The impact of these weather models on composite generation and transmission system adequacy indices are compared and discussed in the thesis.

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CHAPTER 1

INTRODUCTION

The basic function of a power system is to supply customers, both large and small, with electrical energy as economically and as reliably as possible. Modern society, because of its social and working habits, has come to expect the electric supply to be continuously available on demand. It is not feasible economically or technically to attempt to design a power system with one hundred percent reliability. The system reliability should be related to the needs of the system customers. Past practices of expressing the reliability in qualitative terms are not sufficient to relate to the needs of modern society. These practices are slowly being replaced by quantitative indices which are calculated using probabilistic concepts.

An electric power system generates electrical energy at its generating stations, and supplies it to the individual customers through a suitable transmission and distribution network. The reliability evaluation of a power system therefore involves a comprehensive analysis of its three principal parts namely the generation, transmission and distribution functions [1, 2, 3, 4, 5, 6, 7]. In addition to providing the means to move the generated energy to the individual customer load points, the bulk transmission and distribution facilities must be capable of maintaining the following requirements.

(1). Acceptable voltage levels.
(2). Thermal limits on lines.
(3). System stability limits.

The models used to represent the bulk facilities therefore should be capable of including both static and dynamic considerations. The static evaluation of the system's ability to satisfy the system load requirement can be designated as adequacy evaluation. Concern regarding the ability of the system to respond to a given contingency can be designated as security evaluation.

The total problem of assessing the adequacy of the generation and bulk power transmission system in regard to providing a dependable and suitable supply at the terminal stations can be designated as composite system adequacy evaluation.

1.1 Reliability Evaluation of a Generating System

The primary purpose of generating capacity reliability evaluation is to determine the ability of the generating facilities to satisfy the system load requirement. This is shown conceptually in Figure 1-1. A large number of papers which apply probability techniques to generating capacity reliability evaluation have been documented in four comprehensive bibliographies published in 1966, 1971, 1978 and 1983 [3, 4, 5, 7]. The available probabilistic methods can be loosely classified into four techniques. They are the Loss of

Load Expectation, Loss of Energy Expectation, Frequency and Duration and Monte-Carlo Simulation techniques. The basic approach used to evaluate the adequacy of a particular generation configuration is fundamentally the same for all the techniques and consists of three parts as shown in Figure 1-2.

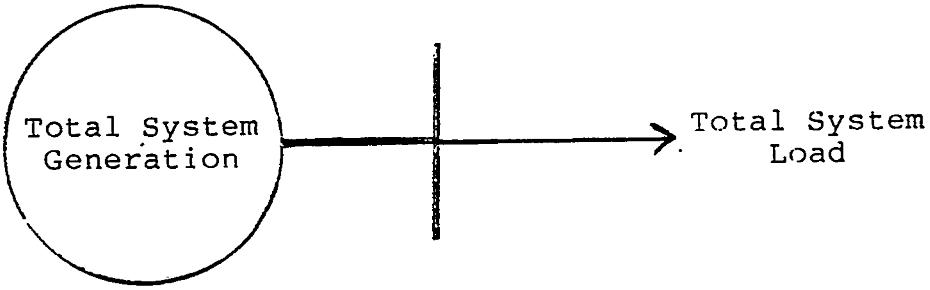

Figure 1-1: Simple Power System

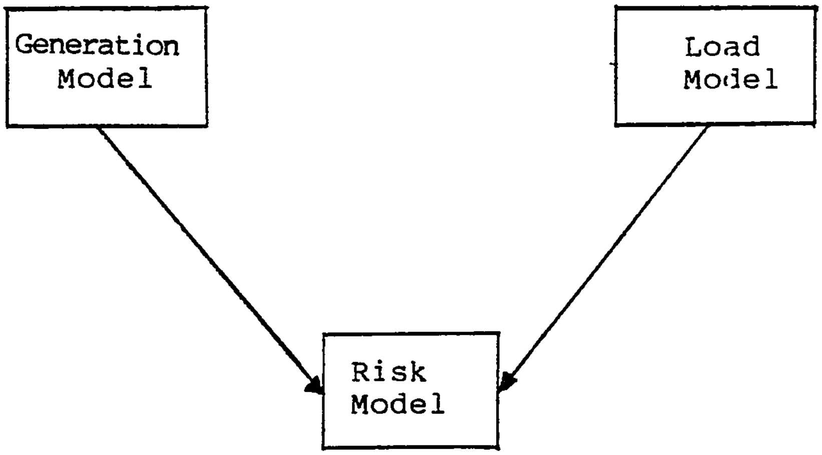

Figure 1-2: Conceptual Tasks in Generating Capacity Reliability Evaluation

A brief description of each of the four techniques is as follows:

(1) Loss of Load Expectation (LOLE) --- The risk of insufficient capacity is evaluated in terms of the expected number of time units that the peak load will exceed the available installed capacity [1, 2, 8].

(2) Loss of Energy Expectation (LOEE) --- This is similar to LOLE. The results of this method are usually given in terms of the probable ratio of load energy curtailed due to deficiencies in the generating capacity available to the total load energy required to serve the requirements of the system [1, 2, 8].

(3) Frequency and Duration (F & D) --- This technique determines the frequency, the mean duration and the probability associated with various levels of generating capacity adequacy and inadequacy [1, 2, 9, 10, 11, 12, 13].

(4) Monte-Carlo Simulation --- This is a very general method which theoretically can be used to produce all of the indices available from the previous methods plus additional distributional information [14, 15, 16].

1.2 Reliability Evaluation of Transmission Systems

The area of transmission system reliability evaluation has historically been somewhat slower to develop than that of generation systems in both modelling techniques and data collection. The activity in this area was initiated by two 1964 publications [17, 18], and was expanded and advanced in a subsequent publication [19]. These papers developed models and equations for series and parallel system configurations which in addition to proposing indices of failure rate, average outage duration and average outage time included considerations of failure bunching due to adverse weather conditions. The Markov process has been applied in the area of transmission system reliability evaluation as described in Reference [20]. A general approach including a complete state space model requires tremendous computer storage and is not feasible for practical power systems. The common cause outage phenomenon has also been examined in several recent publications [21, 22, 23]. A common cause outage is a situation in which multiple outages occur due to a single event, which are not consequences of each other. In the case of adverse weather modelling as conducted in References [18, 19, 20], the common factor is the weather environment to which the multiple components are exposed. The actual failures are then assumed to be independent events occurring with enhanced failure rates due to the common adverse weather environment.

1.3 Reliability Evaluation of Composite Generation and Transmission Systems

The reliability evaluation of a composite generation and transmission system is concerned with the problem of determining the adequacy of the generation and transmission system in regard to providing a dependable and suitable supply at the terminal stations. Relatively few papers are available in this area but it is now receiving considerable attention. The application of probabilistic methods to the area of composite system reliability evaluation was proposed by Billinton in References [24, 25]which includes complete system representation of the form used in load flow analysis. This technique provides the criterion of quality of service rather than just the continuity of service.

The reliability evaluation of a composite system basically involves the simulation and load flow analysis of each "credible" outage condition in the system in order to determine the voltage violations, line and generation overloads, violation of generation MVAR limits, etc. A digital computer program for this purpose was developed at the University of Saskatchewan by Billinton and Bhavaraju [26, 27, 28], and extended by Medicherla [29] to incorporate common cause outages and a fast decoupled load flow. The program is based on two conditional probability approaches [1, 2, 24, 25] and has been further extended by Kumar[30], Vohra[31] and the author. The program now includes higher order contingency outages, station originated outages and adverse weather effects. The reliability indices produced by this program are based on steady state analysis of the system's ability to satisfy the load requirements under selected contingency conditions. The system response to the actual transient caused by element failures is not considered in this analysis.

1.4 Scope of This Thesis

This thesis attempts to include in composite generation and transmission system adequacy assessment the bunching effect due to the transmission line elements being fully or partially exposed to common weather conditions. The application of the conditional probability approach to the area of composite system reliability evaluation as described in References [1, 2, 24, 25] and used in this thesis is briefly reviewed in Chapter 2. The digital computer program based on this conditional probability approach, the simulation and the load flow analysis for each "credible" outage condition is also described in this chapter. The fast decoupled load flow technique proposed in Reference [32] and used in the computer program is described. The set of calculated adequacy indices [2, 29] provided by the composite computer program is also detailed. Numerical values of these indices are presented and discussed in Chapter 5 using a 5 bus test system and the 24 bus IEEE Reliability Test System(RTS).

The failure rate of outdoor components such as transmission lines is a function of the weather environment to which they are exposed. The failure rate of a component can be much higher in stormy weather than that in a normal weather condition. The probability of overlapping failures in stormy weather, therefore, can be very much greater than that in normal weather. This phenomenon is called "failure bunching" due to the fact that component failures are not randomly distributed throughout the year but are more probable in constrained short periods in the year. Initial modelling of varying weather conditions and an evaluation technique using an approximate equation method were proposed by Gaver, Montmeat and Patton in Reference [18]. The approximate equation method was expanded and advanced by Billinton and Grover in publication [19]. Another approach using Markov processes which includes the weather effect was proposed in 1968 by Billinton and Bollinger in Reference [20]. It has been shown that in certain cases, reliability predictions without including weather considerations can be quite optimistic and the results can be considerably in error.

The basic concepts associated with varying weather modelling and its evaluation techniques, the approximate equation method and the complete Markov process approach, are described and discussed in Chapter 3. The results are presented using very simple 2 line and 3 line redundant systems. The difficulty with these models is that the solution becomes very complicated as the complexity of the transmission system increases. The approximate equation method only provides indices for the all components out of service case so that the solution is only suitable for a fully redundant system. The complete Markov process approach as described in Reference [20] is not feasible for a practical power system as it requires tremendous memory space to solve the problem.

Several transmission system models which include weather effects and which can be implemented in a computer program for practical power system studies are proposed in Chapter 4. The approximate 4-state method [33] solves the 4-state weather model of each transmission line instead of solving the full Markov state weather model of the transmission system, and uses conditional probability concepts to evaluate the adequacy indices. The model assumes that the entire bulk transmission system is exposed to the same weather environment. The line or area addition approach attempts to recognize the regional aspect of adverse weather rather than assuming that the entire bulk transmission system is exposed to the same weather environment. The bunching effect is recognized for those transmission line sets which are adjacent to each other.

The results of these weather models are presented using a 5-bus test system and the IEEE Reliability Test System. Each weather model is utilized to examine the sensitivity of selected adequacy indices to individual parameter variation in the composite systems. The comparison and discussion of different weather models are given in Chapters 4 and 5. Conclusions are provided in Chapter 6.

In summary, reliability evaluation in composite generation and transmission systems is now receiving considerable attention. This thesis attempts to further the state of the art in this area by including the effect of varying weather conditions.

CHAPTER 2

A QUANTITATIVE METHOD FOR ADEQUACY EVALUATION OF A COMPOSITE SYSTEM

2.1 Introduction

The main function of a modern power system is to satisfy the customer load requirements as economically as possible and with a reasonable assurance of availability and quality. These requirements lead to the need for obtaining the quantitative reliability indices for the system and for each of the major distribution points. The calculated indices can then be used to evaluate the individual customer load point indices. System reliability can be divided into two distinct aspects of system adequacy and system security.

(1) System adequacy relates to the existence of sufficient facilities within the system to satisfy the customer load demand. The concept of adequacy therefore can be associated with static system conditions which do not include disturbances such as those considered under security.

(2) System security involves the ability of the system to respond to disturbances arising within that system. The concept of security can therefore be associated with the dynamic response of the system to whatever perturbation it is subjected to.

A power system can be divided into three basic functional zones designated as generation facilities, transmission facilities and distribution facilities. Reliability assessment can be conducted at various levels in the functional categorization. Figure 2-1 illustrates the combinations of the functional zones which can be used in adequacy assessment. These combinations are referred to as hierarchical levels. The work in this thesis is concerned with adequacy evaluation in a composite system containing generation and transmission facilities. The evaluation is therefore at the hierarchical level II.

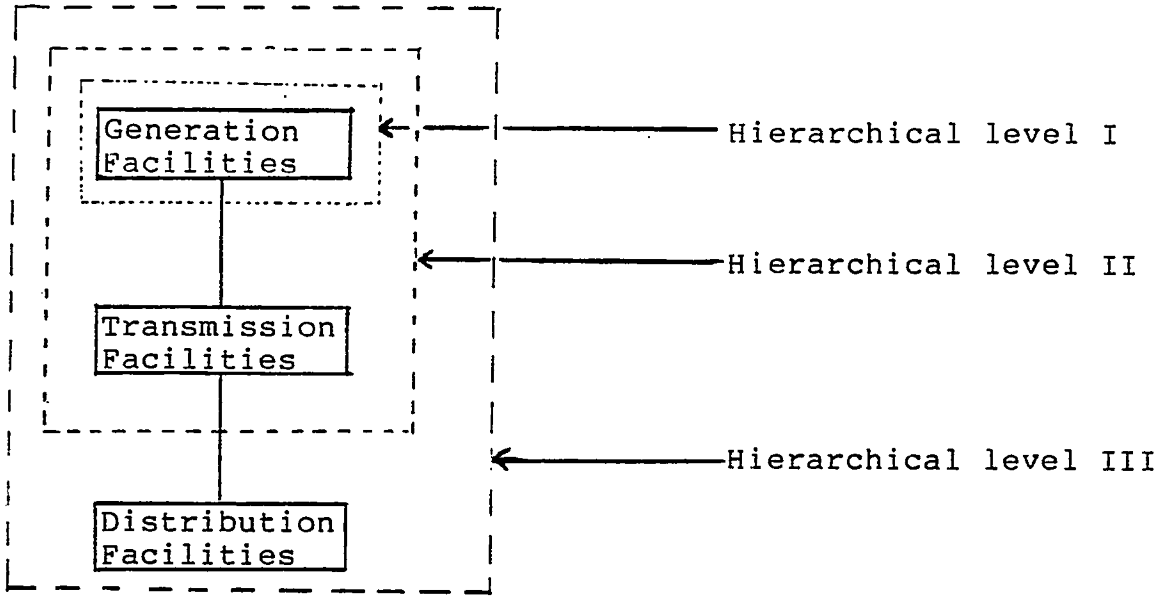

Figure 2-1: Hierarchical Levels in Adequacy Assessment

The reliability evaluation of a composite system basically involves the simulation and load flow analysis of each "credible" outage condition in order to determine deficiencies in the system. Billinton and Bhavaraju proposed two composite system reliability approaches [26, 27] which include a system representation of the form used in load flow analysis. These two approaches are briefly reviewed in this chapter. A digital computer program based on these conditional probability approaches was developed at the University of Saskatchewan by Billinton and Bhavaraju and extended by Medicherla. The main algorithm of the computer program and its associated techniques are described. The adequacy indices produced by this program are also detailed.

2.2 Conditional Probability Approach in Composite System Reliability Evaluation

The application of the conditional probability approach to composite generation and transmission system reliability evaluation was proposed by Billinton and Bhavaraju in Reference [26, 27] and is briefly described in this section.

If the occurrence of an event A is dependent upon a number of events B_j which are mutually exclusive then the probability of event A is given by

$$P(A)=\sum_i P(A/B_i).P(B_i) \qquad (2.1)$$

If the occurrence of A is dependent upon only two mutually exclusive events for component B, success and failure, designated as B_s and B_f respectively then :

$$P(A)=P(A/B_s).P(B_s)+P(A/B_f).P(B_f) \qquad (2.2)$$

In the case where event A is system failure then

P(system failure)

=P(system failure/B is good).P(B is good)

+P(system failure/B is bad).P(B is bad) (2.3)

2.2.1 Approach I

This approach considers generation inadequacy and transmission inadequacy as two independent events. The generation inadequacy is assessed in a total system context using the probability of generating capacity outage exceeding the reserve capacity. This probability is determined from the capacity outage probability table of the total system. The transmission inadequacy is assessed by simulating and analyzing all "credible" outage combinations of the transmission elements. The maximum load that can be supplied at a bus is determined using load flow analysis for each "credible" outage condition in the transmission system. The probability of the load at the bus exceeding this maximum value is then combined with the probability of generation inadequacy to obtain the probability of failure as follows :

$$Q_k = \sum_j P_j . [P_{gj} + P_{qj} - P_{gj} . P_{qj}] \qquad (2.4)$$

where :

k is a bus in the system.

j is an outage condition in the network.

P_j is the probability of existence of the outage j.

P_{qj} is the probability of the load at bus k exceeding the maximum load that can be supplied at that bus during the outage j.

P_{gj} is the probability of generating capacity outage exceeding the reserve capacity due to the outage j.

The expected frequency of failure at any bus can also be calculated. The generating unit outages and the load variation are considered in terms of probability only and not in terms of the frequency of occurrence. An estimate of the expected frequency of failure F_k at bus k is given by

$$F_k = \sum_j F_j . [P_{gj} + P_{qj} - P_{gj} . P_{qj}] \qquad (2.5)$$

where : F_j is the frequency of occurrence of the outage j.

This approach considers the generating facility as a single entity. This may be acceptable in a radial configuration but may not be suitable when the generation is dispersed throughout the system.

2.2.2 Approach II

In this approach, all generating units, transmission lines and transformers are considered individually to determine each outage condition j. A general set of equations can be obtained from Equation 2.1.

Probability of failure at bus k

$$Q_k = \sum_j P_j \cdot P_{qj} \tag{2.6}$$

Frequency of failure at bus k

$$F_k = \sum_j F_j \cdot P_{qj} \tag{2.7}$$

This approach utilizes a more complete picture of the system and the evaluated reliability indices therefore are more indicative of the actual system performance.

2.3 Fast Decoupled Load Flow Technique

Load flow calculations are an important part of system planning, operation planning and operation control. Various load flow techniques are available depending on the use to be made and the quality required of the analysis. A D.C. load flow calculation is simple and fast but it does not provide any estimates of the voltage phase angles and the reactive power flows in the power system. A.C. load flow is computationally more expensive than D.C. load flow but it provides the additional information for system analysis. The fast decoupled load flow technique was proposed by Stott and Alsac in Reference [32] and is used for adequacy assessment in this thesis. The technique can be derived by neglecting the weak coupling which exists in a power system between MW flow and voltage magnitude, and MVAR flow and voltage phase angle.

2.3.1 Derivation of the Fast Decoupled Load Flow Technique

As shown in Figure 2-2, the complex power flow from bus k to bus m is given by

$$S_{km}=P_{km}+jQ_{km} \tag{2.8}$$

In Figure 2-2 :

Y_{km} =admittance between buses k and m.

Bc_{km}=capacitance at bus k due to line km.

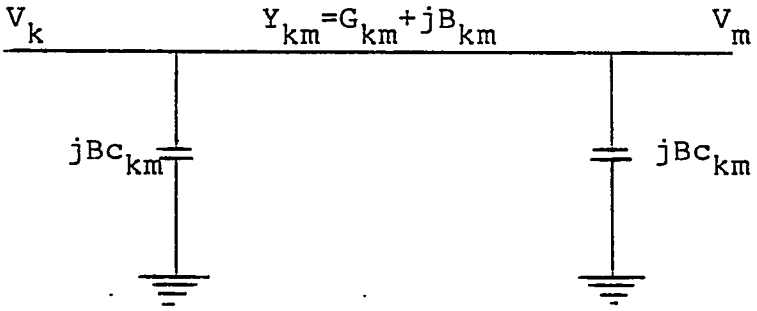

Figure 2-2: Transmission Line Model Between Buses k and m

If $\theta_{km} = \theta_k-\theta_m$
=Difference of phase angle between buses k and m

Real power flow P_{km} (2.9)

$$= V_k^2.G_{km}-V_k.V_m[G_{km}\cos\theta_{km}+B_{km}\sin\theta_{km}]$$

Reactive power flow Q_{km} (2.10)

$$= -V_k^2[B_{km}+Bc_{km}]-V_k.V_m[G_{km}\sin\theta_{km}-B_{km}\cos\theta_{km}]$$

The sum of all powers flowing in the transmission lines originating at bus k will be equal to the difference between the power generated at that bus and the load connected. The active and reactive power balance equations at bus k are therefore written as follows :

$$P_k(\theta_1,\theta_2 \ldots . V_1,V_2 \ldots .) = P_G - P_L = \mathrm{Re}[\vec{V}_k \sum_m \vec{Y}^*_{km} \vec{V}^*_m] \qquad (2.11)$$

$$Q_k(\theta_1,\theta_2 \ldots . V_1,V_2 \ldots .) = Q_G - Q_L = \mathrm{Im}[\vec{V}_k \sum_m \vec{Y}^*_{km} \vec{V}^*_m] \qquad (2.12)$$

Equations 2.13 and 2.14 are obtained using Taylor's Series Expansion and neglecting the second and higher order terms.

$$\Delta P_k = \left.\frac{\partial P_k}{\partial \theta_m}\right|_0 \Delta\Theta_m + \left.\frac{\partial P_k}{\partial V_m}\right|_0 \Delta V_m \qquad (2.13)$$

$$\Delta Q_k = \left.\frac{\partial Q_k}{\partial \theta_m}\right|_0 \Delta\Theta_m + \left.\frac{\partial Q_k}{\partial V_m}\right|_0 V_m \frac{\Delta V_m}{V_m} \qquad (2.14)$$

The equations can be rewritten in the form of 2.15 and 2.16 by neglecting the weak coupling between MW flow and voltage magnitude, and reactive power flow and voltage phase angle.