Individual Generating Station Reliability Assessment

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Abstract

Failures originating within a generating station can create significant system disturbances. It is essential to carefully design the station arrangement in order that faults originating in the station have minimum effect on the overall power network. Reliability assessment of an individual generating station can highlight the effect of a particular configuration and thus provide detailed and comparative information for decision making when planning that station. This thesis is concerned with individual generating station adequacy and security assessment. New indices, models and techniques have been developed in this research work, which recognize the application and purpose behind the assessment of an individual generating station.

A series of indices are proposed. These include adequacy parameters, indices implicitly indicating operating security and indices that can be used to express the effect of station originated outages on the related power network. The possible weaknesses of the conventional three state model are investigated. The results show that the existing dependencies and practical restorative actions cannot be completely represented using this model. In order to overcome these weaknesses, system originated state transition models for several types of failure events were established and a generalized n+2 state system Markov model formed. The numerical comparisons show that the difference between the results calculated using the generalized n+2 state model and the three state model are significant for some cases. A systematic technique and a prototype computer program for large individual generating station reliability assessment were developed based on the index structure and the generalized n+2 state system model. Factors such as stuck breaker conditions, normally open components and the optimal switching sequence are incorporated in the algorithm and computer program.

The Three Gorge power station in China, which will be the largest hydro generating station in the world, is used as a particular engineering example to illustrate and investigate the possible applications of the proposed techniques in practical engineering planning. Nine alternative switchgear arrangements have been assessed. An adequacy assessment, a security assessment and an overall comparison are presented. An optimum design based on the available date is given. The reliability engineering assessment of the Three Gorge project described in this thesis indicates that the developed indices, models and quantitative techniques can be applied in practical engineering situations to provide valuable information for planning decisions.

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List of Symbols and Abbreviations

λ	Active failure rate of a component
λ_{ai}	Active failure rate of component i
λ_{pi}	Passive failure rate of component i
λ_i''	Scheduled maintenance outage rate of component i
λ_E	Equivalent failure rate
λ_{Ea}	Equivalent active failure rate
λ_{Eaa}	Equivalent overlapping active failure rate
$\lambda_{Ea}(j / i)$	Equivalent conditional active failure rate of component j on component i
$\lambda_{Ea}(i / j)$	Equivalent conditional active failure rate of component i on component j
$\lambda_{Ea}(F_i)$	Equivalent active failure rate associated with failure event F_i
λ_{Ep}	Equivalent passive failure rate
$\lambda_{Ep}(F_i)$	Equivalent passive failure rate associated with failure event F_i
μ	Repair rate of a component
μ_i	Repair rate of component i
μ_i''	Scheduled maintenance repair rate of component i
μ_E	Equivalent repair rate
$\mu_E(F_i)$	Equivalent repair rate associated with failure event F_i
l	Length of a transmission line
n	The number of required actions
N	The number of system elements
U	State before the fault
S	State after the fault but before isolation
R	State after isolation but before repair is completed

$AP_s(FS_i)$	Available power output in the sub-network s in failure state FS_i
$AP(FS_i)$	Total available power in failure state FS_i
$C(i)$	Capacity of component i
$DLOL^{(S)}$	Average Duration of system Loss of Load
$EDNG(F_i)$	Expected Demand Not Generated when failure event F_i occurs
$EDNS^{(S)}$	Expected Demand Not Supplied due to station originated outages
$EENG(F_i)$	Expected Energy Not Generated when failure event F_i occurs
$EENG(F_i, S)$	Expected Energy Not Generated for switching sequence S when failure event F_i occurs
$EENS^{(S)}$	Expected Energy Not Supplied due to station originated outages
F	The set of failure events
F_i	A failure event
$F^{(S)}$	The set of failure events that cause the (bulk power) system Loss of Load
$F_m^{(IS)}$	The set of failure events that cause the m units to be isolated
$F_m^{(LG)}$	The set of failure events that cause the lose of m transmission lines linking the generating sources
FS_i	A failure state
$Freq(F_i)$	Frequency of failure event F_i
$Freq\_IS(m)$	Frequency of m units being isolated
$Freq\_LG(m)$	Frequency of losing m lines which link the generation source
$FLOG(F_i)$	Frequency of Loss of Generation when failure event F_i occurs
$FLOL^{(S)}$	Frequency of system Loss of Load
$LOG(F_i)$	Required power that is not generated due to failure event F_i
$LOG(FS_i)$	Demanded power not generated in state FS_i
LOG_j	Demanded power not generated in the state j of the generalized model shown in Figure 4.15 when failure event F_i occurs

$LOG_j(F_i, S)$	Demanded power not generated at sub-state *j* for switching sequence *S* when failure event F_i occurs
$LOG_3(F_i, S_k)$	Demanded power not generated in sub-state *3* when failure event F_i occurs if the first switching component is S_k
$LOGP(F_i)$	Loss of Generation Probability when failure event F_i occurs
$LOL(F_i)$	Required power that is not supplied in the bulk power system due to failure event F_i
$LOLP^{(S)}$	Probability of system Loss of Load
$LOLE^{(S)}$	Expectation of system Loss of Load
M_λ	Modified component failure rate
N_switch	The number of switching actions in a year
N_normal	The number of normal switching actions in a year
P_k	Probability of state *k*
P_{si}	Probability of a stuck breaker *i*
$Prob(F_i)$	Probability of failure event F_i
$Prob\_IS(m)$	Probability of *m* units being isolated
$Prob\_LG(m)$	Probability of losing *m* lines which link the generating source
$P_j(F_i, S)$	Probability at sub-state *j* for switching sequence *S* when failure event F_i occurs
$P_2(F_i, S_k)$	Probability in sub-state *2* when failure event F_i occurs if the first switching component is S_k
$RG(F_i, S_k)$	Restored generation due to switching component S_k
r_i	Repair time of component *i*
r_i''	Scheduled maintenance time of component *i*
$S(F_i)$	The set of available switching components when a failure event F_i occurs
$S^{(opt)}(F_i)$	The optimal switching sequence
$S_1^{(opt)}$	The first relative optimal switching component

$S_2^{(opt)}$	The second relative optimal switching component
T_d	Expected operating decision time after a failure
T_{is}	Expected time to isolate a failure
t_{si}	Switching time or commitment time of component *i*
$t(S_k)$	Time for switching component S_k
x	Switching rate of a component
$\overline{x}$	The total switching rate when both components are in the S state
X_k	Switching rate of the *k th* switching action
ASAI	Average Service Availability Index
BPII	Bulk Power Interruption Index
BPACI	Bulk Power Supply Average MW Curtailment Index
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DFS	Depth First Searching
DLOG	Duration of Loss of Generation
DLOL	Duration of Loss of Load
ECOPT	Extended Capacity Outage Probability Table
EDNG	Expected Demand Not Generated
EDNS	Expected Demand Not Supplied
EENG	Expected Energy Not Generated
EENS	Expected Energy Not Supplied
FLOG	Frequency of Loss of Generation
FLOL	Frequency of Loss of Load
GSRAP	Generating Station Reliability Assessment Program
HL I	Hierarchical Level I
HL II	Hierarchical Level II
HL III	Hierarchical Level III
HVDC	High Voltage Direct Current
LOEE	Loss of Energy Expectation

LOGE	Loss of Generation Expectation
LOGP	Loss of Generation Probability
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SI	Severity Index

Chapter 1

Introduction

1.1 Power System Reliability Evaluation

Electricity began to penetrate into daily life with the introduction of public power supply in the early 20th century. Today, electricity dominates almost every sector of life in industrialized countries. As deregulation escalates, the importance of high quality electricity supply will constantly grow as consumers increase their expectations [1]. Failures in any part of a power system can cause poor quality of power supply, load curtailment or interruptions, which range from inconvenience to a small number of local residents, to widespread catastrophic disruptions of supply. Almost every country has suffered serious power interruptions in the past. The social and economic losses due to these outages can be substantial. The cost in the case of the 1977 New York blackout was estimated to be as high as $350 million [2]. Catastrophic events such as this indicate the importance and necessity of developing realistic power system reliability evaluation techniques. Using these quantitative techniques, utilities can determine a reasonable balance between reliability and economics, locate weak links in a power system, determine improvement measures and conduct optimum expansion planning within their socioeconomic constraints.

The reliability associated with a power system, in a general sense, is a measure of the overall ability of the system to generate and supply electrical energy. Power system reliability can be further divided into the two distinct categories of system adequacy and system security [2, 3, 4, 5, 6, 7], as shown in Figure 1.1.

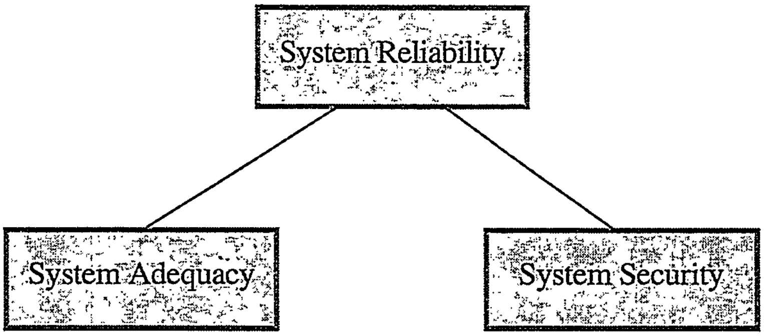

Figure 1.1 Subdivision of system reliability

Adequacy is an indicator of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. It relates to the existence of the facilities necessary to generate sufficient energy, and the associated facilities required to transmit and distribute the energy to the actual consumer load points. Steady state system conditions are considered in adequacy evaluation. This assessment is mainly used in power system planning.

Security is a measure of the ability of the system to respond to dynamic and transient disturbances arising within the system. It relates to the response of the system to whatever perturbation it is subjected to. Contingency events such as abrupt losses of major generation and transmission facilities, which can lead to dynamic, transient or voltage instability of the system, are considered in security evaluation. Security assessment is used in both power system planning and operation.

Most probabilistic techniques available at the present time for power system reliability evaluation are in the domain of adequacy assessment. The ability to assess security is very limited [3, 8]. The reason for this limitation is due to the complexity associated with modeling the dynamic and transient characteristics of a system. The main indices presently utilized in power utilities are adequacy indices associated with Loss of Load rather than the overall reliability indices. The indices obtained by assessing past system performance, however, include the effect of all the system faults and failures irrespective of cause, and therefore encompass insecurity as well as inadequacy.

A complete power system can be categorized into the three segments, or functional zones, of generation, transmission and distribution. This division is an appropriate one as most utilities are either divided into these zones for the purpose of organization, planning, operation and analysis or are solely responsible for one of these functions. As shown in Figure 1.2, the three functional zones can be combined to create three hierarchical levels, which provide a basic framework for power system adequacy evaluation [6, 7].

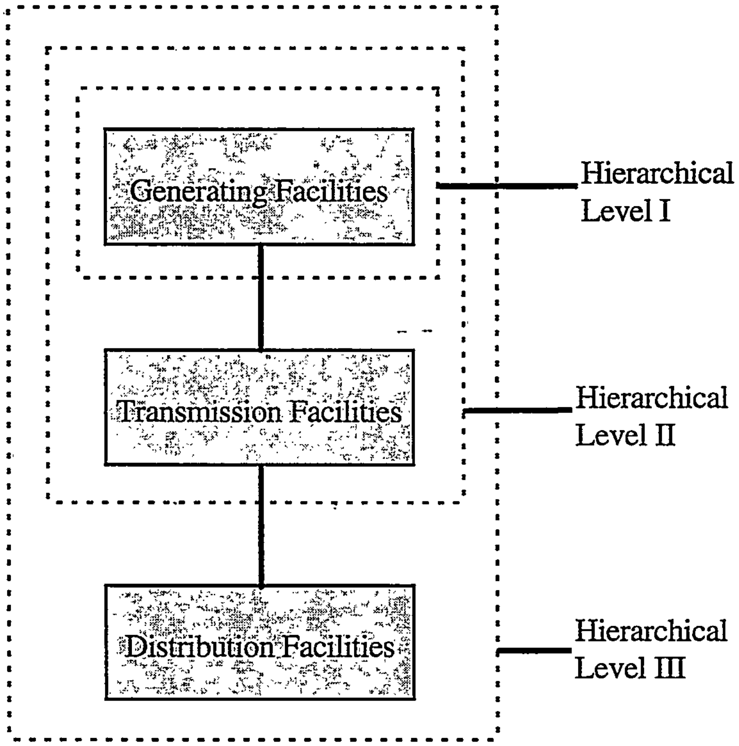

Figure 1.2 Hierarchical level structure

Hierarchical Level I (HL I) assessment, usually termed as "generating capacity reliability evaluation", is mainly concerned with assessing the amount of generating capacity that must be installed in order to satisfy the perceived system load and to perform necessary corrective or preventive maintenance with an acceptable level of risk.

The effects of both the transmission network and the distribution facilities are neglected. Conceptually, a capacity model and a load model are created and then convolved to obtain probabilistic risk indices.

Hierarchical Level II (HL II) analysis, which is usually termed as "composite system reliability evaluation" or "bulk power system reliability evaluation", considers both generation and transmission systems. The techniques for HL II adequacy evaluation are concerned with the composite problem of assessing the generation and transmission facilities in regard to their ability to supply adequate, dependable and suitable electrical energy at the bulk power load points. The inclusion of the transmission network usually results in a sharp increase in computational effort and analysis complexity.

Hierarchical Level III (HL III) analysis, which can be termed as "complete power system reliability evaluation", includes all three functional zones, starting with the generation and terminating at individual consumer load points. The objective of an HL III study is to obtain suitable adequacy indices at actual consumer load points. HL III reliability assessment is not usually conducted in a practical system due to the computational complexity involved in this assessment. This analysis is therefore normally performed only in the distribution functional zone, in which the effects of HL II can be incorporated as the input to the distribution system.

In addition to the basic three hierarchical levels of reliability evaluation, the assessment can be also performed separately on any system subset such as generating stations, switching stations and substations, in order to examine the effect of a particular topological change within the subset, or to create an equivalent component for reliability evaluation in HL I, HL II or HL III.

1.2 Station Reliability Evaluation

Generating stations, switching stations or substations (subsequently referred to as stations) serve important functions in an electric power system. They are the main points of energy transfer between generating facilities, transmission systems and distribution circuits. Stations, in a general sense, can be categorized into two types: voltage step-up stations and voltage step-down stations. Voltage step-up stations provide the connection between generating units and transmission systems, while voltage step-down stations provide the connection between transmission (subtransmission, distribution) systems and consumer facilities.

Stations are essential and critical segments of an electric power system and play an important role in reliability assessment. The station elements are important factors in improving the adequacy or security of a power system. Failures originating within a station can create significant system disturbances. A single short-circuit fault occurring in a particular configuration may result in the interruption of several transmission circuits or the isolation of many generating units.

Stations generally contain relatively complex switching arrangements. For this reason, models and techniques were developed for evaluating the reliability of such systems and estimating the effects of station originated outages on power network reliability. It is not easy to identify the actual year in which interest developed in this area. Systematic studies, however, could be said to have begun in the 1970's. In 1971, Endrenyi formulated a three state Markov model which simulates the states of a power system component during faults more closely than the conventional two state model [9, 10]. The effects of switching after faults on transmission system reliability were further studied in 1973 [11]. The concept of component active and passive failures, which permits the inclusion of all the realistic component failure modes in the reliability prediction, was introduced into the evaluation of substations and switching stations by Billinton and Grover [12, 13, 14]. Factors associated with normally open switching devices were considered by Guertin and Lamarre [15]. A method for considering auxiliary systems in power stations was developed by Allan et al. [16]. Models and concepts for reliability assessment including protection-system failures were proposed in the 1980's [17, 18]. The effects of station originated outages on composite systems were widely investigated using HL II techniques [19, 20, 21, 22, 23]. In addition to extensive studies using analytical methods, Monte Carlo simulation techniques were applied to power station reliability assessment using the three state non-Markov model [2, 24, 25, 26].

The independent, component-based three state representation is considered as a basic model in station related reliability evaluation. The main advantage of this model is that it has a simple form, is easy to understand and requires relatively little data. In certain situations, however, the weaknesses of the conventional model should be investigated both quantitatively and qualitatively. An extended model can be developed as an alternative if the error associated with the three state model is significant for a particular application or the model does not recognize some pertinent factors.

1.3 Objective and Scope of the Thesis

One of the most basic elements in power system expansion planning is the determination of how much incremental generation capacity is required to give a reasonable assurance of satisfying the increasing load requirements. The incremental load can be satisfied by purchases from associated interconnected systems or supplied by non-utility generation and cogeneration facilities. It is, however, usually obtained by constructing new generating stations. This is particularly true in developing countries.

Generating stations are functionally designed with considerable flexibility in the arrangement of their basic components, such as circuit breakers, bus sections and transformers. Factors considered in selecting a particular station configuration include operating flexibility, short-circuit current limitations, relay protection, equipment maintenance, future extensions, cost as well as service adequacy and security. Among these factors, power supply reliability is an important element as failures originating in a generating station can create significant system disturbances. It is essential to carefully design or select the station arrangement, particularly for large scale generating stations, in order that the faults originating in the station have minimum effect on the overall power network.

The objective of the research described in this thesis was to develop a reliability evaluation technique for individual generating station planning and design. Relatively few studies have been conducted in this area as attention has been mainly focused on overall HL I, HL II or distribution system assessment. In addition, the need for individual generating station assessment has not been fully recognized. The objective of station evaluation was usually limited to creating an equivalent component for more extensive system assessments associated with that station. Adequacy and security assessments of an individual generating station, however, can highlight the effect of different alternative station configurations and thus provide detailed and comparative information for decision making when planning that station. It is quite possible that these detailed results cannot be obtained by overall HL I or HL II assessment, as the contribution of an individual generating station on the overall reliability of a large system may be relatively small.

Individual generating station reliability assessment, in a general sense, can be considered as a part of an HL I or HL II study. The system indices, models and techniques utilized in HL I or HL II assessment, however, cannot be directly applied to an individual generating station due to the special characteristics associated with the switching arrangements and the different intent underling an individual generating station analysis. New indices, models and techniques have been developed in this research work, which recognize the application and purpose behind the assessment of an individual generating station.

Chapter 2 presents a series of indices for individual generating station reliability assessment, which include adequacy parameters, indices implicitly indicating operating security and indices that can be used to express the effects of the station originated outages on the related power network. A new concept of Loss of Generation is introduced in this chapter.

Chapter 3 introduces the conventional three state model and analyzes the possible weaknesses. Factors, such as existing dependencies and the required restorative actions