Application of Monte Carlo Simulation Method for finding Reliability Indices of the Iraqi (400KV) Networks

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Application of Monte Carlo Simulation Method for Finding Reliability Indices of the Iraqi (400 KV) Network.

A Thesis
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بسم الله الرحمن الرحيم

وفاء وذكرى

تحية خالصة مخلصة إلى روح الشهيد السعيد
المشرف السابق

الأستاذ الدكتور نهاد الراوي

تغمده الله بواسع رحمته وفاء وذكرى لا ولن تزول.

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الإهداء

Dedicated To

Whom Makes Hearts
Bleeding
Before Eyes.

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Abstract

This thesis has discussed the application of Monte Carlo Simulation (MCS) method for evaluating system reliability indices of Iraqi (400KV) network which cannot easily be obtained using an analytical methods.

This technique is becoming a widespread tool in the systems analysis and much easier task because the recent development of high speed computers with large storage, therefore, two approaches of the (MCS) method are studied in this work ; the first is the State Sampling approach (SS) and the second is the State Transition Sampling approach (STS) .

The presented study in this thesis is conducted on two hierarchical levels of the power system ; level I involves only the generation facilities and level II involves both the generation and transmission facilities. The system performance indices are evaluated using two-state and multi-state generating unit models in system adequacy assessment of level I and level II.

The algorithms developed of the effective approaches and their implementation are successfully examined by determining the adequacy indices for two test systems (RBTS, and IEEE-RTS), and Iraqi (400KV) network. The programs that are used in this project are implemented by using MATLAB package and FORTRAN language.

Finally, one feel all the aforementioned aims of the research work in this thesis are successfully achieved. The results obtained can provide useful information for the staff of the Iraqi (400KV) network.

Tables of Contents

Chapter One
General Introduction

Chapter Two
Study of Various Indices' Types Associated with Reliability Analysis

Chapter Three
Basic Concepts of Monte Carlo Simulation methods

Chapter Four
Monte Carlo Simulation Methods Applied to the RBTS and IEEE-RTS

Chapter Five
Monte Carlo Simulation Methods Applied to the Iraqi (400KV) Network

Chapter Six
Conclusions and Suggestions for Future Work

Appendix A
Statistical distributions

Appendix B
Partial forced outage rate for unit classifications covered in Edison Electric Institute Equipment Availability Report

Appendix C
Random number generation

Appendix D
Data of the RBTS

Appendix E
Data of the IEEE-RTS

Appendix F
Data of the Iraqi super grid (400KV) network.

List of Tables

List of Abbreviations

Symbol	Description
ADLC	Average Duration of Load Curtailment
AMN4	Alameen 400
BAB4	Babil 400
BAJG	Baiji Gas Power Station
BAJP	Baiji Power Station
BGE4	Baghdad East 400
BGN4	Baghdad North 400
BGS4	Baghdad South 400
BGW4	Baghdad West 400
BPACI	Bulk Power-Supply Average MW Curtailment Index
BPECI	Bulk Power/Energy Curtailment Index
BPII	Bulk Power Interruption Index
DAL4	Dyala 400
EDLC	Expected Duration of Load Curtailment
EDNS	Expected Demand Not Supplied
EEI	Edison Electric Institute
EENS	Expected Energy Not Supplied
EFLC	Expected Frequency of Load Curtailment
EFOR	Equivalent Forced Outage Rate
EIR	Energy Index of Reliability
ELC	Expected Load Curtailment
ENLC	Expected Number of Load Curtailment
EPRI	Electric Power Reliability Indices
FMEA	Failure Method Enumeration Analysis
GB	Giga Byte
GE	General Electric
HDTH	Hadiytha Dam Hydro
HL	Hierarchical Level
HRTP	Hartha power station
IEEE-RTS	IEEE-Reliability Test System
KAZG	Khor Alzuber
KDS4	Kadisiyah 400
KRK4	Kirkuk 400
KUT4	Kut 400
LOEE	Loss Of Energy Expectation
LOLD	Loss Of Load Duration
LOLE	Loss Of Load Expectation

Symbol	Description
LOLF	Loss Of Load Frequency
MATLAB	Matrix Laboratory
MB	Mega Byte
MBPECI	Modified Bulk Power/Energy Curtailment Index
MCS	Monte Carlo Simulation
MECORE	Monte Carlo Enumeration COmposite Relibility Evaluation
MMDH	Mosul Main Dam Hydro
MSL4	Mosul 400
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
MUSP	Musayab power station
NSRP	Nassiriyah power station
PC	Personal Computer
PFOR	Partial Forced Outage Rate
PLC	Probability of Load Curtailment
QDSG	Qudis Gas Power Station
QIM4	Qaim 400
QRNA4	Qurna 400
RAM	Random Access Memory
RBTS	Roy Billinton Test System
SI	Severity Index
SS	State Sampling
STS	State Transition Sampling

List of Symbols

Symbol	Description
A	Availability
$A(S^J)$	Relation matrix between line flow and power injection
C_i	Load curtailment
C_{ij}	The jth load curtailment sub variable at bus i
C^M	Number of MWs of load
D_i	Duration of system state i
E(X)	Expected value
E(φ)	Test function
F	Frequency of departing system state
f	Portion of F
F(t)	Cumulative probability density function
$f_i(t)$	Probability density function
G	Set of system state
L	Number of lines
LP	The annual system peak load in MW
M	Sub matrix composed of the columns corresponding to the outage lines
N	Set of all possible departure rates
n(s)	Number of occurrence of system state
NB	Number of buses
ND	Set of load bus
NG	Set of generator buses
NS	Simulation year
P	Conditional probability

PD	Load power vector
PG	Generator output vector
PG^{max}	Minimum limit for generation vector
PG^{min}	Maximum limit for generation vector
p_i	Probability of system state
PT_i	Line flow vector
PT^{max}	Limit vector for line flow
Q	Unavailability
S	System state
S^J	System state vector
T	Time unit
t_0	Starting instant
U_i	Random number
V(X)	Variance of reliability index
W_i	Weighting factors associated with each bus load
X_m	Reactance of the mth line
$Z(S^0)$	Bus impedance of the normal state
$Z(S^J)$	Bus impedance matrix
B_j	Weighting factors associated with each sub variable

Symbol	Description
β	Coefficient of variation
ε	Acceptable tolerance
δ	Standard deviation
X	Diagonal matrix
λ	Failure rate
μ	Repair rate
λ_k	The departure rate
α	Load percentage associated with each sub variable
$\Phi(S)$	Reliability index function

List of Figures

CHAPTER ONE

General Introduction

1.1 Introduction:

The basic function of an electric power system is to supply its customers with electrical energy as economically as possible, and with a reasonable degree of continuity and quality. It is not economical and technically feasible to attempt to design a power system with one hundred percent reliability, therefore, attempt to achieve an acceptable level of reliability within existing economic constraints [1].

In order to resolve the conflict between the economic and reliability constraints, a wide range of techniques and criteria has been developed and used in the system design, planning and operation. Deterministic and probabilistic techniques can be used to assess power system reliability. The basic drawback of deterministic criteria is their inability to consider the probabilistic or stochastic nature of system behavior customer demands or of component failures. In the past, the used techniques are deterministically based and the probabilistic methods were not widely used due to lack of data and computational resources, etc. At this time, the data required to support probabilistic techniques is generally available and computational resources are not a problem[1]. References [2-7] present an excellent bibliography on the application of probability methods in power system reliability evaluation. These papers were published over the period from 1971 to 1999. The area of search in previous papers has included static generation capacity reliability evaluation, operating reserve reliability evaluation, transmission and distribution system reliability evaluation, reliability cost/worth analysis and general consideration. This thesis uses a one main method of reliability indices evaluation, called Monte Carlo Simulation method (MCS).

The most efficient approaches of the suggested method used in this research work are State Sampling approach (SS) and State Transition Sampling approach (STS). These techniques are very useful to calculate various types of proposed indices to evaluate the performance for overall system.

Two hierarchical levels of the power system for two test system (RBTS, and IEEE-RTS) and Iraqi (400KV) network are studied. The first level involves only generation facilities. The results obtained for adequacy indices for this level are LOLE, LOEE, LOLF, and LOLD. The second level involves the generation and transmission facilities. The wide range of indices for this level are calculated such as PLC, ENLC, EDLC, ADLC, ELC, EDNS, EENS, BPII, BPECI, BPACI, MBECI, and SI.

1.2 Analytical and Simulation Techniques of Power System Reliability Evaluation:

The techniques used in power system reliability evaluation can be divided into two basic categories of analytical and simulation methods. The analytical techniques include:

1. Markov Modeling
2. Network Reduction
3. Fault Tree Analysis
4. Cut-Set Analysis
5. Zero Branch
6. Boolean Algebra
7. Path Tracing Method
8. Reliability Block Diagram
9. FMEA
10. Petri Networks.

The steps of procedure and developed algorithms of these methods are illustrated in the References [8,9,10].

On the other hand, the simulation methods include:

1. Sequential Monte Carlo method
2. Non – Sequential Monte Carlo method [11].

Analytical techniques represent the system by mathematical models and evaluate the reliability indices from these models using mathematical solutions. The exact approximations may be required when the system is complicated. A range of approximate techniques, therefore, has been developed to simplify the required calculations [12]. Monte Carlo Simulation (MCS) method is currently receiving considerable attention as the simulation method. It is quite general, and is not restricted to situations in which component behavior follows constant transition rates or the state residence time are exponentially distributed [11].

The present work in the content of this thesis is the application of Monte Carlo Simulation method for finding reliability indices of the Iraqi (400KV) network. This method has also proved efficient in solving system problems that cannot easily be solved, such as a modern electric power system.

1.3 Literature Review of the Power System Reliability Studies in Iraq::

In general there are few studies in the field of reliability engineering performed in Iraq. In the following paragraphs we introduce some of these attempts especially in the field of electrical engineering:

Dr. M. T. Lazim [13] can be considered as the first researcher in the field of power system reliability. He studied reliability of the three main parts of power system.

1. Generation system reliability evaluation.
2. Transmission system reliability.
3. Distribution system reliability evaluation.

In the field of generation reliability evaluation he used loss of load probability approach to evaluate the risk level and to check reserve position of Iraqi generation system. His implementation is limited for 1000 states but such a size is not enough to deal with systems of higher number of units.

In the field of transmission, he studied in detail the effect of fluctuation environment in Iraq on the failure characteristics of transmission system. He applied Markov exact method for investigation of the reliability of two parallel lines in the southern region.

In the field of distribution, he used the probabilistic approach to evaluate reliability of some distribution configurations. Under certain assumptions he developed a general symbolic reliability expression for reliability evaluation of different load points of ring system (two- end feeding sources and multi-output feeders in between).

In 1989, Imad N. [14], extended the application of probabilistic approach for more complicated distribution systems. He also studied failure statistical distribution of some distribution feeders.

In 1991, Jamil M. [15], presented his study about evaluation of generation production and its importance for system planning. This document introduces statistical information of availability and forced outage of different power station. He studied the effect of different problems on the availability of power station, like generation capacity outage due to unit derated states, limitation due to substation problems , limitation due to line over-loading and postponing of scheduled maintenance....etc. He had not used analytical or probabilistic techniques

In 1994, Tara [16] studied many techniques to perform long term load forecasting for Iraqi system demand, then she used the same approach in [13], with same program capability to evaluate loss of load expectation of Iraqi system. So she had made many assumptions to reduce the generation modeling of Iraqi system. For example a power station of four units, which has 16 outage states, is modeled by a two state model only.

As observed from the above studies, no one tried to use techniques of graph theory or the powerful application of Boolean algebra, especially in the field of network analysis. The only single attempt is made by Dargam, 1996 [17]. He used cut-set method for evaluation of reliability indices of some system of Nuclear Plant. His approach divides the reliability problem for two stages.

The first stage depends upon enumeration of minimal paths from the reliability block diagram by inspection, and then a binary path matrix is constructed from the inspected minimal paths. This binary matrix is inserted into the program as input data, then first, second, and third order minimal cut sets are enumerated.

In the second stage the cut sets are used as input to the second program, and finally the different reliability indices are calculated. No information is given about the computation time required for executing the two programs and there is no certainty that the first stage program can check the minimality of different cut sets, when the configuration is more complicated.

In 1997 Asso. R. [9] used different algorithms to solve several standard networks such as serial redundant, directed a cyclic, and complex network. Basrah region in Iraqi power system is investigated from reliability point of view. He develops a computational technique for evaluation of generation reliability indices. Two problems of Iraqi power system generation assessment are studies; the first is the historical adequacy evaluation, and the second is calculation of risk level for the period 1988-1996.

In 1997 Yousif I. [18] solved the same example given by A. Billin [19]. Reliability evaluation of 900 MW Nuclear power station is obtained by using Eigen value and Eigen vector .

In 2000 Adnan A. [10], he used different methods to calculate the reliability of each region of 400 KV Iraqi network. He suggested new method for reliability evaluation, which is called " Reduced tie set method "

As observed from the above studies, no one tried to use Monte Carlo Simulation method to solve the super grid of Iraqi network and evaluate the reliability indices for this network.

1.4 General Review of Reliability Studies by using Monte Carlo Simulation (MCS):

It seems appropriate to start this research with excerpts from notable early papers on the subject to obtain a good idea of the models and indices.

P.L.Noferi and L.Paris [20] have described the fundamental criteria adopted in planning studies of generating and transmission systems by using Monte Carlo Simulation techniques. This paper points out the advantages resulting from the adoption of this simulation method even in the most complex cases.

O.Bertoldi et al. [21] have presented two versions of programs based on Monte Carlo methods to evaluate system adequacy, and to conduct a refined evaluation of system operation cost. This paper provides RTS user with a series of indications on the behavior of the RTS transmission system, and is intended to simulate comparison with other alternatives that can be found by applying to the RTS other alternatives that can be found by applying to the RTS other methodologies of composite system adequacy evaluation.

A.D.Pattan et al.[22] have described Monte Carlo Simulation models which have been developed under EPRI projects for the reliability analysis of generating systems with explicit recognition of those unit and system operation consideration, rules, and constraints, which influence system reliability indices.

M.Walton [23] has described method to provide an efficient way to approximate the distribution of a plant's generation as functions of uncertainty in load forecasts and the plant performance. The general method and Equivalent Forced Outage Rates (EFOR) which are derived by modeling a Monte Carlo process.

M. Th. Schilling et al. [24], have presented a comprehensive bibliography on composite system reliability (1964-1988). In the paper, an international set of publications was covered for a time span of approximately 20 years. Chronologically order and organized in three sections :(i) Books ;(ii) Reports ;(iii) Papers. Only one report can be considered the first detailed study in planning electrical systems by using Monte Carlo Simulation method published in Aug. 1977. Nine papers have published on power systems reliability by using (MCS) method over thirteen years (1975-1988).

R. N. Allan and J. Roman [25] have presented a method for finding reliability assessment of generation system containing multiple hydro plant. The different simulation methods can be applied to a generation system by series of real experiments. Simulation methods require a large amount of computing time.

R. Billinton and Li. Meriyuan [26] have described some of the basic modeling concepts of a computer program developed for composite generation and transmission system reliability assessment by using (MCS) method.

R. Billinton and L. Wenyan [27] have presented a hybrid approach using (MCS) and an enumeration technique for the reliability evaluation of large scale composite generation – transmission systems.

R. Billinton and W. Li. [28] have discussed multi-area generation system reliability assessment. A linear programming model is used to minimize the total load curtailment. Area load uncertainty, correlation between area loads and generation unit derated states has been considered.

M. V. F. Pereira et al.[29] have described a general framework for combining analytic models and Monte Carlo method. In other words, the component of probabilistic indices, which can be "explained" by analytical model is "factored out" out from of the Monte Carlo sampling scheme, which then handles only the "unexplained" residuals

R. Ubeda and R. N. Allan [30] have presented a realistic option available to provide a comprehensive range of reliability indices of the composite power system. Sequential Monte Carlo Simulation method can be used to estimate the indices by simulating the actual process and random behavior of the system in which the history of the system is simulated in fixed discrete time.

M.V.F.Pereira and L.M.V.G.Pinto[31] have described the modeling assumptions and computational aspects of a new computational tool for composite reliability evaluation based on Monte Carlo sampling.

R. Billinton and L. Gan [32] have discussed a Monte Carlo Simulation model and procedure for reliability assessment of multi – area generation system. A chronological simulation scheme is described, which is capable of recognizing different unit failure and repair distributions, different unit types, load forecast uncertainly, and tie –line directional transfer capabilities and capacity distribution. Distributions of reliability indices can be obtained by taking advantage of a wide range of output data provided by chronological results based on two multi – area configurations, created by connecting several IEEE reliability test systems together. The results show that the proposed model can be an effective tool in multi-area generation system adequacy evaluation.

R. Billinton and G. Lian [33] have presented a time sequential Monte Carlo Simulation approach to reliability assessment of substation and switching station. The technique is illustrated by application to a practical configuration, and used to evaluate the station reliability indices, which are then compared with those obtained using analytical method. the study results show that the simulation method can provide acceptable indices. The simulation approach is also used to perform station sensitivity analysis by varying selected station component parameters. This type of analysis can play an important role in improving power system reliability, and is essential and necessary in the selection of critical components.

R. Billinton and W. Li [34] have described a non-sequential Monte Carlo Simulation method, called "State Transition Sampling". This method can apply to composite generation and transmission test system to find system reliability evaluation. This paper also illustrated the steps followed in composite system adequacy assessment. The state transition sampling technique focuses on state transitions of the whole system rather than on component states or component state duration.

J. C. O.Mello et al. [35] have described a new methodology for calculating total system interruption costs in composite generation and transmission systems. This approach, called " Pseudo-Sequential Simulation", is based on the non-sequential Monte Carlo Sampling of system state, and on the chronological simulation of only the sub-sequences associated with failed states.

R. Billinton and A.San [36] have discussed a system State Transition Sampling technique for reliability evaluation. This method does not require sampling state duration distribution functions of all the components and the storage of chronological information as required in the sequential methods. It is, therefore, computationally faster than the sequential approach, but slower than the State Sampling method.

R. Billinton and A. Sankarakrishnan [37] have illustrated three Monte Carlo Simulation approaches. The three different Monte Carlo Simulation methods were applied to a composite generation and transmission test system utilizing an annualized peak load, and the results compared. The paper also illustrates the utilization of annual chronological load curve for each load bus in the test system and sequential Monte Carlo simulation approach for composite system reliability assessment. An equivalent method, using a load duration curve of the system load and an enumeration process had been applied to the load model, and the results compared in the paper.

A. Sankarakrishnan and R. Billinton [38] have illustrated the development and utilization of an annual chronological load curve for each load bus in a composite generation and transmission system and a Sequential Monte Carlo Simulation approach for composite system reliability assessment. An approximate method, using a load duration curve of the system load, and an enumeration process were applied to the developed load model, and the results were compared in the paper.

A. Sankarakrishnan and R. Billinton [39] have discussed a technique for evaluating the costs of interruption and the reliability worth in composite power system network with time varying loads at load buses using Sequential Monte Carlo Simulation.

J. C. O. Mello et al. [40] have described a methodology to evaluate the maximum simultaneous power transfer of large interconnected power system. This approach combines Monte Carlo Simulation and AC optimal power flow, solved by a direct Interior point algorithm in order to calculate the maximum simultaneous transfer capability.

R. Billinton and A. Jonnavithula [41] have discussed the reliability of composite generation and transmission system with time varying loads at each bus that can be effectively assessed using Sequential Monte Carlo Simulation method. This method can also provide information on the distribution of the adequacy indices, which is not possible with other Non-Sequential approaches. The approach presented uses an annual chronological load curve for each load bus and Sequential Monte Carlo approaches for composite system reliability assessment. The paper presents the basic sequential simulation technique and illustrates its application to obtain distribution of the various composite system indices for the IEEE reliability test system.

L. Goel and R. Gupta [42] have presented a PC-based MS Windows application software for evaluating the reliability indices of electrical power generating system using the Monte Carlo Simulation technique.

R. Billinton and Peng Wang [43] have presented a time Sequential Monte Carlo Simulation technique, which can be used in complex distribution system evaluation, and described a computer program developed to implement this technique.

Y. Q. and L. Goel [44] have illustrated the Monte Carlo Simulation approach by application to the distribution systems of all the five load buses associated with a complex test system. In the paper, different radial system operating philosophies are incorporated and their impacts are analyzed.

A.A.Chowdhury and D.O.Koval [45] have derived the optimal number of gas turbines for critical load that should maintained in order to satisfy the plant's reliability criteria in the case of grid failure of continuity of its operation . Also, a Monte Carlo Simulation model is developed to assess the adequacy of the backup gas turbine system.

Daniela E. Popescu and et. al. [46] have discussed the Monte Carlo Simulation using Excel spreadsheet to determine the reliability of a geothermal power plant. This simulation technique utilizes the powerful mathematical and statistical capabilities of Excel.

Walid El-Khattan et al. [47] have presented a novel algorithm to evaluate the performance of electric distribution system, including distributed generation (DG). Monte Carlo Simulation is employed to solve the system operation randomness problem, taking into consideration the system operation constraints.

A. A Chowdhury et al. [48] have described a Monte Carlo Simulation tool, which was developed by General Electric (GE) company for the reliability analysis of multi-area generation system with explicit recognition of those unit and system operating considerations, rules and constraints that influence system reliability indices.

Andrea M.Rei et al. [49] have discussed two methods to find reliability assessment of bulk power system: contingency enumeration and Non-Sequential Monte Carlo Simulation. Both have their wellknown advantages and drawbacks. Contingency enumeration is conceptually simple and usually requires low computational effort. Conversely, Monte Carlo Simulation is computationally harder, but much more versatile to model random aspects. The paper depicts some major aspects regarding both methods.

R. Billinton and Wijarn Wangdee [50] have illustrated a significant advantage when utilizing Sequential Monte Carlo Simulation in bulk electric system reliability analysis. This advantage is the ability to provide reliability index probability distributions in addition to the expected values of their indices. Reliability index probability distributions provide a pictorial representation of the annual variability of these parameters around their mean values.

Wijarn Wangdee and R. Billinton [51] have presented bulk electric system well-being analysis using Sequential Monte Carlo Simulation. This approach provides accurate frequency and duration assessments and the index probability distributions associated with the mean values.

Yi Ding et al. [52] have presented a technique to evaluate reliability of a restricted power system with a bilateral market. This technique is based on the combination of the reliability network equivalent and pseudo-sequential simulation approaches. The reliability network equivalent techniques have been implemented in the Monte Carlo Simulation procedure to reduce the computational burden of the analysis.

As observed from the area of search in previous references [20-52]:

* MCS method is becoming a widespread tool in the system analysis even in the most complex cases.

* New computational tools for planning and operation studies are described.

* A comprehensive range of reliability indices of two level of the power system are provided by using simulation approaches.

* The results illustrate a significant advantages when utilizing MCS to evaluate the reliability indices , which are then compared with those obtained using analytical methods.

1.5 Power System Reliability and Related Concepts:

The term reliability, when used in the context of power networks, is generally defined as the concern regarding the ability of a power system to provide an adequate supply of electrical energy. In order to be more specific it is usual to divide the term into two aspects, adequacy and security, as shown in Fig.1.1 [1].

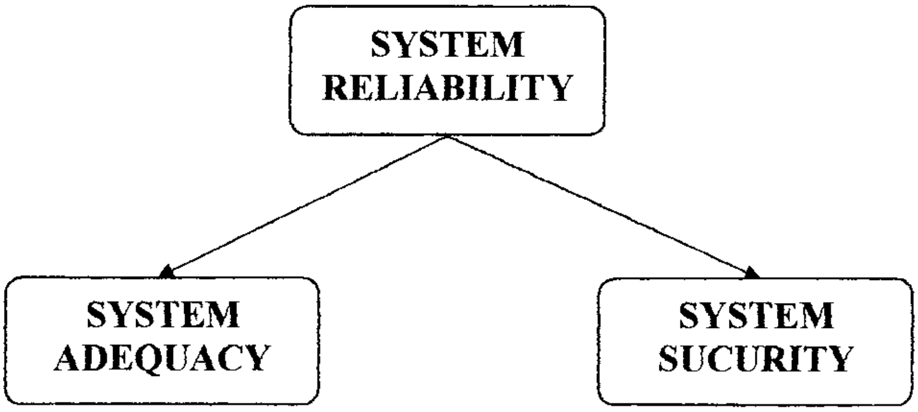

Fig 1.1 Subdivision of system reliability.

1) ***System adequacy*** relates to the existence of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. Adequacy is, therefore associated with static conditions which do not include system disturbances.

2) ***System security*** relates to the ability of the system to respond to disturbances arising within it. These include the conditions associated

with both local and widespread disturbances and the loss of major generation and/ or transmission facilities which can cause dynamic, transient, or voltage instability of power system, etc. Security is, therefore associated with the response of the system to whatever perturbations arise [1,53].

The research work in this thesis is restricted to adequacy evaluation of the two test system(RBTS, and IEEE-RTS) and Iraqi (400KV)network.

An overall power system can be divided into the three basic functional zones of generation, transmission, and distribution, and be organized into the three hierarchical level (HL) shown in Fig.(1.2) Hierarchical Level I (HL-I) involves only the generation facilities. Hierarchical Level II (HL-II) involves both the generation and transmission facilities. Hierarchical Level III (HL-III) involves all three functional zones.

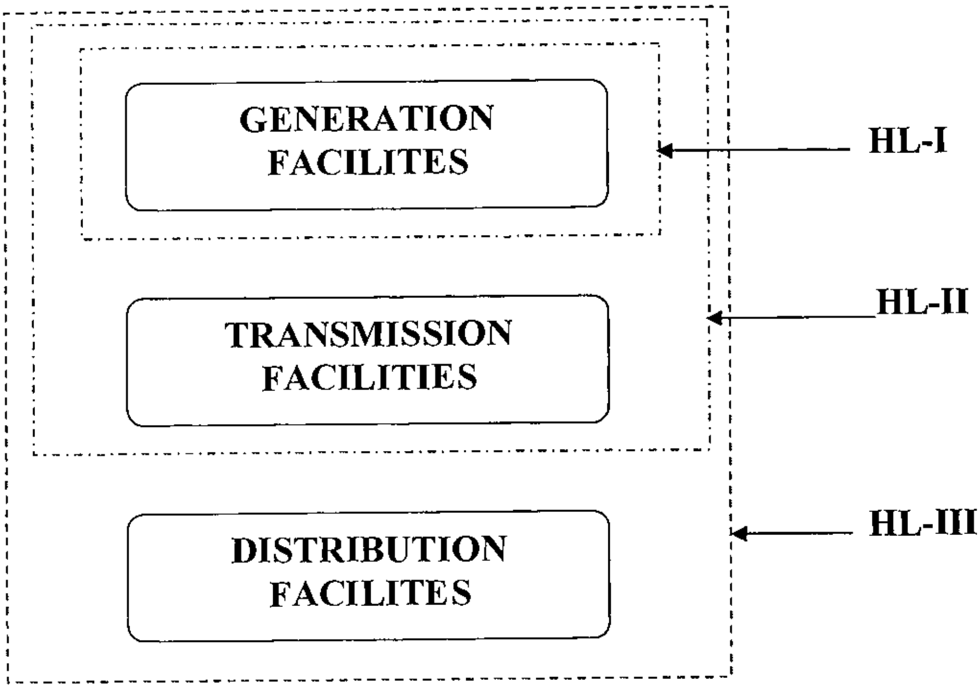

Fig. (1.2): Power system hierarchical levels

Adequacy evaluation at HL-I is usually termed as generating capacity adequacy evaluation and examines the total system generation in order to determine adequacy to meet the total system requirement. The transmission system is not part of the analysis at this level. Adequacy evaluation at HL-II is usually termed as composite system or bulk system evaluation because it includes both the generation and the transmission facilities. Technical studies at HL-II involve many activities, such as load flow analysis, contingency analysis, overload alleviation, generation rescheduling, load curtailment philosophy, etc. Adequacy evaluation at HL-III is concerned with all three functional zones, and includes all the associated equipment from the generating sources to the individual consumer load points. In practice, HL-III studies are not usually conducted directly due to the scale of the problem. Reliability analysis at HL-III is very complex and is rarely done. The present work deals with adequacy assessments at HL-I and HL-II [1,54].

Two basic tools i.e. analytic method and Monte Carlo Simulation have been extensively utilized for HL-I reliability evaluation. Similar techniques have been applied to HL-II evaluation and consequently published [53]. The first fundamental developments in composite system reliability evaluation are associated with analytical approach. In recent years, the focus has been on the utilization of Monte Carlo Simulation in HL-II studies.

MCS method was first introduced in the 1940's for solving mathematical problems. This method simulates the behavior of the system by performing a series of experiments [11]. With the recent and rapid developments of digital computer, Mont Carlo Simulation has been extensively used for simulating stochastic processes.

There are two basic techniques utilized when MCS methods are applied to power system reliability evaluation. These approaches are known as the sequential and non-sequential techniques.

Sequential simulation can fully take into account the chronological behavior of the system, while the non-sequential method involves non-chronological system state considerations. The sequential techniques, therefore, provide more accurate frequency and duration assessments than the non-sequential method. The significant merit when utilizing the sequential simulation approach is the ability to provide information on the mean or average values, and on the probability distributions of the indices. Both sequential and non-sequential techniques, however, have advantages and disadvantages[55,56]. These issues are addressed in detail in chapter three in conjunction with the simulation procedures used in the different proposed methods.

These methods have many advantages over analytical methods in certain circumstances, and application to power system reliability is still developing

There are wide ranges of HL-II indices that can be calculated using the available reliability techniques. These indices can be used to assess the performance at the individual load points or for the overall system and reflect the response of various parameters which actually affect the system reliability.

1.6 Predictive Indices and Past Performance Indices:

HL-II reliability indices can be divided into the two categories of predictive indices and past performance indices [57]. Predictive indices provide information on the future performance of the system, and are important planning parameters. Past performance indices indicate the actual system performance and are related to real time operation of the system. Most utilities collect past performance indices in order to assess their composite system performance.

1.7 Deterministic Data and Stochastic Data:

The data required for reliability analysis can be divided into deterministic data and stochastic data as shown in Fig. (1.3). Deterministic data is required at both system and actual component level; such as:

- Line length
- Number and type of different component in the system
- Number of power stations
- Number of units of each power station
- Generation unit MW limit.

Stochastic data can again be divided into two parts; component and system data; such as:

- * Failure parameters
- * Repair parameters
- * Unit outages
- * Common cause or common mode outage [1].

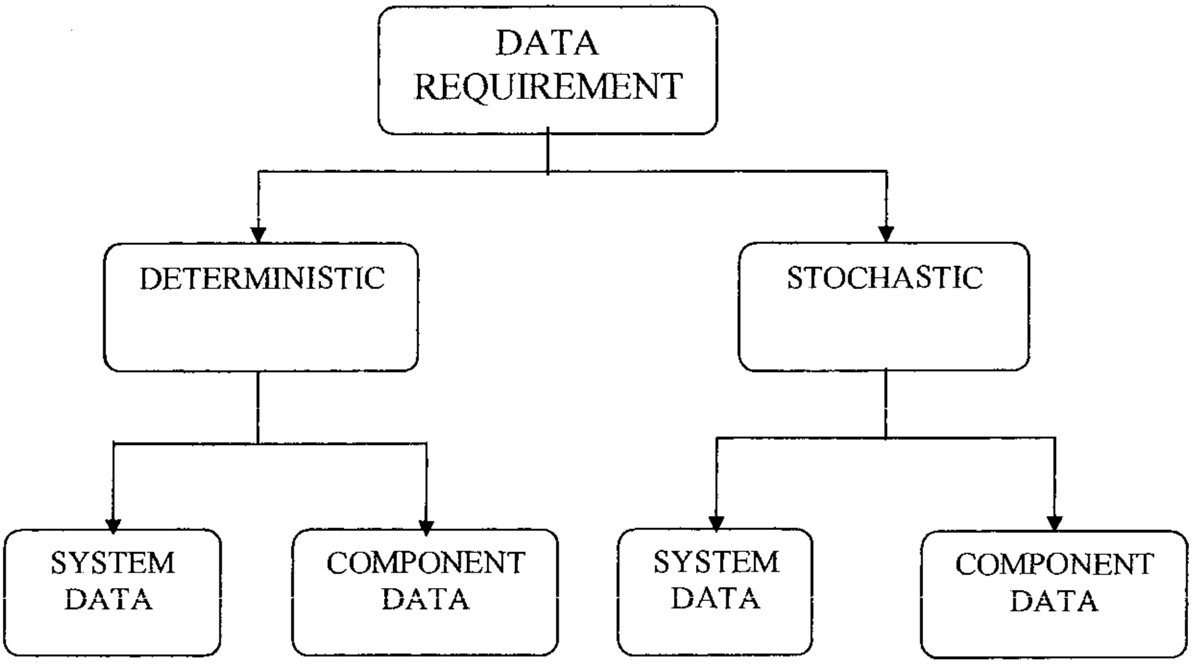

Fig.(1.3): Data requirements

1.8 Aim of the thesis:

The aim of this study is application of a comprehensive technique for reliability indices evaluation of Iraqi (400 KV) super grid network. This method is called Monte Carlo Simulation method, where no one tried to use Monte Carlo Simulation method to solve the super grid of Iraqi network and evaluate the reliability indices for this network.

1.9 Software language:

The RBTS, IEEE-RTS, and Iraqi super grid (400KV)network are simulated using MATLAB program (Version 7.3.0.267 (R2006b)), because it is powerful and general[58]. The basic tools (rand, randn, and simulink) are used to generate random numbers and simulate the samples for specified period. Other programs are written in FORTRAN language because it is simple and fast. These processes are conducted using PC (Processor :3GHz, with Cache memory :8MB, RAM:2GB, Hard disk:2*160GB).

1.10 Outline of the thesis:

The thesis is presented in six chapter and five appendices:

Chapter one introduces important background and comprehensive historical development of the suggested method to evaluate reliability indices that is called "Monte Carlo Simulation method". Also, this chapter describes a primary objective of the research, interpretation terms and concepts associated with reliability analysis.

The significant information in Chapter two covers general review and essential usage for each reliability index. These indices can reflect the capability , reliability and availability of the power system . such indices give a general idea about overall performance of the system , therefore, it is a vital part of this research in the operation and future planning of generation , transmission, and distribution.

The basic concept of Sequential Monte Carlo Simulation and two Non-Sequential Monte Carlo Simulation methods, namely the State Sampling (SS) and State Transition Sampling (STS) techniques used for power system reliability analysis are described in detail in Chapter three.

The different types of Monte Carlo Simulation methods presented in previous chapter are applied to the system adequacy analysis of the Roy Billinton Test System (RBTS) and IEEE-Reliability Test System(IEEE-RTS) in Chapter four.

Chapter five shows the single line diagram of Iraqi (400KV)network . In the chapter ,all reliability indices of Iraqi network are evaluated by using different types of Monte Carlo Simulation methods.

Chapter six summarizes the thesis and presents the conclusions.

In appendix A , basic shapes of common failure density reliability for each of the distributions are given in the related field of this thesis.

Appendix B shows the Partial Forced Outage Rate (PFOR) for generating units of different size.

In appendix C, the linear congruential method for generating random numbers is briefly discussed.

In appendix D, data of the Roy Billinton Test System are given.

In appendix E, data of the IEEE- Reliability Test System are given.

In appendix F, data of the Iraqi system (400KV)are given.

CHAPTER TWO

Study of Various Indices' Types Associated With Reliability Analysis

2.1 Introduction:

A modern electric power system is complex , integrating many different types of generating resources to provide electricity to a number of customers with varying requirements. Even large computer installations are not powerful enough to be able to analyze in a completely realistic and exhaustive manner of the power system as whole. This is not a problem, however, because the system can be divided into appropriate subsystems which can be analyzed separately. The main subsystems are generating stations, generating capacity, networks, composite generation/transmission, interconnected systems, substations and protection systems. But, one aspect must be considered that is how reliable the system and its various parts of the system. It is pointless to reinforce quite arbitrarily a strong part of the system, where weak areas still exist. Consequently, a balance is required between generation, transmission and distribution. This is a vitally important aspect. This does not mean that the reliability should be equal [1]. Reliability is usually measured against a baseline maximum of 100% for 365 days per year. The reliable electric power system delivers 99.9% up time or " three nines of power ", which is equivalent to between eight and nine hours of outages per year. Table (2.1) illustrates the relationship between the degree of reliability and the time without power [59]. Also, in gross numbers, the distribution component of power system is responsible for about 85% of interruptions. The transmission and generation components are responsible for about 5% and 10% of interruptions respectively [53].

This chapter illustrates some concepts of various parts of a power system and explains the significance of the various reliability indices that can be evaluated for two major subsystems. The first subsystem is the generation capacity, and the second is the composite generation and transmission systems. The proposed indices for the first level are LOLE, LOEE, LOLF, and LOLD. Also, for the second level, the suggested indices are PLC, EFLC, EDLC, ADLC, ELC, EDNS, EENS, BPII, BPECI, BPACI, MBECI, and SI. The reliability indices are a better indicator of the performance measures, and are expected to give operators more vital information on reliability aspects of the supply. In this chapter, the representation of two state and multistate for the generating units is presented.

Table (2.1) : Reliability and outage duration

Reliability	Outage Duration
99.9% (3 nines)	8.76 hours/year
99.99%(4 nines)	52.6 minutes/year
99.999%(5 nines)	5.2 minutes/year
99.9999%(6 nines)	31.5 seconds/year

2.2 Measures of components reliability:

Individual components reliability may be expressed in a number of ways. In essence, the reliability expresses the proportion of time the component is " in service " or " available for ". Data may also be used, however, to express the probability of the component being in service at a particular time.

The availability (A) of a component is expressed as :

$$A=\frac{\Sigma(\text{uptime})}{\Sigma(\text{uptime})+\Sigma(\text{downtime})} \qquad (2.1)$$

Where the " up time " is the total time the component is in service and the " down time " is the total time when it is not. (A) may be re-expressed in terms of the Mean Time To Failure (MTTF) and the Mean Time To Repair (MTTR) so that

$$A=\frac{MTTF}{MTTF+MTTR} \quad \text{...} (2.2)$$

The summation of MTTF and MTTR is the Mean Time Between Failures (MTBF) or the cycle time (T) . Fig.(2.1) shows the mean time diagram for a two state component [56].

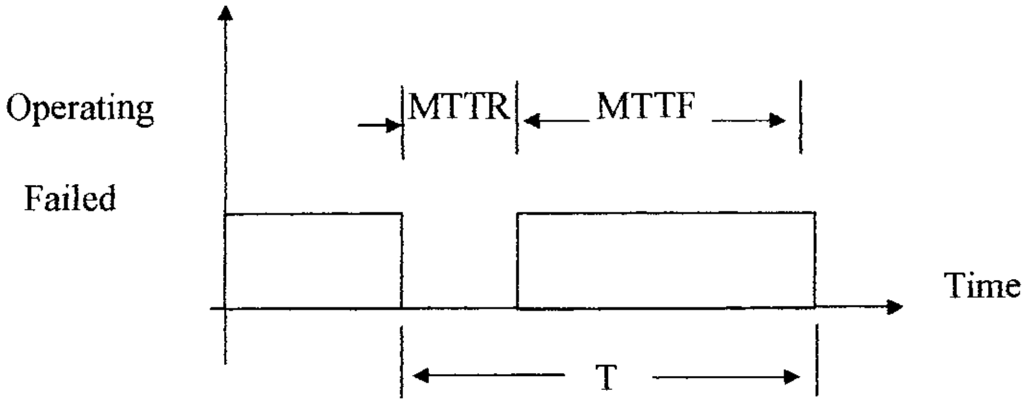

Fig. (2.1) : Mean time diagram for a two state component.

Power system components can be represented by discrete system states with constant transition rates between these states. In Fig.(2.2), " state 0 " represents the healthy state of the component and the component is in an operating condition. The component when it cannot perform its intended function is in " state 1 " or the failed state. Transition occurs between " state 0 " and " state 1 ".The transition rates between the states are the failure rate " λ " and the repair rate " μ " and are shown in Fig.(2.2) [52,56].

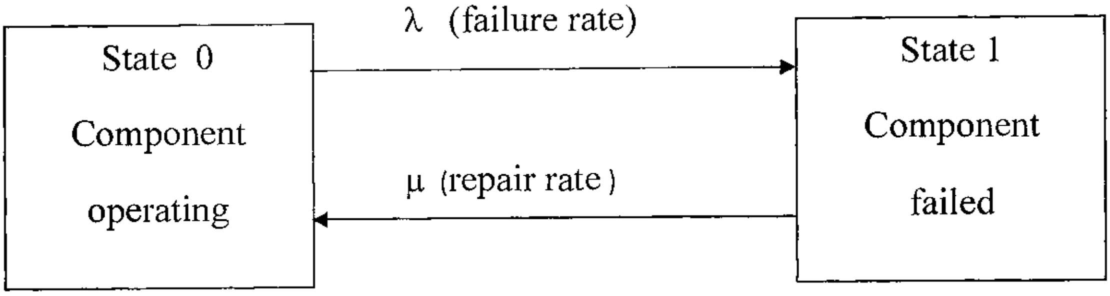

Fig. (2.2) : A component two – state space diagram.

Equations (2.3) to (2.5) show the relationship between the transition times and the transition rates, shown in figures (2.1) and (2.2) respectively .

$$\text{MTTF} = \frac{1}{\lambda} = \text{number of failures per unit time} \ldots\ldots\ldots\ldots (2.3)$$

$$\text{MTTR} = \frac{1}{\mu} = \text{number of repairs per unit time} \ldots\ldots\ldots\ldots (2.4)$$

$$T = \text{MTBF} = \text{MTTF} + \text{MTTR} = \frac{1}{\text{frequency}} \ldots\ldots\ldots\ldots (2.5)$$

Equation (2.2) may be re-expressed in terms of failure rate and repair rate such that

$$A = \frac{\mu}{\mu + \lambda} \ldots\ldots\ldots\ldots (2.6)$$

The converse of the availability is unavailability (Q) and it can be defined in similar terms .

$$Q = \frac{\Sigma(\text{downtime})}{\left(\Sigma(\text{uptime}) + \Sigma(\text{downtime})\right)} \ldots\ldots\ldots\ldots (2.7)$$

$$Q = \frac{MTTR}{MTTF + MTTR} \quad \text{...(2.8)}$$

$$Q = \frac{\lambda}{\lambda + \mu} \quad \text{...(2.9)}$$

The unavailability is sometimes known as the Forced Outage Rate (FOR) [56].

In general, the failure and repair rates are not constant ,but may be function of time such as the Normal, Lognormal, Exponential, Gamma, Weibull, Binomial, and Poisson [60]. A brief description of each is provided in appendix A.

2.3 Generating System Reliability Indices :

The determination of the required amount of system generating capacity to ensure an adequate supply is an important aspect of power system planning and operation [1].

A number of generating units, system operating consideration, and constraints influence system reliability performance. These parameters have been identified through analysis of utility system data and reliability indices.

2.3.1 Generation Units Representation:

Generators just as any other element in a power system are prone to random failures. Two-state or multi-state model of the generator are considered to account for the random failures of generators. This means, the generator is usually represented by two-state, as shown in Fig. (2.2) or in the multi-state, as shown in Fig. (2.3). Multi-state generating unit models create a significant increase in the number of generating contingency states and can result in considerable increase in the overall solution time. In order to avoid this problem, the derated states are usually amalgamated with totally forced outage rate. Many utilities now use multi-state representation to assess generating capacity reliability in order to obtain a more accurate appraisal [1,42].

In the next chapter, the basic sampling procedure of a two state and multi-state representation are given by the Forced Outage Rate (FOR) and Partial Forced Outage Rate (PFOR) for a given derated state respectively.

The FOR for a generating unit is obtained by dividing the number of hours, the unit is on forced outage, by the total number of hours, the unit is exposed to outage. Similarly, the PFOR, for a given derated states is obtained by dividing the number of hours, the unit is operated in the given forced derated state, by total number of hours, the unit is exposed to outage[61]. The Edison Electric Institute (EEI) Annual Equipment Availability Report provides PFOR for generating units of different size. The EEI data provide representive profiles based on the actual outage data for different types of generating units. Appendix B shows the PFOR based on ten derated states (60-89MW), (200-389MW), and (390-599MW) [62].

The reliability indices in chapter four and five are calculated using different multi-state generating unit model to demonstrate the effect of model variations, attention is focused on how many derated states should be used in a multi-state.

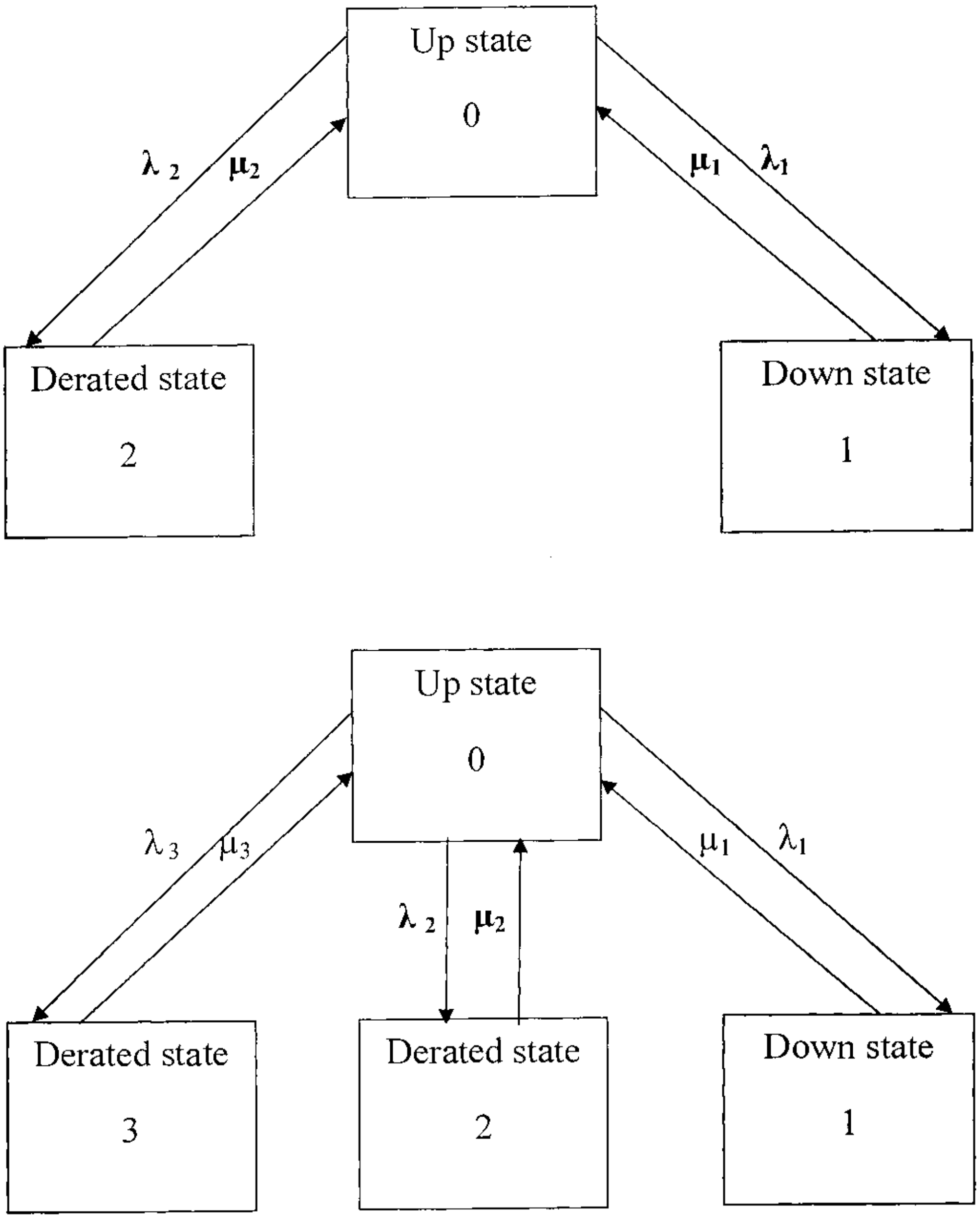

Fig. (2.3): Three and four-state generating unit model.

2.3.2 Basic Indices for Generating System:

Various indices have been used in the generating system adequacy evaluation. Most of them are expected value of random variables (though some give a p.d.f). Among these are [56]:

1)Loss Of Load Expectation (LOLE) in days/year or hours/year.

$$LOLE = \sum_{i \in S} p_i T \quad (2.10)$$

where p_i is the probability of system state i, T is the time unit of the index (i.e. either one day or one hour), and S is a set of all possible system states associated with loss of load. The index gives the expected (or mean) number of days or hours in a given period (usually on year) in which the daily peak load or hourly load exceeds the available generating capacity.

Note that neither the severity of the generating deficiency nor the frequency or duration of the loss of load are indicated.

2)Loss Of Energy Expectation (LOEE) in MWh/year

$$LOEE = \sum_{i \in S} 8760 C_i^M p_i \quad (2.11)$$

where p_i and S are as above and C_i^M is the number of MWs of load for system state i. It gives the expected energy not supplied by the generating system due to the load exceeding the available generating capacity. When the energy actually supplied is divided by the total energy demanded, a normalized index known as the Energy Index of Reliability(EIR) is found.

3)Loss Of Load Frequency (LOLF) in number of occ. per year:

$$\text{LOLF} = \sum_{i \in S} (F_i - f_i) \qquad (2.12)$$

where F_i is the " frequency of departing system state i " and f_i is the " portion of F_i which does not change from being part of the "loss-of-load state " to being part of "no-loss-of-load state set " "

4)Loss Of Load Duration (LOLD) in hour per occurrence:

$$\text{LOLD} = \frac{\text{LOLE}}{\text{LOLF}} \qquad (2.13)$$

This represents the duration of each state in which load had been lost.

2.4 Composite Generation and Transmission System Reliability Indices:

Composite generation and transmission system adequacy evaluation is concerned with the total problem of assessing the ability of the generation and transmission system to supply adequate and suitable electrical energy to the major system load points. The transmission configuration which links the generating units to the major load buses is usually complicated, and it is seldom possible to model the configuration using simple series / parallel reduction techniques. Quantitative assessment of the adequacy of a composite system can be performed using the Monte Carlo Simulation approach. There is a wide range of indices which can be calculated at each major load points and for the overall system [63].

Reliability indices are an important outcome of quantitative adequacy assessment of a composite system. Both load point and system indices can be used to measure composite system adequacy. Load point indices indicate the reliability at the individual load buses while system indices provide an overall evaluation of total system reliability. Load point indices are usually used when the focus of the adequacy assessment is to find and strengthen unreliable buses in the system. System indices are used when the purpose of the adequacy assessment is to provide a global assessment of the system, and to compare different alternatives. The overall system indices indicate the adequacy of the composite system to meet its total load demand and energy requirements, and therefore quite useful to the system planner and to the system manger [64]. Adequacy assessment of composite system involves the solution of network configuration under random outage situations (contingencies). Various techniques depending upon the adequacy criteria, used and the intent behind these studies are used in analyzing the adequacy of a power system. The basic tasks involved in composite system reliability evaluation are:

1)load flow calculation (fast decoupled load flow)

2)contingency analysis.

3)generation rescheduling

4) overload alleviation.

In the next sections of this chapter, a brief description of these objectives are introduced.

2.4.1 Annual and Annualized Indices:

There are two ways to calculate the system and load point indices. The first is to calculate the indices under peak load conditions and express them on a one year basis. The indices are then known as annualized indices. The second is to calculate them using the annual load duration curve. In this case, they are known as annual indices. Annual indices are the most useful indices as they incorporate the variations in load level and reflect the actual load profiles throughout the year. The advantage of annualized indices is that they require less computing time and can be used to roughly reflect the system reliability performance [34].

In this thesis, the annualized system peak load is used to obtain the adequacy indices for the two test systems in chapter four and Iraqi 400KV network in chapter five.

2.4.2 Basic Indices for Composite System :

There is a wide range of possible indices associated with composite system adequacy assessment. Common indices for composite system reliability include the same ones for generating system reliability indices in section (2.3.2) and a set of basic indices are presented in the following section. These indices are also used in the research in this thesis [1].

1) Probability of Load Curtailment (PLC)

$$PLC = \sum_{i \in S} p_i \qquad \text{.......(2.13)}$$

where p_i is the probability of system state i and S is the set of all system states associated with load curtailments.

*2)*Expected Frequency of Load Curtailment (EFLC)

$$EFLC = \sum_{i \in S} (F_i - f_i) \quad \text{occurrence/year} \quad \ldots\ldots\ldots\ldots\ldots(2.14)$$

where F_i is the frequency of departing system state i and f_i is the portion of F_i ,which corresponds to not going through the boundary wall between the loss-of-load state set and the no-loss-of-load state set.

It is a difficult task in composite system adequacy assessment to calculate the frequency index using the state sampling technique. This is due to the fact that for each load curtailment state i ,it is necessary to identify all the no-load-curtailment states which can be reached from state i in one transition. The Expected Number of Load Curtailment (ENLC) is often used to replace the (EFLC) index.

$$ENLC = \sum_{i \in S} F_i \quad \text{occurrence/year} \quad \ldots\ldots\ldots\ldots\ldots(2.15)$$

The (ENLC) index is the sum of the occurrences of the load curtailment states, and is therefore an upper boundary of the actual frequency index. The system state frequency F_i can be calculated by the following relationship between the frequency and the system state probability p_i :

$$F_i = \sum_{k \in N} \lambda_k \quad \text{occurrence/year} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.16)$$

where λ_k is the departure rate of component corresponding to system state i, and N is the set of all possible departure rates corresponding to state i.

*3)*Expected Duration of Load Curtailment (EDLC)

$$\mathrm{EDLC} = \mathrm{PLC} \times 8760 \qquad \text{hrs./year} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.17)$$

*4)*Average Duration of Load Curtailment (ADLC)

$$\mathrm{ADLC} = \frac{\mathrm{EDLC}}{\mathrm{EFLC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.18)$$

*5)*Expected Load Curtailments (ELC)

$$\mathrm{ELC} = \sum_{i \in S} C_i F_i \qquad \text{MW/year} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.19)$$

where C_i is the load curtailment of system state i.

*6)*Expected Demand Not Supplied (EDNS)

$$\mathrm{EDNS} = \sum_{i \in S} C_i p_i \qquad \text{MW} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.20)$$

7) Expected Energy Not Supplied (EENS)

$$\mathrm{EENS} = \sum_{i \in S} C_i F_i D_i = \sum_{i \in S} 8760 C_i p_i \qquad \text{MWh/year} \ldots\ldots (2.21)$$

where D_i is the duration of system state i.

*8)*Bulk Power Interruption Index (BPII)

$$\mathrm{BPII} = \frac{\sum_{i \in S} C_i F_i}{\mathrm{LP}} \qquad \text{MW/MW-year} \ldots\ldots\ldots\ldots\ldots (2.22)$$

where LP is the annual system peak load in MW.

*9)*Bulk Power / Energy Curtailment Index (BPECI)

$$\text{BPECI} = \frac{\text{EENS}}{\text{LP}} \qquad \text{MWh /MW-year........(2.23)}$$

*10)*Bulk Power-Supply Average MW Curtailment Index(BPACI)

$$\text{BPACI} = \frac{\text{ELC}}{\text{EFLC}} \qquad \text{MW/disturbance.....(2.24)}$$

*11)*Modified Bulk Energy Curtailment Index (MBECI)

$$\text{MBECI} = \frac{\text{EDNS}}{\text{LP}} \qquad \text{........................(2.25)}$$

*12)*Severity Index (SI)

$$\text{SI} = \text{BPECI} \times 60 \qquad \text{system min. /year........(2.26)}$$

2.5 Load Flow Analysis [43]:

The following relationship is obtained using load flow formulation:

$$PT_i(S^j) = A(S^j) \times (PG - PD) \text{....................(2.27)}$$

where PG : generation output vector

PD : load power vector

S^j : system state vector

$PT_i(S^j)$: line flow vector for state S^j

$A(S^j)$: relation matrix between line flow and power injection for state (S^j).

The mth row of $A(S^j)$ can be calculated as follows:

$$A_m(S^j) = \frac{Z_p(S^j) \quad Z_q(S^j)}{X_m} \qquad \text{.......................} \quad (2.28)$$

Where p,q : bus numbers of the mth line

X_m : reactance of the mth line

$Z(S^j)$: bus impedance matrix of the system for state (S^j) in which the resistance of all lines are neglected, and

$Z_p(S^j), Z_q(S^j)$: pth and qth rows of $Z(S^j)$

The bus impedance matrix Z need not be completely calculated every time the network configuration changes due to outages. The bus impedance matrix after the outage of specified lines, $Z(S^j)$ can be directly obtained from the bus impedance matrix of the normal state without any line outages, i.e., $Z(S^0)$

$$Z(S^j) = Z(S^0) + Z(S^0) MQM^T Z(S^0) \qquad (j \neq 0) \text{ ....} (2.29)$$

Where

$$Q = [\, X - M^T Z(S^0)\, M\,]^{-1} \text{ ....} (2.30)$$

X is a diagonal matrix whose dimension is the same as the number of outage lines, and whose diagonal elements are the reactance's of outage circuits. M is submatrix composed of the columns corresponding to the outage lines of the bus-line incidence matrix.

The above simplifications enables a faster DC load flow calculation.

2.6 Minimization Models for Load Curtailment:

The system states can be divided into four states S1, S2, S3, and S4 and are displayed below [26,34]

$$S \begin{cases} S1 \\ \overline{S1} \begin{cases} S2 \\ \overline{S2} \begin{cases} S3 \\ S4 \end{cases} \end{cases} \end{cases}$$

S1 : Normal state subset with no contingencies

S2 : Subset composed of the contingency states, which definitely have no load curtailment.

S3 : Subset composed of contingency states, which have no load curtailment after rescheduling the generation.

S4 : Subset composed of contingency states, which still have load curtailment after rescheduling the generation.

$\overline{S1}$: Contingency subset

$\overline{S2}$: Subset composed of contingency states, which may have load curtailment.

The following two major load curtailment philosophies are used to reschedule generation outputs in order to maintain generation- demand balance and alleviate line overloads, at the same time, to avoid load curtailment, if possible or to minimize total load curtailment if unavoidable:

- Loads are curtailed at the buses which are as close to the elements on outage as possible.
- Loads are classified according to their importance and divided into categories of firm load and curtailable load.

The minimization model with the load curtailment philosophies incorporated is described in these equations [26,34].

$$\text{Min} \quad C \sum_{i \in ND} (w_i \sum_{j=1}^{m} \beta_j C_{ij}) \quad \ldots\ldots(2.31)$$

Such that

$$PT_i(S^j) = \sum_{k=1}^{NB} A_{ik}(S^j)(PG_k + \sum_{j=1}^{m} C_{kj} - PD_k) \quad \ldots\ldots(2.32)$$

$$(\, i = 1, \ldots\ldots, L)$$

$$\sum_{i \in NG} PG_i + \sum_{i \in ND} \sum_{j=1}^{m} C_{ij} = \sum_{i \in ND} PD_i \quad \ldots\ldots(2.33)$$

$$PG^{min} \leq PG \leq PG^{max} \quad \ldots\ldots(2.34)$$

$$0 \leq C_{ij} \leq \alpha_j PD_i \quad (i \in ND; j = 1, \ldots.. m) \quad \ldots\ldots(2.35)$$

$$|PT(S^j)| \leq PT^{max} \quad \ldots\ldots(2.36)$$

Where:

C : load curtailment vector

C_{ij} : the jth load curtailment sub variable at bus i

w_i : the weighting factors associated with each bus load. The buses closest to the elements on outage have relatively small w_i ,and those far from outage have relatively large w_i . The value of these factors for each bus load is variable, and therefore depends on outage location in the particular contingency system state.

β_j : the weighting factors associated with each subvariable. The least important load corresponds to smallest β_j and the most important load corresponds to largest β_j.

NG : Set of generator buses

ND : Set of load buses

NB : Number of buses

α : load percentage associated with each subvariable

T^{max} : limit vector for the line flow $T_i(S^j)$

L : number of lines

PG^{min}/PG^{max} : Minimum /Maximum limit for the generation vector.

m : load curtailment variable at each bus is divided into m sub variables (in general m =2 or 3)

CHAPTER THREE

Basic Concepts of Monte Carlo Simulation Methods

3.1 Introduction:

The application of Monte Carlo Simulation started in North America. The use of this method is continually increasing and becoming a widespread tool in system analysis. The MCS techniques , which is the general designation for stochastic simulation using random numbers, is used in many fields such as complex mathematical calculations, stochastic process simulation, medical statistics, engineering system analysis, and electric power system reliability evaluation [65]. The simulation process is used to imitate the system components and their behavior patterns including the random nature of all the system actions including the number of failures, the time between failures, the restoration time, etc. during the simulated time. The objective of this process is to simulate the expected or average value of the various reliability parameters, and to obtain, if required, the frequency / probability distribution of each parameter [1]. The simulation is achieved by using random numbers and converting them into density function to represent the behavior of the components and variables under consideration. Random numbers, their generation, and conversion are therefore important and essential parts of the proposed approaches. The procedure used to generate the pseudo-random numbers is described in Appendix C [55].

Many attempts have been made to apply Monte Carlo Simulation to evaluate power system reliability. Power systems usually have very complex and large networks, and in these situations, reliability evaluation with this technique can be a difficult task and requires large amount of computer storage and computing time. The recent development of high speed computers with large storage has made the application of the suggested methods a much easier task. It has been used successfully for reliability evaluation at HL-I and HL-II [37,42].

This chapter describes the basic concepts and methodology of two non-sequential techniques(state sampling approach and state transition sampling approach) and sequential Monte Carlo Simulation. The advantages and disadvantages when applying these methods to electric power system reliability analysis are briefly addressed.

3.2 Monte Carlo Simulation (MCS):

As previously mentioned in chapter one, both analytical methods and Monte Carlo Simulation can be used to perform power system adequacy evaluation including composite system assessment. Monte Carlo Simulation techniques have the advantage compared to analytical methods, when complex operating conditions are incorporated into the assessment process, as they can mimic the actual process and random behavior of the system more accurately. The main advantages of MCS in power system reliability evaluation are as follows [42]:

- In theory, it can include system effects or processes that may have to be approximated in analytical methods.
- The required number of samples for a given accuracy level is independent of the size of the system, and therefore, the proposed simulation is suitable for large scale system evaluation.
- It can simulate the probability distribution associated with component failure and restoration activities. This generally cannot be done using analytical methods.
- It can calculate not only reliability indices in the form of expected values of random variables, but also the distributions of these indices, which analytical techniques generally cannot do.

- Non-electrical system factors such as reservoir operating conditions in hydro systems, weather effects, etc. can also be simulated.

The two basic Monte Carlo Simulation methods used in power system reliability evaluation are generally known as the sequential and non-sequential techniques. The non-sequential techniques sample the states of all components and evaluate the obtained system state without considering system chronology. The non-sequential technique can be divided into the two basic techniques of state sampling and state transition sampling based on their different sampling approaches. The sequential techniques simulate the up and down cycles of all the system components chronologically. An entire system operating cycle is then obtained by combining all the component cycles[42]. These methods are described in the next sections.

3.2.1 Non-sequential Methods: State Sampling Approach

In this approach, the states of all components are sampled and the obtained system state is evaluated without considering its chronological characteristics. The sampling procedure is conducted by assuming that the behavior of each component can be categorized by a uniform distribution under [0,1]. The component can be represented by a two-state or multi-state model in accordance with the actual conditions. In the case of a two-state component, the component state can be categorized by the component Forced Outage Rate (FOR). The system state can be represented by a vector $S = (S_1, S_2, S_3, \ldots\ldots\ldots\ldots, S_i, \ldots\ldots\ldots\ldots, S_m)$ where S_i is the state of each element in the system (generators, lines, transformers, etc.). The steps in evaluating power system reliability indices using the state sampling technique are summarized below[26,37]:

- ▶**STEP 1:** The component states are obtained by generating a uniform random number U_i in the range of 0 to 1 for each component i.
- ▶**STEP 2:** The random number of each component i is compared with FOR_i, where FOR_i is the ith component's forced outage rate. When the random number $\geq FOR_i$, the component is considered to be available ; when the random number $< FOR_i$, the component is considered to be in the failed state .

$$S_i = \begin{cases} 0 \text{ (up state)} & \text{if } U_i \geq FOR_i \\ 1 \text{ (down state)} & \text{if } U_i < FOR_i \end{cases} \qquad \ldots\ldots. (3.1)$$

- ▶**STEP 3:** The system state is obtained by repeating step (2) for the entire components.
- ▶**STEP 4:** If S , which represents the system state ; is equal to 0 , the system is in the normal state , otherwise the system is in an abnormal state and load curtailment may occur.
- ▶**STEP 5:** A linear programming minimization model is normally used to reschedule generation, alleviate line overloads and avoid load curtailment if possible or to minimize the total load curtailment if it is unavoidable [34].
- ▶**STEP 6:** The desired adequacy indices are calculated and steps from (1) to (5) are repeated until the coefficient of variation of a specified index is less than the tolerance error.

One of the advantages of the system state sampling method is that multi-state component can be incorporated in the analysis without a significant increase in computing time. The probabilities of the ith component including a single derated state for step 2 are expressed in

Equation (3.2) where PFOR is probability of single derated state of the ith component.

$$S_i = \begin{cases} 0 \text{ (up state) if } & U_i \geq PFOR_i + FOR_i \\ 1 \text{ (down state) if } & PFOR_i \leq U_i < PFOR_i + FOR_i \\ 2 \text{ (derated state) if } & 0 \leq U_i < PFOR_i \end{cases} \quad \ldots\ldots(3.2)$$

Additional derated states can be simulated in similar manner .

The advantage of the state sampling approach is that it is a relatively simple process involving the utilization of uniformly distributed random numbers and has a relatively short computation time with small memory requirements. The major disadvantage of the state sampling approach when applied to power systems is that it cannot be used by itself to calculate an actual frequency index, as this approach cannot recognize the impact of failure state transitions and transitions associated with a chronological load model. These factors directly affect frequency index calculation.

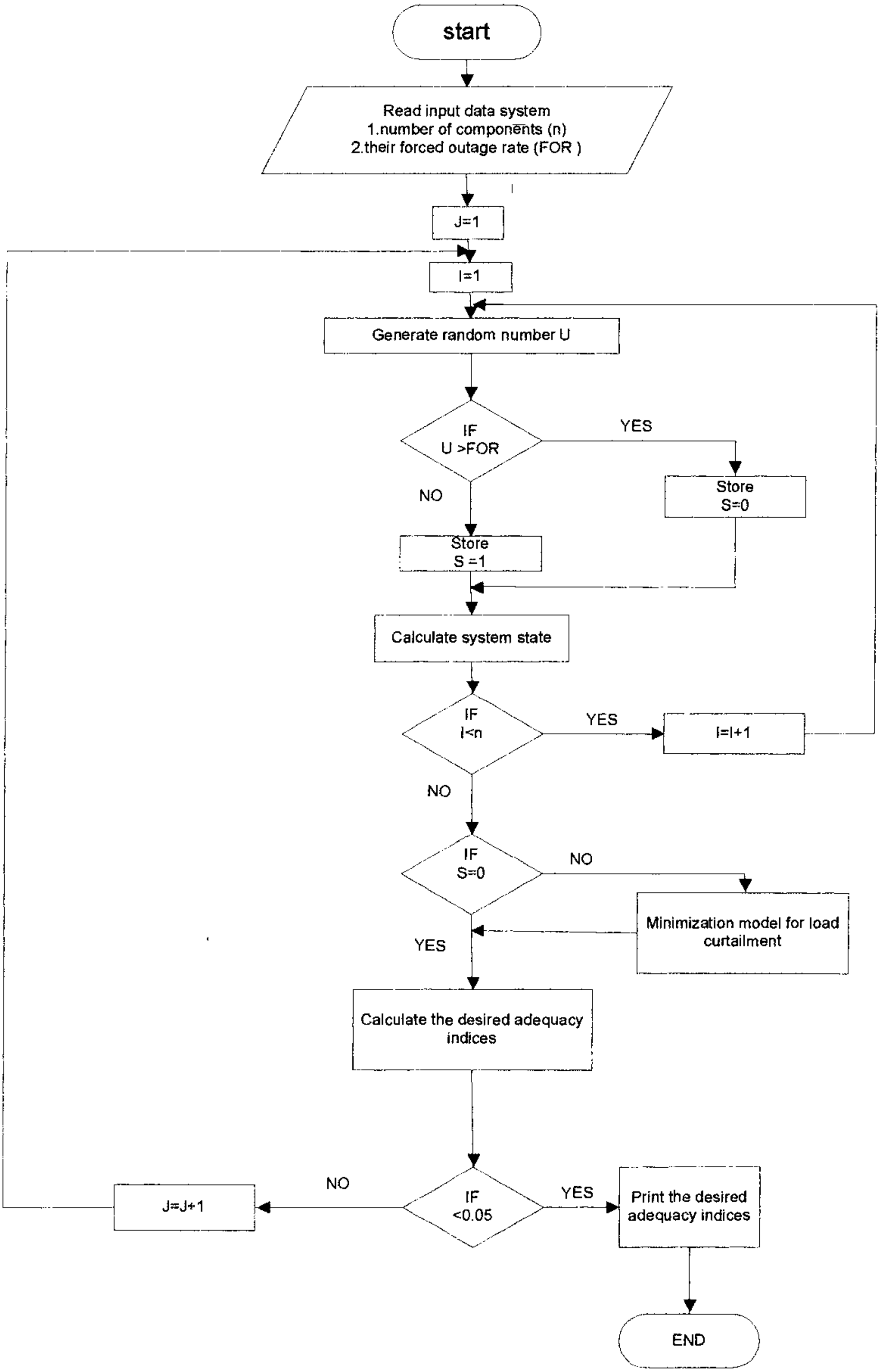

Fig.(3.1): Flow chart of the State Sampling Approach.

3.2.2 Non-Sequential Methods: Transition Sampling Approach:

The state transition sampling technique focuses on system state transition as a whole, instead of component states or component state processes method. It is explained as follows [34]:

Assume that a system contains m components and that the state duration of each component follows an exponential distribution. The system can experience a system state transition sequence $G = \{ S^1, S^2, \ldots, S^n \}$, where G is the system state space. Suppose that the present system state is S^k and the transition rate of each component relating to is λ_i (i=1, 2,....,n). The state duration T_i of the ith component corresponding to system state S^k ,therefore, has the probability density function: $f_i(t) = \lambda_i \exp(-\lambda_i t)$. Transition of the system state depends randomly on the state duration of the component, which departs earliest from its present state , i.e., the duration T of the system state S^k is a random variable can be expressed by :

$$T = \min \{ T_i \} \quad \ldots\ldots (3.3)$$

It can be shown that since the state duration T_i of each component follows an exponential distribution with parameter λ_i, the random variable T also follows an exponential distribution with the parameter

$\lambda = \sum_{i=1}^{m} \lambda_i$,i.e. T has the probability density function

$$f(t) = \sum_{i=1}^{m} \lambda_i \exp(-\sum \lambda_i t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.4)$$

Assume that transition of the system state from S^k to S^{k+1} takes place at instant t_0.The probability, that this transition is caused by departure of the jth component from its present state, is the conditional probability $P_j = P(T_j = t_0)/(T = t_0)$.

According to the definition of conditional probability and Equation (3.3), it follows that

$$\begin{aligned} P_j &= P(T_j = t_0 / T = t_0) \\ &= P(T_j = t_0 \cap \ T = t_0) / P(T = t_0) \\ &= P(T_j = t_0 \cap \ (T_i \geq \ t_0, i = 1, \ldots\ldots\ldots, m) / P(T = t_0) \\ &= P(T_j = t_0) \prod_{\substack{i=1 \\ i \neq j}}^{m} P(T_i \geq \ t_0) / P(T = t_0) \ldots\ldots\ldots\ldots\ldots(3.5) \end{aligned}$$

Since both T_i (i=1,……….,m), and T follow an exponential distribution

$$P(T_i \geq \ t_0) = \int_{t_0}^{\infty} \lambda_i \ \exp(-\lambda_i t)dt = \exp(-\lambda_i t) \ldots\ldots\ldots\ldots\ldots(3.6)$$

$$P(T_j = t_0) = \lim_{\Delta t \to 0} \ \lambda_j \exp(-\lambda_j t)\Delta t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.7)$$

and

$$P(T = t_0) = \lim_{\Delta t \to 0} \ (\sum_{i=1}^{m} \lambda_i \exp(-\sum_{i=1}^{m} \lambda_i t_0))\Delta t \ldots\ldots\ldots\ldots\ldots\ldots(3.8)$$

Substituting Equations (3.6), (3.7), and (3.8) into Equation (3.5) yields

$$P_j = P(T_j = t_0 / T = t_0) = \lambda_j / \sum_{i=1}^{m} \lambda_i \text{..............................}(3.9)$$

State transition of any component in the system can lead to a system state transition. Consequently, starting from system state S^k, a system containing m components has n possible reached states. The probability that system reaches one of these possible states is expressed by the following equation.

$$\sum_{j=1}^{m} P_j = 1 \text{..}(3.10)$$

therefore, the next system state can be determined by the simple sampling approach. The probabilities of n possible reached states are successively placed in the interval [0,1]as shown in Fig.(3.1). Generate a uniform distributed random number U between [0,1]. If U_i falls into the segment corresponding to P_j, this means that transition of the jth component leads to the next system state. A long system state transition sequence can be obtained by a number of samples and the reliability of each system state can be assessed. The system state transition sampling techniques described above is quite general. It can be applied to a generation system, a composite system, or to any basic engineering system reliability evaluation.

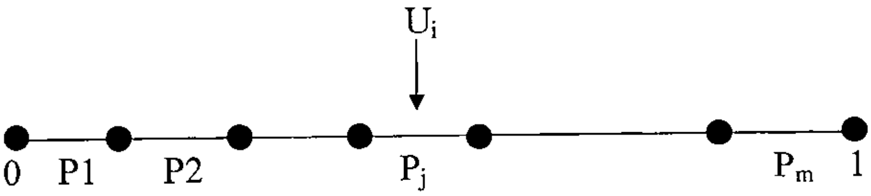

Fig.(3.2) : Explanation of the system state transition sampling.

The following steps describe the procedure used in power system adequacy assessment:

►**STEP 1:** The simulation process starts from the normal system state in which all the generating units and transmission lines are in up state, which means every component in the system is available.

►**STEP 2:** Calculate each P_j (j=1,2,…….n) using equation (3.9) and generate a uniform distributed random number U_i between [0,1], then determine the next system state.

►**STEP 3:** If the present system state is a contingency state in which at least one component is in the outage state, the minimization model of load curtailment is used to evaluate the adequacy of this system state. Otherwise, proceed to the next step without utilizing the minimization.

►**STEP 4:** The process is repeated until the selected convergence criterion is satisfied. This procedure requires more time than basic state sampling approach described earlier.

The major advantage of this approach is that it can be used to calculate an actual frequency index by creating a system state transition chain. The state transition sampling approach in general does not involve sampling component state duration distribution functions nor the storage of chronological information as required in the sequential approach. The disadvantage of the state transition sampling approach is that it only applies to components with exponentially distributed state residence duration characteristics, which may not always be true.

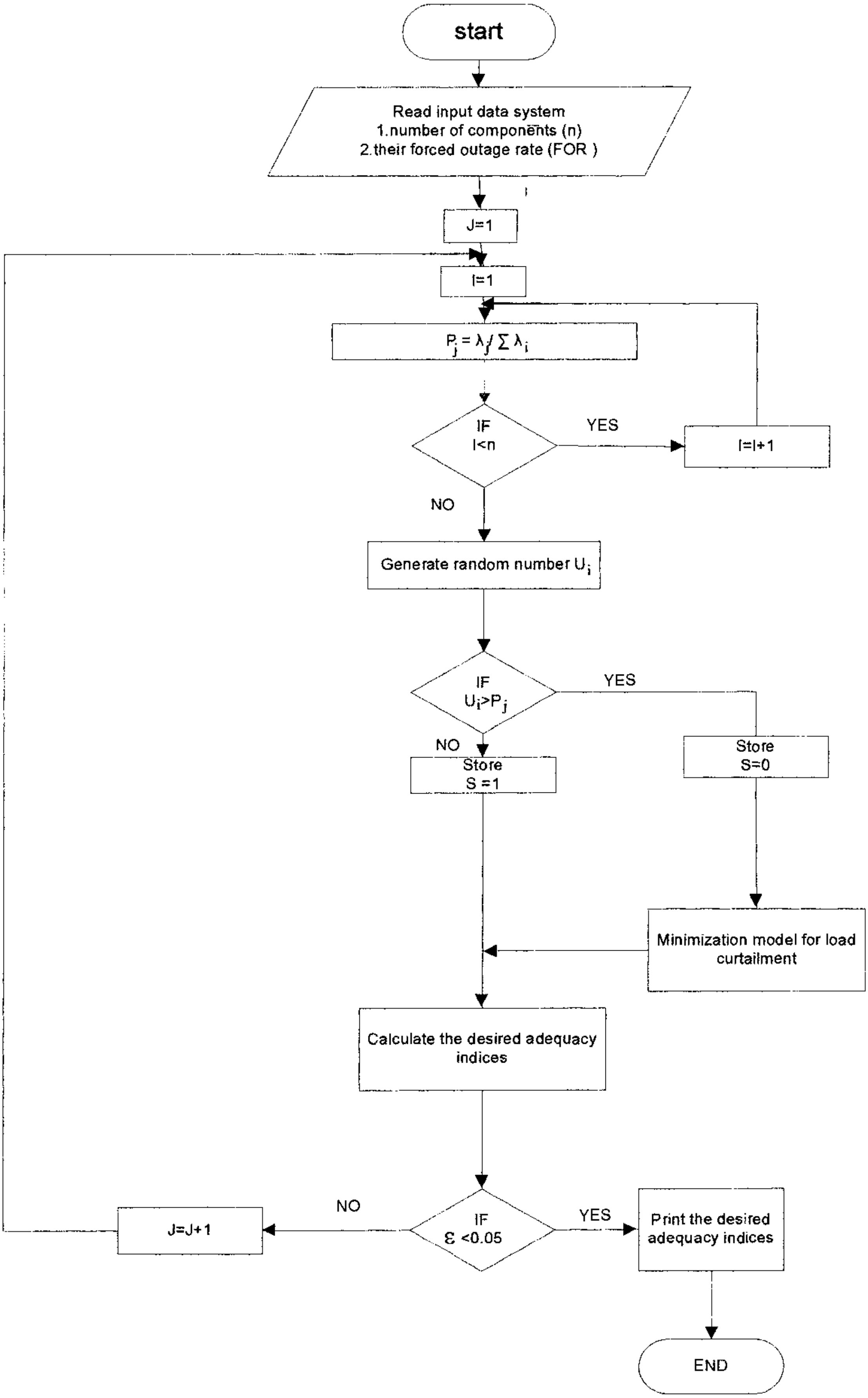

Fig. (3.3): Flow chart of the State Transition Sampling Approach.

3.2.3 Sequential Methods: State Duration Sampling Approach:

The state duration sampling approach is based on sampling the probability distribution of the component state duration. In this approach, chronological component state transition processes for all components are first simulated. The chronological system state transition process is then created by combining the individual chronological component state transition processes. The term sequential simulation in the engineering sense, in which any event occurring within a particular time step is considered to occur at the end of the time step, and the system states are updated accordingly. A time step of one hour is considered to be adequate for power system reliability assessment since the numbers within that period is generally small [30,38,41].

A sequential time evaluation of system behavior is created which enables a wide range of reliability indices to be assessed. This approach is very useful when the system to be analyzed is past-dependent; i.e the state of the system at any given time is partially determined by the historical time evolution of the system. If the operating life of the system is simulated over a long period of time, it is possible to study the behavior of the system and to obtain a clear picture of possible deficiencies from which the system suffers. The recorded information can be used to calculate the expected values of selected reliability indices together with an appreciation of the dispersion of these indices. There is frequently a need to know the likely range of reliability indices, the likelihood of certain values being exceeded, and similar parameters. These can be assessed from knowledge of the probability distribution associated with the expected value. At the present time, sequential simulation is the only realistic option available to investigate the distributional aspects associated with system index mean values.

The sequential simulation approach can be used to represent most of the contingencies and operation inherent in electric power system and provide a comprehensive range of reliability indices. This comprehensive information provides a detailed description, and hence understanding, of system reliability. The major disadvantage of the sequential simulation method is that it requires more computation time and storage than non-sequential methods because it is necessary to generate a random variant following a given distribution of each component and store information on the chronological component state transition processes of all the components over a long time span. This disadvantage is now becoming less significant due to the availability of high speed computation facilities. The sequential simulation method can be summarized by the following steps [38]:

▶**STEP 1:** The initial state of each component is specified. Generally, it is assumed that all components are initially in the success or up state (operating state).

▶**STEP 2:** The duration of each component residing in its present state is sampled from its probability distribution. For example, an exponentially distributed random variant T has the probability distribution function. Other distributions can be easily utilized.

$$f_T(t) = \lambda\, e^{-\lambda t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.11)$$

where λ is the mean value of the distribution. Its cumulative probability distribution function is:

$$F(t) = 1 - e^{-\lambda t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.12)$$

using the inverse transform method the random variant T is given by

$$T = -\frac{1}{\lambda}\ln(1-U_i) \quad \ldots\ldots (3.13)$$

where U_i is a uniformly distributed random number obtained from a multiplicative pseudo – random number generator. The procedure used to generate the pseudo – random number is described in Appendix A. since the term $(1-U_i)$ distributes uniformly in the same way as U in the interval [0,1],

$$T = -\frac{1}{\lambda}\ln(U_i) \quad \ldots\ldots (3.14)$$

If the present state is the up state (success state), λ is the failure rate of the component. If the present state is the down state (failure state), λ is the repair rate of the component.

►**STEP 3:** Step (2) is repeated in the given time span, i.e normally a year, and sampling values of each state duration for all components are recorded. The chronological component state transition processes in the given time span of all components are then combined to create the chronological system state transition processes.

►**STEP 4:** System analysis is conducted for each different system state to obtain the reliability index function $\Phi(S)$**.** The expected value of index $\Phi(S)$ is designated as $E(\Phi)$**.** The mathematical expectation of the index or test function $E(\Phi)$ of all system state is given by:

$$E(\Phi) = \sum_{S \in G} \Phi(S)\, P(S) \quad \ldots\ldots (3.15)$$

where S is the system state and G is the set of the system states. Assuming that each system state has the probability P(S) results in:

$$E(\Phi) = \sum_{S \in G} \Phi(S) \frac{n(S)}{N} \qquad \text{.........................(3.16)}$$

where N is the total number of samples and n(S) is the number of occurrences of system state S. Φ(S) can be obtained by appropriate system analysis. For example, to determine the system probability of load curtailment, the index Φ(S) is given as:

$$\Phi(S) = \left\{ \begin{array}{l} 1 \text{ if there is a load curtailment associated} \\ \quad \text{with system state S.} \\ \\ 0 \text{ if there is no load curtailment} \end{array} \right\} \text{..(3.17)}$$

Equations 3.7 and 3.8 are associated with the random state sampling approach (non-sequential), when the sequential technique is used. The concept used to estimate the expected value of the index can be extended as follows:

$$E(\Phi) = \frac{\sum_{i=1}^{NS} \left[\sum_{j=1}^{n_i(S)} \Phi(S_{j,i}) \right]}{NS} \qquad \text{...(3.18)}$$

where : $n_i(S)$ = Number of occurrences of system state S in year i.

$\Phi(S_{j,i})$= Index function corresponding to j^{th} occurrence in year i.

NS= Number of simulation years.

Sequential Simulation Illustration

The sequential simulation process described above is briefly illustrated using the simple system composed of two parallel redundant components. This system is in the failed state when both components are in the failed state at the same time.

The chronological component state transition processes of the two components obtained using steps 1-3 for the first three simulation years are illustrated in Fig.(3.4). The chronological system state transition process is obtained by combining the chronological component state transition processes as shown in the bottom of Fig.(3.4). There is no system failure in the first simulation year, and there are one and two failures in the second and third simulation years respectively. If the desired reliability index Φ(S) is the system failure frequency index, the expected value E (Φ) based on the three simulation years can be calculated as follows using Equation (3.14).

$$E(\Phi) = \frac{\Phi(S_{fail,1}) + \Phi(S_{fail,2}) + \Phi(S_{fail,3})}{3}$$

$$E(\Phi) = \frac{(0) + (1) + (1+1)}{3} = 1.0 \text{ occurrence /year}$$

It is important to note that a large number of simulation years is required in order to obtain a reasonable result when utilizing Monte Carlo Simulation. The following section addresses the stopping criterion used to terminate the simulation process.

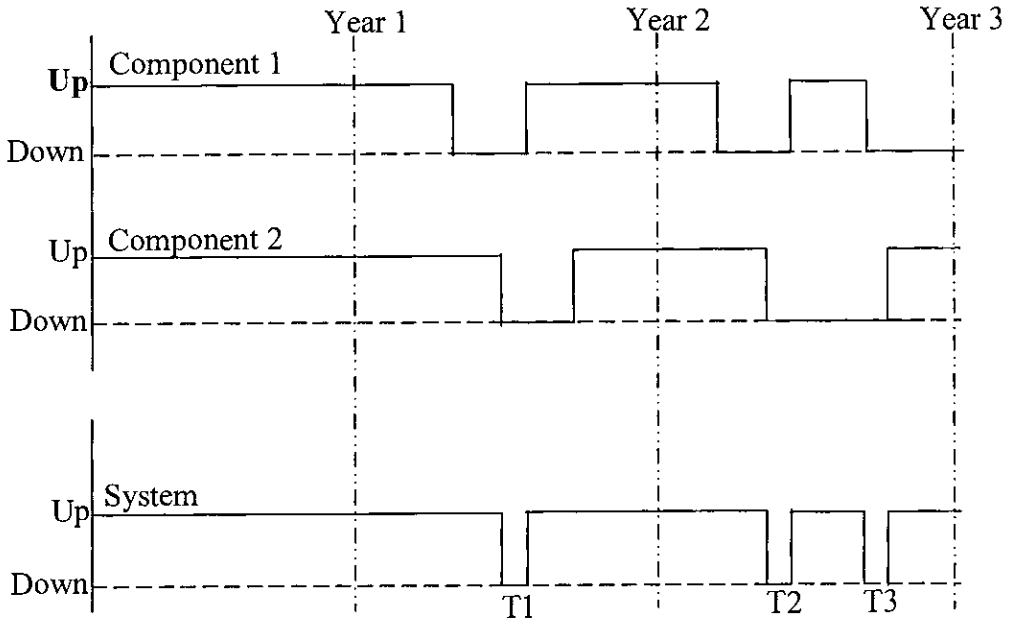

Fig.(3.4): Chronological component and system state transition process of a simple parallel redundant system during the first three simulation years

3.3 Convergence and Stopping Criterion

Monte Carlo Simulation creates a fluctuating convergence process, and there is no guarantee that a few more samples will definitely lead to smaller error. It is true, however, that the error bound or the confidence range decreases as the number of samples increases. It is, however, not practical to run the simulation for an extremely large number of samples requiring an extensive computation time. A compromise, therefore, must be made between the required accuracy and the computing time. The purpose of a stopping rule is to allow the simulation to run until the reliability index achieves a specified degree of accuracy. The basic parameters used in the stopping criterion are the coefficient of variation and is derived as follows

A fundamental parameters in reliability evaluation is the mathematical expectation of a given reliability index. Salient features of

Monte Carlo Simulation for reliability analysis, therefore, can be discussed from an expectation point of view. Let X be the reliability index to be estimated. In sequential simulation, the number of samples is the number of simulation years. The expectation value of the reliability index (X) is given by:

$$E(X) = \frac{\sum_{i=1}^{NS} X_i}{NS} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.19)$$

where X_i = The observed value of x in year i

NS = The total number of simulation years .

The unbiased variance of reliability index (X) is

$$V(X) = \frac{\sum_{i=1}^{NS} (X_i - E(X))^2}{NS - 1} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3.20)$$

It is important to note that Equation (3.19) provides only the expected value of the reliability index (X). The uncertainty around the estimate can be measured by the variance of the expectation estimate :

$$V(E(X)) = \frac{V(X)}{NS} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.21)$$

The standard deviation of the expectation estimate is given by:

$$\sigma (E(X)) = \sqrt{V(E(X))} = \sqrt{V(X) / NS} \qquad \ldots\ldots\ldots\ldots(3.22)$$

The accuracy level of a sequential Monte Carlo Simulation can be expressed by the coefficient of variation (β), shown in Equation (3.19), can be rewritten using Equation (3.18) as:

$$\beta = \frac{\sqrt{V(X)} / NS}{E(X)} = \frac{\sigma(X)}{E(X) * \sqrt{N}} \qquad \ldots\ldots\ldots\ldots(3.23)$$

where $\sigma(X) = \sqrt{V(X)}$. The simulation can be terminated when a specified coefficient of variation has been achieved. The selected stopping criterion is designated as the acceptable tolerance (ε) in the simulation as shown in Equation (3.20).

$$\frac{\sigma(X)}{E(X) * \sqrt{N}} < \varepsilon \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.24)$$

where ε is the maximum (tolerance) error allowed, i.e 5%.

As shown in Equations (3.23) and (3.24) the value of β will decrease with increasing number of simulation years, and the simulation process can be terminated when β is less than ε. It is important to note that the specified accuracy of the number of simulation samples is not dependent on the size of the system. Monte Carlo Simulation techniques are therefore quite suitable for handling large systems with complex features. In power system reliability analysis, different reliability indices have different convergence speed. It has been found that the coefficient of variation of the Expected Energy Not Supplied (EENS) index has the lowest rate of convergence. The advantage and disadvantage of the sequential simulation approach are summarized as follows:

Advantages:

- The sequential method can be easily used to calculate the actual frequency index.
- Any state duration distribution can be easily considered.
- The statistical probability distribution of the reliability indices can be calculated in addition to the expected values.

Disadvantages:

- Compared to the basic state sampling approach, this method requires more computation time and memory storage because it is necessary to generate a random variant following a given distribution for each component and store information on the chronological component state transition process of all the components in a long time span.
- This approach also requires parameters associated with all component state duration distributions. In some cases, especially for a multi -state component representation, it may be difficult to provide all transition rates between states of each component.