İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

DISTRIBUTION SYSTEM RELIABILITY ASSESSMENT

STRUCTURAL APPROACH

M.Sc. THESIS

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Date of Submission : January 13, 1996

Date of Approval : January 30, 1996

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JANUARY 1996

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ELEKTRİK DAĞITIM SİSTEMLERİNDE YAPISAL YAKLAŞIMLA GÜVENİLİRLİK ANALİZİ

YÜKSEK LİSANS TEZİ

Müh. Fahrudin MEKİÇ

Tezin Enstitüye Verildiği Tarih: 13 Ocak 1996

Tezin Savunulduğu Tarih : 30 Ocak 1996

Tez Danışmanı : Doç.Dr. Aydoğan ÖZDEMİR 16.2.96

Diğer Jüri Üyeleri : Prof.Dr. R. Nejat TUNÇAY 16.2.96

Yrd.Doç.Dr. Serhat ŞEKER 16.2.1996

OCAK 1996

ACKNOWLEDGEMENTS

This thesis study was pursued with the invaluable suggestions of my advisor, Doç.Dr. Aydoğan Özdemir. I am grateful for his guidance towards the successful completion of this work.

I am grateful to the Selim Yusufoğlu and Osman Laviç for their invaluable support.

I am deeply indebted to my mother and father for the strength that they have given me, and to my wife, Amela, and children Amina and Irfan. The encouragements that they have made, I offer with the completion of this thesis. My special thank you.

CONTENTS

ABSTRACT

This study presents a method for distribution system reliability assessment. The proposed method is based on the system structure and does not take into consideration the system constraints. Reliability assessment of distribution system with constraints can be considered as a future step of the method.

Chapter 1 gives the historical background of reliability, especially reliability evaluation in electric power systems. Hiearchical levels of power system reliability studies are introduced.

Chapter 2 begins with the definitions of basic reliability parameters. Markov modelling of a two state component as well as serially and parallel connected components are summarised. The chapter continues with the several types of the classifications of the failures and terminates with reliability indices and their applications.

Chapter 3 is devoted to the steps of distribution system reliability assessment. Determination of minimal paths by conventional method and by the proposed "predecessor method" are introduced and compared. Minimal cut sets of total failures called basic minimal cut sets are deduced by Conventional algorithms. Minimal cut sets resulting from active failures and inadequate operation of circuit breakers are deduced by proposed S and SS groups of the specific nodes.

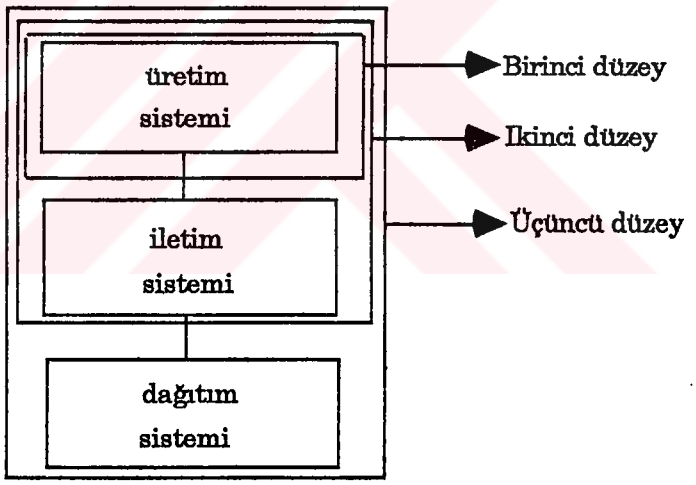
Application of the proposed method on a typical distribution network is presented in Chapter 4. Using component reliability data, three basic reliability indices are evaluated at a specified busbar. The comparison of the results with those presented in the literature shows that the same numerical values are attained with less computational effort.

ÖZET

ELEKTRİK DAĞITIM SİSTEMLERINDE YAPISAL YAKLAŞIMLA GÜVENILIRLIK ANALİZİ

Günümüz modern toplumunda mühendisliğin temel işlevi çeşitli ürün ve sistemlerin güvenilir bir şekilde tasarımı, üretimi ve işletimidir. Sözkonusu ürün ve sistemlerin "ne derece güvenilir" oldukları, güvenilirlik analizleriyle belirlenen bazı indislere göre değerlendirilirler.

1930'lu savaş yıllarında ortaya çıkan ilk güvenilirlik analizlerinin elektrik-enerji sistemlerine yansıması 1960'lı yıllarda olmuştur. Elektrik-enerji sistemlerinde bu tarihden günümüze kadar yapılan güvenilirlik analizleri, Şekil 1'de gösterildiği gibi üç gurupta değerlendirilir.

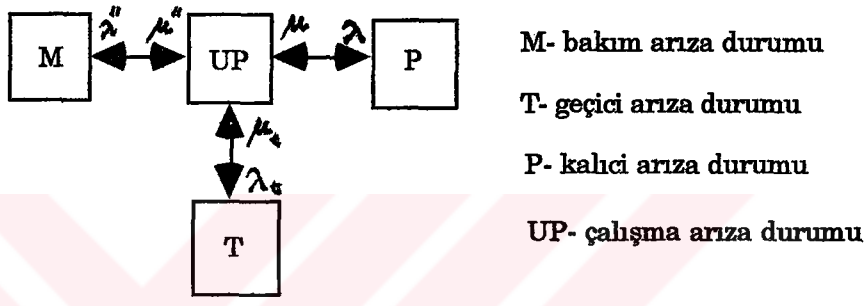


Şekil 1 Elektrik enerji sistemlerinde güvenilirlik aşamaları

Çok sayıda bileşen içeren elektrik dağıtım sistemlerine ilişkin güvenilirlik analizleri genellikle üretim ve iletim aşamalarından bağımsız olarak yapılır. Bu analizler bileşenlerin (hat, kesici,vb) kapasitesi açısından Toplam Yük Kaybı (Total Loss of Continuity) ve Kısmi Yük Kaybı (Partial Loss of Continuity) şeklinde iki kısımda değerlendirilir. Bu çalışmada sonsuz kapasiteli (tam fazlalıklı) bileşenlerden oluşan bir dağıtım sisteminde güvenilirlik analizi konusunda bir hesaplama yöntemi sunulmuştur. Önerilen yöntemde yaklaşık hesap teknikleri benimsenmiştir.

Sabit hızlı, onarılabilir bileşenlerden oluşmuş sistemlerin güvenilirlik analizleri tüm bir yaygın olarak kullanılan yöntem Markov modellemesidir. Durum uzayı gösterilimi adı verilen bu modelleme ile sistemin olası tüm durumları ve durum geçişleri dikkate alınır. Sistemin durumu ise bileşenlerin durumlarına bağlıdır. Dolayısıyla Markov modellmesinin ilk adımını bileşenlerin olası durumlarının (çalışma, arıza, bakım) modellenmesi oluşturur.

Bir elemanın veya sistemin işlevini yerine getirmemesi olarak tanımlanan "arıza kavramı", oluşum şekli, oluşum anı ve etkileri açısından çeşitli şekilerde sınıflandırılır. Güvenilirlik analizinde arızalar ve sistemin bir tür işlevini yerine getirmeme durumu olarak değerlendirilen programlı bakımlarda dikkate alınarak Şekil 2'deki gibi modellenirler.



Şekil 2 Çeşitli çalışma türleri

Şekil 2'de verilen model sadece çalışma ve pasif arıza olarak adlandırılan arıza durumlarını içermektedir. Yanlış anahtarlamalar ve bir anahtarlama elemanının çalışmasını gerektiren arızalar (kısadevre) aktif arızalar olarak adlandırılırlar. Bu arızaların etkileri ve giderilme yöntemleri pasif arızalardan farklıdır. Şekil 3'de heriki arızanın nasıl giderileceği şematik olarak gösterilmiştir.

Dağıtım sistemlerinde Toplam Yük Kaybına dayalı güvenilirlik analizleri dört aşamada yapılır. Bu aşamalar

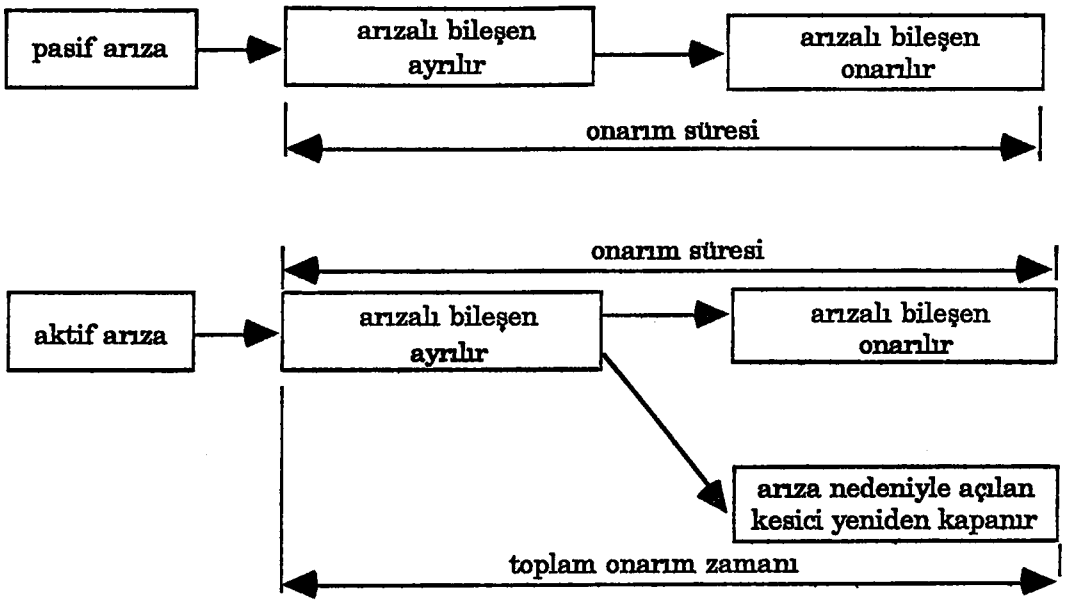
a) temel yolların belirlenmesi;

b) temel kesitlemelerin belirlenmesi;

c) temel indislerin hesaplanması ve

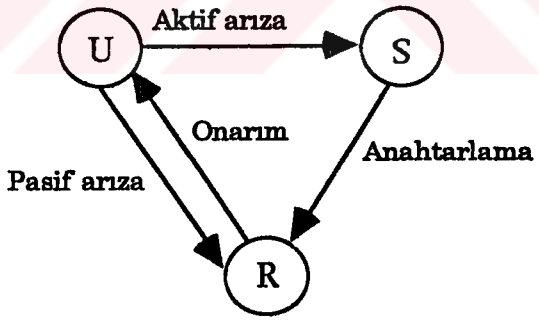
d) türev indislerin hesaplanması

şeklindedir. Her aşama için modelleme ve hesaplama bakımından farklı seçenekler vardır.



Şekil 3 Pasif ve Aktif Arızaların Giderilmesi

Dağıtım sistemlerinde aktif arızalar önemli rol oynarlar. Dolayısıyla bu arızaların da dikkate alınması gerekir. Şekil 4'de heriki arıza tümünün dikkate alındığı durum uzayı gösterilimi verilmiştir.



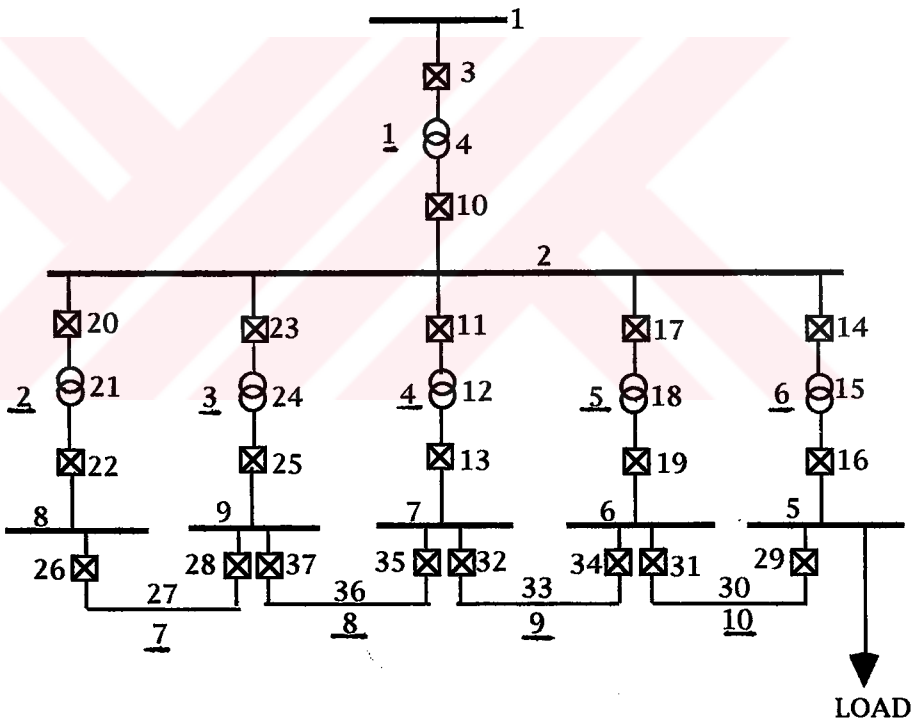
Şekil 4 Bir Birimin Çalışma ve Arıza Durumları

Bu çalışmada yapılan katkılardan biri temel yolların değişik bir yöntemle belirlenmesidir. Temel yolların belirlenmesi işlemi alışılagelmiş yöntemlerde eleman-düğüm bağlantı matrisi kullanılırak yapılır. Baraların 100% güvenilir olduğu ve ilgilenilenin dışında bir dallanmanın sonuca etkimediği varsayımına dayanan bu yöntem, dağıtım sistemlerinde bazı problemlere yol açmaktadır. Koridorlar yöntemi adını verdiğimiz yöntemle, dağıtım sisteminin giriş ve çıkış arasındaki temel yolların belirlenmesi yukarıda belirtilen sakıncaları ortadan kaldırmaktadır.

Çalışmada aktif ve pasif arızalara karşı düşen ve ana kesitlemeler adını verdiğimiz kesitlemelerin belirlenmesi için bilinen yöntemlerden biri kullanılmıştır. Aktif arızalara ve yanlış anahtarlamalara ilişkin ikincil kesitlemeler adı verilen kesitlemelerin belirlenmesi için, ana kesitlemelerde yer alan baralara ait S ve SS eleman gurupları tanımlanmıştır. Her eleman için söz konusu son iki arızayı ayrı ayrı modellemenin getireceği hesaplama ve hafıza problemlerini gidermek amacıyla, önerilen yöntemde, sadece S ve SS guruplarına giren ikincil kesitlemeler dikkate alınmaktadır.

Ana ve ikincil temel kesitlemeler bellirlendikten sonra dağıtım sisteminin temel kesitlemelerden oluşmuş eşdeğeri kurulmakta ve buradan öngörülen herhangi bir baraya ilişkin temel indisler (arıza hızı, onarım süresi ve yokluk) hesaplanmaktadır. Gerekirse türev indisler de belirlenerek karşılaştırmalar yapılabilmektedir.

Önerilen yöntemin doğruluğu ve üstünlüklerini ortaya koymak için Şekil 5'de verilen dağıtım sisteminin 5 numaralı barasına ait güvenilirlik indisleri hesaplanmıştır.



Şekil 5 Örnek dağıtım sistemi

Hesaplama sonuunda temel güvenilirlik indisleri,

λ =1.34794 arıza/yıl

r = 7.6599 saat

U = 10.325327 saat/yıl

Bu sayısal değerler literatürdekilerle karşılaştırıldığında sonuçların aynı olduğu görülmüştür. Daha az bellek ve daha az işlemle aynı değerlerin elde edilmiş olması, yöntemin geçerliliğinin ve üstünlüğünün bir ölçüsü olarak vurgunalanabilir. Yine de mutlak bir yargıya varmak için yöntemin programlanması ve karşılaştırılmaların daha fazla örnek sistem üzerinde yapılması gerekmektedir.

CHAPTER I
INTRODUCTION

In a modern society engineers and technical managers are responsible for the planning, design, manufacture and operation of products and systems ranging from simple products to complex systems. As it is expected users, customers and society in general want to have reliable and safe product or system. The problem is "How reliable will the system be during its future operating life? This question can be answered by the use of quantitative reliability evaluation.

Going through the history of reliability evaluation techniques it can be revealed that application associated with the aerospace and military industries have taken part firstly. So, in the 1930s statistical reports were published the statistical data on the failure rate of various aircraft components were collected. The first predictive reliability models appeared in Germany on the missile project. During 1950s reliability had taken part in the electronics. In the same years advisory group on reliability of electronic equipment was established and Korean war proved how important these problems were. Little by little, the idea took shape that there is more sense in designing reliable equipment than in waiting for failures and having to repair them. In 1960s new reliability techniques were emerged. Predictive failure analyses played a greater part, especially in the field of nuclear weapons. The failure mode and effects analysis (FMEA) method was devised in the early 1960s. Gathered fault combination method for aircraft projects was developed. In 1965 reliability programs for system and equipment was published. This document recommended that a reliability and manufacturing activities. After the three Mile Island accident (1979) probability risk analysis method was recommended. Modern reliability techniques are also used in a much wider range of application including domestic appliances, automobiles and other products that have socioeconomic effect when they fail .

Frequently used term in modern society and of course in technique is **reliability**. This term can be defined as follows: Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered. On the other hand, it is probability of component/system staying in the operating state without failure. This definition is suitable for mission oriented systems. For continuously operated system such as electrical systems, "availability" is frequently used term. That can be defined as the probability of finding the component/system in the operating state at some time into the future.

In this thesis the concern will be power system reliability and all discussion will be devoted to power system. A power system serves one function only and that is to supply customers. Both large and small, with electrical energy as economically as possible and with an acceptable degree of reliability and quality. Modern society has come to expect that the supply should be continuously available on demand. This is not physically possible due to random system failures which are outside the control of engineers. The concept of power-system reliability, however, is extremely broad and covers all aspects of the ability of the system to satisfy the consumer requirements. So, the general meaning of power-system reliability can be defined as ability of the system to perform its function. A simple subdivision of power-system reliability can be shown as:

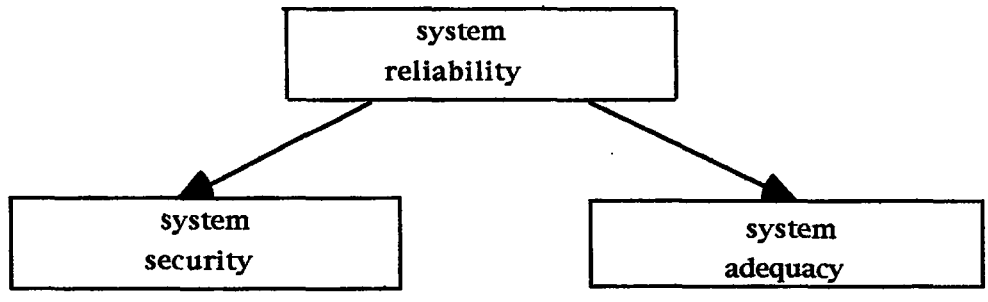


Figure 1.1 Subdivision of system reliability

Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to

the actual load points. Adequacy is therefore associated with static conditions which don't include system disturbances.

Security relates to the ability of the system to respond to disturbances arising within that system. Security is therefore associated with the response of the system to whatever perturbations it is subject. Most of the probabilistic techniques for power-system reliability evaluation are in the domain of adequacy assessment. Transient stability assessment is example of security analysis.

1.1. Functional Zones

Power system adequacy studies can be conducted individually in three functional zones. The functional zones can be combined to give the hierarchical levels shown in Figure 1.2.

HL I is concerned only with the generation facilities. HL II includes both generation and transmission facilities and HL III includes all functional zones. Analysis in HL III is done only in the distribution functional zoned to the enormity of the problem?

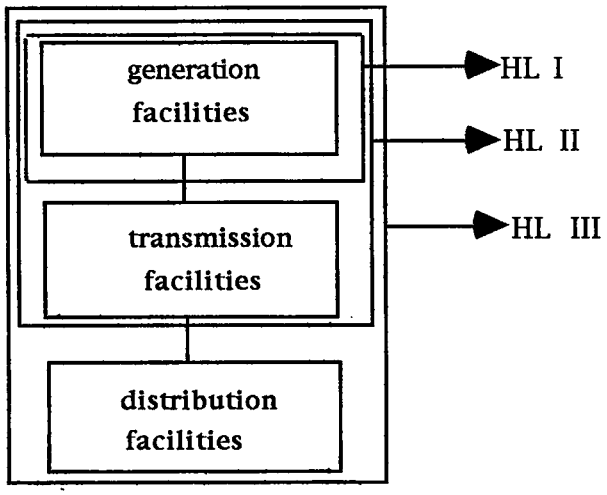


Figure 1.2 Hierarchical levels

1.2 Adequacy Evaluation at HL I

At HL I the total system generation is examined to determine its adequacy to meet the total system load requirement. The only concern is in estimating the necessary generating capacity to satisfy the system demand and to have sufficient capacity to perform corrective and preventive maintenance on the generating facilities.

The basic modelling approach for an HL I study is shown in Figure 1.3.

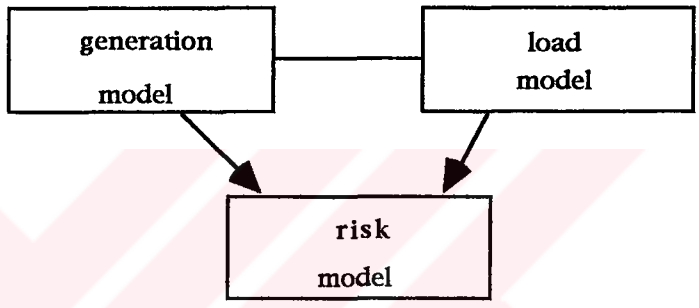


Figure 1.3 Conceptual tasks for HL I evaluation

The capacity model is formed in the direct analytical methods by creating a capacity outage probability table. The load model can either be daily peak load variation curve (DPLV) or load duration curve (LDC). The risk indices are evaluated by convolution of the capacity and load models. Risk indices are Loss of Load Expected (number of days during the period of study when the load will exceed available capacity) or Loss of Energy Expected (expected energy that will not be supplied by the generating system due to those occasions when the total demanded exceeds available generating capacity).

1.3. Adequacy Evaluation at HL II

Adequacy analysis at this level is termed as composite system reliability analysis. HL II studies are required to assess the adequacy of an existing system and the impact of various reinforcement schemes, at both the generation and transmission levels. These effects can be assessed by evaluating two sets of indices: individual bus (load-point) indices and overall system indices.

1.4. Adequacy Evaluation at HL III

The overall problem of HL III evaluation can become very complex in most systems because this level involves all three functional zones, starting at generating points and terminating at the individual consumer load points. For this reason, the distribution functional zone is usually analysed as a separate entity. The HL III indices can be evaluated, however, by using the HL II load-point indices as the input values at the sources of the distribution functional zone being analysed.

In this thesis reliability analysis of the distribution system, i.e., HL III will be considered. A main point will be focused on the structural analysis, i.e., a various topology of the distribution systems will be analysed. The method of predecessors will be introduced in order to find all minimal paths. All possible situations in the system will be taken under consideration, excluding functional constraints. The particular attention is devoted to analysis of active failures.

CHAPTER II

BASIC RELIABILITY TERMINOLOGY

A system is a deterministic entity comprising an interconnected or interacting collection of discrete elements (or components). Also, this definition indicates that the system is made of interacting components: it is assumed that it is not simply the sum of its subsystems or components. Of course, if the physical nature of a subsystem or component is altered as a result of a failure, the system itself is modified. Frequently used terminology for defining boundaries are [1]:

(PART) $\subset$ (COMPONENT) $\subset$ (SUBSYSTEM) $\subset$ (ELEMENTARY SYSTEM) $\subset$ (SYSTEM).

Some example of systems are: a chemical plant, a nuclear power plant or a plane. A control system is example for elementary system, a train in a safety system made of two independent trains (redundancy) is a subsystem, a relay is component and coil is part of a relay.

Every system is defined by one or several function (or missions) it must fulfil, with given components, under given conditions and in a given environment. The most important characteristics of the systems are: the system function, the system structure, how the system is operated, and the system environment.

2.1. Failure and Repair Rates of a Component

This is the limit, if it exists, of the ratio of the conditional probability that the instant of time T of a failure of an entity falls within a given time interval $[t , t + \Delta t]$ to the length of this time interval when Δt tends to zero given that the entity has not failed over $[0 , t]$ [1].

$$\lambda(t) = \lim \frac{1}{\Delta t} P \text{ [E failed from time t to } t+\Delta t \text{ given that it did not fail over time period } [0 , t] \text{] .}$$

Using the principle of conditional probabilities, we obtain:

$$\lambda(t) = \lim \frac{1}{\Delta t} \frac{P[\text{E failed from t to t+}\Delta t \text{ and E not failed over [0,t]}}{P\,[\text{E not failed from [0 , t]}]}$$

$$\lambda(t) = \lim \frac{1}{\Delta t} \frac{(P[\text{E failed over [0 , t +}\Delta t]] - P\,[\text{E failed over [0,t]}])}{R(t)}$$

$$\lambda(t) = \lim \frac{1}{\Delta t} \frac{R(t) - R(t + \Delta t)}{R(t)}$$

$$\lambda(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} = \frac{f(t)}{R(t)} \geq 0 \qquad (2.1)$$

From this it is possible to say that failure density function permits the probability of failure to be evaluated in any period of time into the future whereas the hazard rate permits the probability of failure to be evaluated in the next period of time given that it has survived up to time t.

Repair Rate:

This is the limit, if it exists, of the ratio of the conditional probability that the instant T corresponding to the completion of the entity repair be included within a given time interval [t , t +Δ t] to the length of this time interval when Δ t approaches zero assuming that the entity was failed over time period [0 , t] [1].

$$\mu(t) = \lim \frac{1}{\Delta t} P\,[\text{E repaired between time t and t+}\Delta t \text{ given that it failed over [0 , t]}]$$

It is assumed that entity falls at time t=0 and remain failed until time t.

So , using the Principe of conditional probability it is easy to show that :

$$\mu(t) = \frac{1}{1 - M(t)} \frac{dM(t)}{dt} \geq 0 \qquad (2.2)$$

Where M(t) is maintability of an entity E i.e.,
M(t) = P [E repaired over [0 , t]]

The exponential distribution is often used in calculations as they are much simpler. However, this distribution describes neither the case of "young" components (early failures), whose failure rate decreases with time, nor the case of "old" components, whose failure rate increases with time.

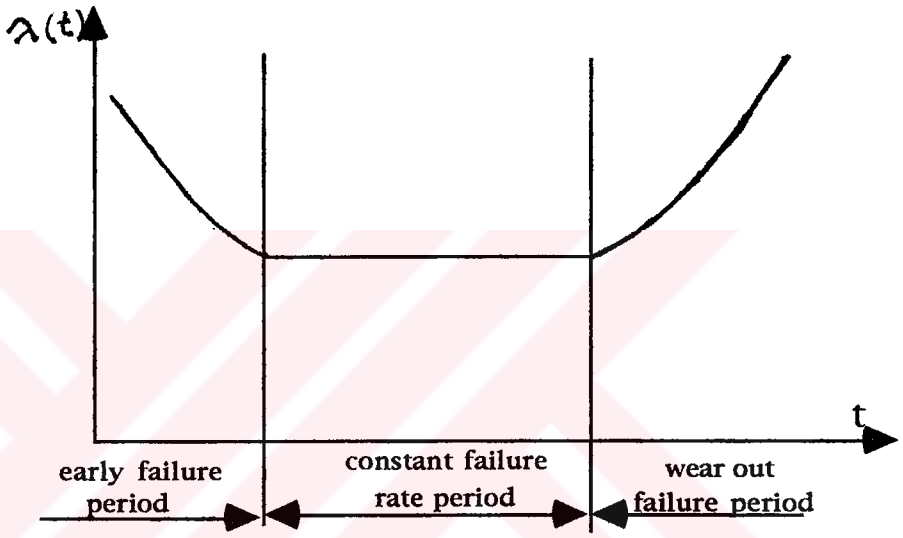


Figure 2.1 Failure rate as a function of age

This distribution gives:

$$f(t) = \lambda * e^{-\lambda t}$$
$$R(t) = e^{-\lambda t} \qquad (2.3)$$
$$M(t) = 1 - e^{-\mu t}$$

2.2. A Two State Markov Model of a Component

The state space diagram for the single component can be represented as follows [2]:

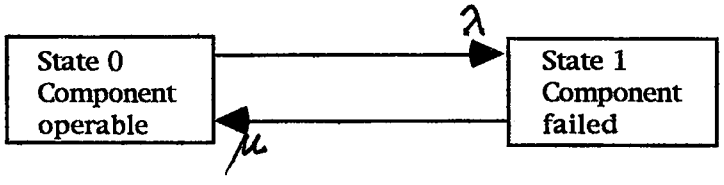


Figure 2.2 State space diagram of a single component

The probability of being in the operating state can be expressed as follows:

$$P_0(t+dt) = P_o(t)(1-\lambda dt) + P_1(t)\mu dt \tag{2.4}$$

$$P_1(t+dt) = P_1(t)(1-\mu dt) + P_0(t)\lambda dt \tag{2.5}$$

From Equations (2.4) and (2.5) it can be written:

$$P_0'(t) = -\lambda P_0(t) + \mu P_1(t) \tag{2.6,a}$$

$$P_1'(t) = \lambda P_0(t) - \mu P_1(t) \tag{2.6,b}$$

The system of differential Equations (2.6,a) and (2.6,b) and satisfying initial conditions must be solved [2]. Time-dependent probabilities of a single repairable component are:

$$P_0(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{2.7,a}$$

$$P_1(t) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{2.7,b}$$

The probabilities given in (2.7,a) and (2.7,b) are the probabilities of being found in the operating state and failed state respectively as a function of time given that the system started at time t=0 in the operating state.

The limiting state probabilities will be obtained, letting $t \to \infty$. So, from Equations (2.7):

$$P_0 = P_0(\infty) = \frac{\mu}{\lambda+\mu} \tag{2.8,a}$$

$$P_1 = P_1(\infty) = \frac{\lambda}{\lambda+\mu} \tag{2.8,b}$$

The equations (2.8) are applicable irrespective of whether the system starts in the operating state or in the failed state. The values of P_0 and P_1 are generally referred to as the steady-state or limiting availability A and unavailability U of the system respectively.

$$A(\infty) = P_0(\infty) = P_0 \qquad (2.9,a)$$

$$U(\infty) = P_1(\infty) = P_1 \qquad (2.9,b)$$

Throughout the following chapters limiting probabilities will be used.

2.3. Markov Models of Systems

The Markov technique and the frequency and duration approach [3] form precise modelling and evaluation methods for reliability applications. They become less amenable, however, for hand calculations and even for digital computer solutions as the system becomes larger and more complex. In such cases, alternative methods are available which are based on the Markov approach and which use a set of appropriate but approximate equations. The essence of these approximate techniques is to derive a set of equations suitable for a series system in which all components must operate for system success and for parallel system in which only one component need work for system success.

2.3.1. Series System

Consider a system comprising two components connected in series.

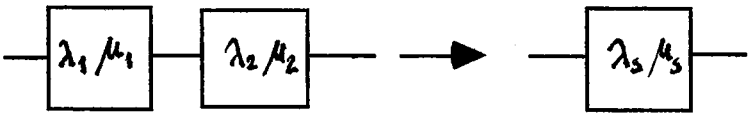


Figure 2.3 Representation of a two component series system

The limit probability of the system being in the up state, i.e., both components operating is given by Equation (2.10) [2].

$$P_{up} = \frac{\mu_1\mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \qquad (2.10)$$

where λ_1, λ_2 and μ_1, μ_2 are the failure rates and repair rates of the two components, respectively. It is necessary to find the failure and repair rates λ_s and μ_s, of a single component that is equivalent to the two components in series. The probability of the single component being in the up state is:

$$P_{up} = \frac{\mu_s}{\lambda_s + \mu_s} \tag{2.11}$$

For the single component to be equivalent to the two series component Equations 2.10 and 2.11 must be identical, i.e. ,

$$\frac{\mu_1\mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} = \frac{\mu_s}{\lambda_s + \mu_s} \tag{2.12}$$

Also since the transition rate from the system up state, for the single equivalent component, is λ_s , and for the two component series system, is $(\lambda_1 + \lambda_2)$ then

$$\lambda_s = \lambda_1 + \lambda_2 \tag{2.13}$$

Substituting Equation 2.13 into 2.12 and replacing the repair rates by the reciprocal of the average repair times, gives

$$r_s = \frac{1}{\mu_s} = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1\lambda_2 r_1 r_2}{\lambda_s} \tag{2.14}$$

In many system the product $\lambda_i r_i$ is very small. In such cases Equation 2.14 reduces to:

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_s} \tag{2.15}$$

The failure rate and average outage duration of a general n-component series system may be deduced as:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{2.16}$$

$$r_s = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\lambda_s} \tag{2.17}$$

The probability of the system being in the down state, i.e., the unavailability U can be expressed as:

$$U_s \approx \lambda_s r_s = \sum_{i=1}^{n} \lambda_i r_i \tag{2.18}$$

2.3.2. Parallel System

Let's consider a system comprising two components connected in parallel:

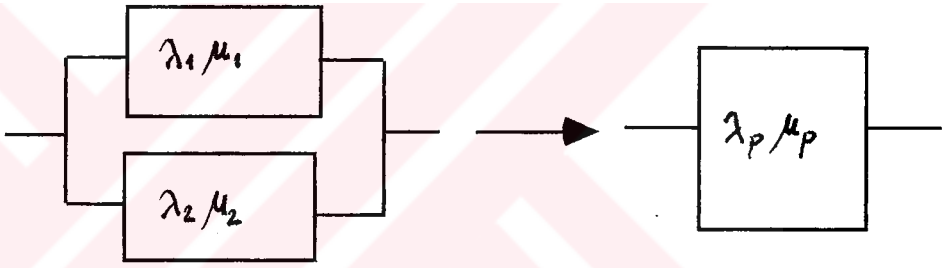


Figure2.4 Representation of a two component parallel system

The probability of the system being in the down state is given as:

$$P_{down} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{2.19}$$

The probability of the single component being in the down state is:

$$P_{down} = \frac{\lambda_p}{\lambda_p + \mu_p} \tag{2.20}$$

So Equations 2.19 and 2.20 must be identical

$$\frac{\lambda_p}{\lambda_p + \mu_p} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{2.21}$$

Considering that $\mu_p = \mu_1 + \mu_2$ it is very easily to show that:

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{2.22}$$

Substituting Equation 2.22 into 2.21 gives:

$$\lambda_p = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \tag{2.23}$$

Considering above mentioned assumption it is easily to show that

$$\lambda_p \approx \lambda_1 \lambda_2 (r_1 + r_2) \tag{2.24}$$

$$U_p = \lambda_1 \lambda_2 r_1 r_2 \tag{2.25}$$

Let's again consider Equation 2.24. This Equation can be written in other form as follow:

$$\lambda_p = \lambda_1 (\lambda_2 r_1) + \lambda_2 (\lambda_1 r_2) \tag{2.26}$$

This equation may be expressed in words as:
'failure of the system occurs if (component 1 fails followed by failure of component 2 during the repair time of component 1) or (component 2 fails followed by failure of component 1 during the repair time of component 2) '.

2.4. Classification of the Failures

Of course, it is necessary to define failures and classifications of component. A failure (outage) is "the termination of the ability of an entity to perform a required function". An entity will be said to have failed when it is no longer able to fulfil its function. To define failure more precisely, classifications are necessary [1].

Classification as to suddenness

- **Gradual failure:** Failure due to a gradual change with time of the given characteristics of an entity.

- **Sudden failure:** Failure that does not result in a progressive loss of the performance characteristic and that could not have been anticipated by prior examination or monitoring .

Classification as to degree

- **Partial failure;** Failure resulting from a deviation in characteristic (s) beyond specified limits but not such as to cause complete lack of the require function.

- **Complete failure:** Failure resulting from a deviation in characteristic beyond specified limits such as to cause complete lack of the required function.

Classification according to the data of occurrence

- **Early failures:** Failures occurring at an early period in the entity lifetime and whose rate decreases rapidly.

- **Random (constant rate) failure:** Failure occurring at an approximately uniform rate during the entity useful life.

- **Wear-out failure:** Failure with a rapidly increasing occurrence probability.

Classification as to causes

- **Primary failure:** Failure of an entity not caused either directly or indirectly by the failure of another entity. The entity has to be repaired to be in working order.

- **Secondary failure:** Failure of an entity caused either directly or indirectly by the failure of another entity this entity was neither qualified for nor designed against.

- **Command failure:** Failure of an entity caused either directly or indirectly by the failure of another entity this entity was qualified for or designed against .

2.5. Outage Modes of a Component

When a failure occurs, the entity is said to be faulty, i.e. a fault is always the result of a failure. So, a fault is the "inability of an entity to perform a required function". According to the detectibility of faults, next classification and basic equations can be made [2,4].

2.5.1. Permanent Forced Outage

An outage whose cause is not immediately self-clearing but must be corrected by eliminating the hazard or by repairing or replacing the component before it can be returned to service. An example of a permanent forced outage is a lighting flashover shatters an insulator, thereby disabling the component until repair or replacement can be made. So, the permanent forced outage duration is the period from the initiation of the outage until the component is replaced or repaired.

Considering overlapping of the permanent outages for two components in parallel it may be expressed (using Equation 2.24)

$$\lambda_{pp} \cong \lambda_1 \lambda_2 (r_1 + r_2)$$

$$r_{pp} = \frac{r_1 r_2}{r_1 + r_2} \qquad (2.27)$$

$$U_{pp} \cong \lambda_{pp} r_{pp}$$

2.5.2. Scheduled Maintenance Outage

A scheduled outage can be defined an outage that results when a component is deliberately taken out of service at a selected time, usually for purposes of construction, preventive maintenance or repair. Consequently, the period from the initiation of the outage until construction, preventive maintenance, or repair work is completed is said scheduled outage duration.

A scheduled outage is not included in the reliability evaluation of a load point if, by this action alone, the load point is disconnected. So, the maintenance is simulated only on overlapping events associated with parallel and meshed networks. Sequence "maintenance followed by a forced outage's considered, because the reverse sequence would cause disruption of the load point due to the maintenance outage alone".

Let $\lambda_i^{"}$ and $r_i^{"}$ be the maintenance outage rate and maintenance time of component i, λ_j and r_j be the forced outage failure rate and repair time of component j and λ_{pm}, r_{pm} and U_{pm} be the rate, duration and annual time of the load point due to forced outages overlapping a maintenance outage.

For two components in parallel it may be written:

$$\lambda_{pm} = \lambda_1^{"}(\lambda_2 r_1^{"}) + \lambda_2^{"}(\lambda_1 r_2^{"})$$

$$U_{pm} = \lambda_1^{"}(\lambda_2 r_1^{"})\frac{r_1^{"} r_2}{r_1^{"} + r_2} + \lambda_2^{"}(\lambda_1 r_2^{"})\frac{r_1 r_2^{"}}{r_1 + r_2^{"}} \qquad (2.28)$$

$$r_{pm} = U_{pm} / \lambda_{pm}$$

2.5.3. Temporary and Transient Forced Outages

A special type of failures that do not damage the component is very important and their effect on the customer must be taken under consideration. An example of this type is a lighting strike which trips the protection breakers or blows the protection fuses. Service is restored by closing the breakers automatically or manually or replacing the fuses. In either case the outage time is relatively small and may be negligible with automatic reclosure. Non-demaged type of failure will be subdivided into transient forced outages which are restored by automatic switching and temporary forced outages which are restored by manual switching.

An outage whose cause is immediately self-clearing so that the effected component can be restored to service either automatically or as soon as a switch or circuit breaker can be reclosed or a fuse replaced is called transient/temporary forced outage. Consequently, the period from the initiation of the outage until the component is restored to service by

switching or fuse replacement is called transient/temporary forced outage duration.

The overlapping events that could be considered are:

(i) a temporary or transient failure overlapping a temporary or transient failure;

(ii) a temporary or transient failure overlapping a permanent failure;

iii) a temporary or transient failure overlapping a scheduled maintenance outage.

(i)Temporary/transient failures overlapping temporary/transient failures

These events may be neglected because the probability is small and contributes very little to the overall result.

(ii)Temporary/transient failures overlapping a permanent failure

In this case it may be written:

$$\lambda_{pt} = \lambda_{t1}\lambda_2(r_{t1} + r_2) + \lambda_1\lambda_{t2}(r_1 + r_{t2}) = \lambda_a + \lambda_b$$

$$U_{pt} = \lambda_a \frac{r_{t1}r_2}{r_{t1} + r_2} + \lambda_b \frac{r_1 r_{t2}}{r_1 + r_{t2}} \qquad (2.29)$$

$$r_{pt} = U_{pt} / \lambda_{pt}$$

where λ_{ti} is transient or temporary failure rate of component i, r_{ti} is restoration or reclosure time following temporary or transient failure of component i. λ_j, r_j are permanent failure rate and repair time of component j.

(iii)Temporary/transient failures overlapping a maintenance outage

In this case it may be written:

$$\lambda_{tm} = \lambda_1''(\lambda_{t2} r_1'') + \lambda_2''(\lambda_{t1} r_2'')$$

$$U_{tm} = \lambda_1''(\lambda_{t2} r_1'')\frac{r_1'' r_{t2}}{r_1'' + r_{t2}} + \lambda_2''(\lambda_{t1} r_2'')\frac{r_{t1} r_2''}{r_{t1} + r_2''} \qquad (2.30)$$

$$r_{tm} = U_{tm} / \lambda_{tm}$$

Finally , the distinct failure modes of a component can be represented as:

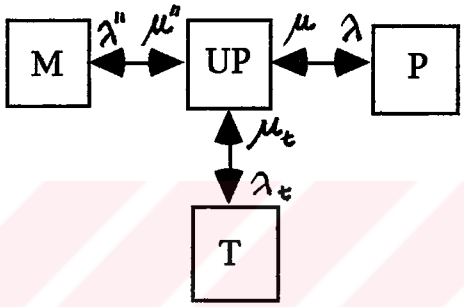


Figure 2.5 Distinct Failure Modes of a Component

where: P.... Permanent outage
T.... Transient/temporary outage
M... Maintenance outage

2.5.4. The Effect of Active Failures

Of course if switching actions are wanted to be considered a three state model is required, the three states being:

(i) state before the fault
(ii) state after the fault but before isolation
(iii) state after isolation but before repair is completed.

This set of states can be shown in Figure 2.6.

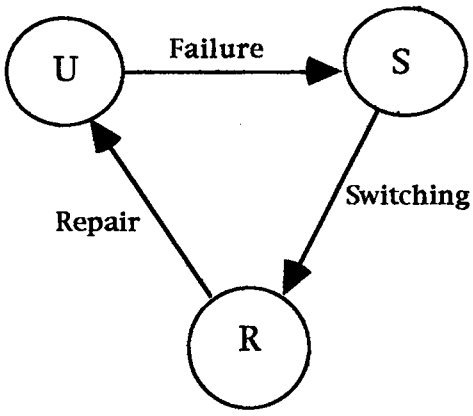


Figure 2.6 Three state component model

In some cases, however, breakers are not required to operate, e.g. open circuits and inadvertent operation of breakers. In these cases, a two state model is only necessary. These states are:
(i) state before the fault
(ii) state after the fault but before repair is completed
This set of states can be shown in Figure 2.7.

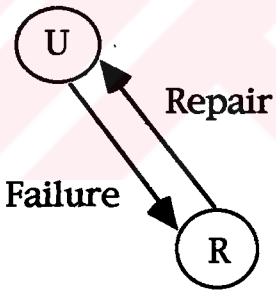


Figure 2.7 Two-state component model

The two modes of failure, one leading to state R and the other to state S, have been designated as passive and active failures [4].

Passive event: A component failure mode that does not cause operation of protection breakers and therefore does not have an impact on the remaining healthy components. Service is restored by repairing or replacing the failed component .

Active event: A component failure mode that causes the operation of the primary protection zone around the failed component and

can therefore cause the removal of other healthy components and branches from service. The actively failed component is isolated and the protection breakers are reclosed. However, the failed component itself can be restored to service only after repair or replacement [4].

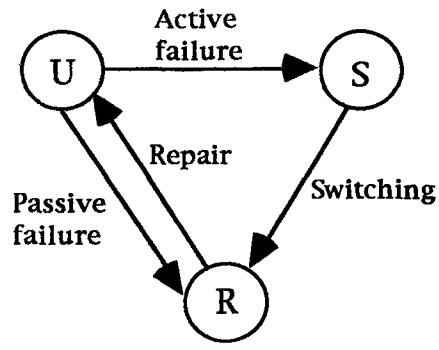


Figure 2.8 State space diagram for active and passive failures

It can be seen that, if a passive event leads to the failure of given load point, i.e. state R is a load point failure event, then an active event on the same component also leads to the failure of the load point. The reverse situation may not be true because state R need not be a load point failure event when state S is. Sequences following passive and active failures can be represented as [4]:

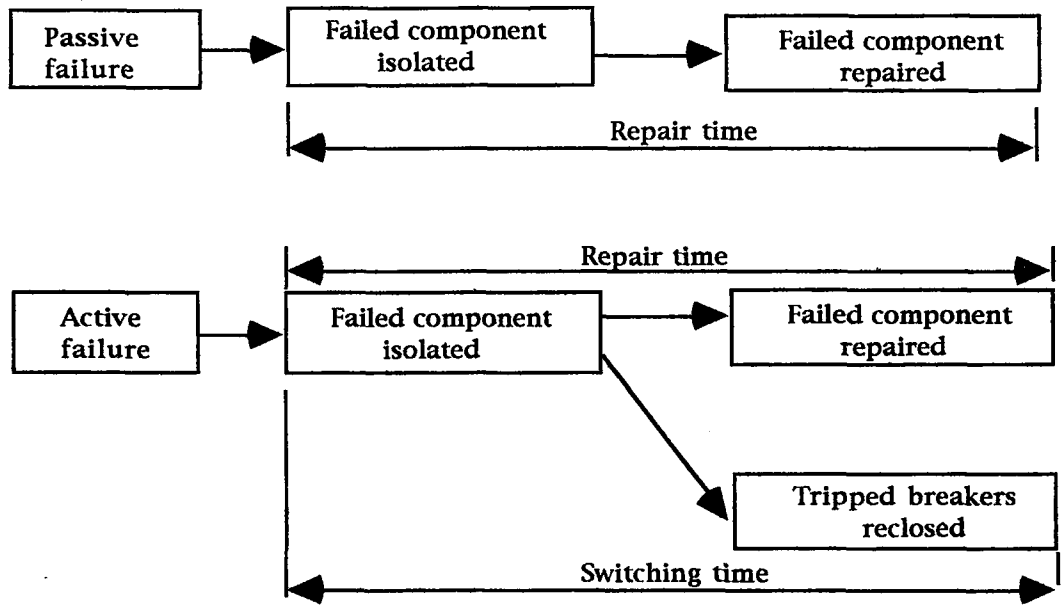


Figure 2.9 Sequences following passive and active failure

As it was said most power system components go through the two-state cycles. The failure of some components will put the system through a more complicated routine than the two-state representation. Therefore three - state model must be used [5].

In order to find all possible system failure events it is necessary to screen all single and double failure events (higher failure events will be neglected).

In addition to finding the actual system failure events, each one of these must be classified according to the way system operation is restored after the fault. For example, in some cases system can be restored through suitable switching (S-type failure) and in other cases, only after the repair of at least of the faulted components (R-type failure).

If, $i^{(r)}j^{(r)}$ is a system failure event of type R, then $i^{(r)}j^{(s)}$ is in the same time system failure event of type S but it is not a system failure event (switching will transfer the system from state S to state R).

Since the probability of state $i^{(s)}j^{(s)}$ occurring is assumed to be negligible, interaction between $i^{(r)}$ and $j^{(s)}$, $i^{(s)}$ and $j^{(r)}$ and $i^{(r)}$ and $j^{(r)}$ will be considered. So, the basic equations that incorporate three-state component model are as follow:

component 1 actively failed :

$$\lambda_{ap} = \lambda_1^a$$
$$r_{ap} = s_1 \qquad (2.31)$$

active failure of component 1 overlapping a total failure of component 2

$$\lambda_{ap} = \lambda_1^a(\lambda_2 s_1) + \lambda_2(\lambda_1^a r_2)$$
$$\lambda_{ap} = \lambda_1^a \lambda_2 (s_1 + r_2) \qquad (2.32)$$

$$r_2 \rangg s_1$$
$$\lambda_{ap} \cong \lambda_1^a \lambda_2 r_2 \qquad (2.33)$$
$$r_{ap} = \frac{s_1 r_2}{s_1 + r_2} \cong s_1$$

active failure of component 1 overlapping a maintenance outage of component 2 :

$$\lambda_{am} = \lambda_2''(\lambda_1^a r_2'')$$
$$r_{am} = \frac{s_1 r_2''}{s_1 + r_2''} \cong s_1 \qquad (2.34)$$

2.6. Reliability Indices and Their Applications

2.6.1. Basic Reliability Indices

Three basic reliability indices, expected failure rate, average outage duration and average annual outage time are evaluated for any load point of any meshed system. These three basic indices permit a measure of reliability at each load point to be quantified and allow additional indices to be evaluated.

2.6.2. Reliability Indices Derived from Basic Indices

a) System Average Interruption Frequency Index - SAIFI

This index is defined as the average number of interruptions per customer served per time unit. It is estimated by dividing the accumulated number of customer-interruptions in a year by the number of customers served [6].

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \qquad (2.35)$$

b) Customer Average Interruption Frequency Index - CAIFI

This index is defined as the average number of interruptions experienced per customer affected per time unit. It is estimated by dividing the number of customer interruptions observed in a year by the number of customers affected [6].

c) System Average Interruption Duration Index - SAIDI

This index is defined as the average interruption duration for customers served during a year. It is determined by dividing the sum of all

customer sustained interruption duration during the year by the number of costumers served during the year, i.e. [6]

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{2.36}$$

d) Customer Average Interruption Duration Index- CAIDI

This index is defined as the interruption duration for customers interrupted during a year. It is determined by dividing the sum of all customer sustained interruption duration during the specified period by the number of sustained customer interruptions during the year, i.e. [6]

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i} \tag{2.37}$$

e) Average Service Availability Index- ASAI

This is the ratio of the total number of customer hours that service was available during a year to the total customer hours demanded. Customer hours demanded are determined as the twelve month average number of customers served times (8760). The complementary value to this index, i.e. the Average Service Unavailability Index (ASUI) may also be sometimes used [6].

$$ASAI = \frac{\sum N_i * 8760 - \sum U_i N_i}{\sum N_i * 8760} \tag{2.38}$$

$$ASUI = 1 - ASAI$$

2.6.3. Load and Energy Oriented Indices

One of the important parameters required in the evaluation of load and energy oriented indices is the average load at each load point busbar [4].

The average load is given by: $L_a = \frac{E_d}{t}$

where: E_d = total energy demand in period of interest

t = period of interest

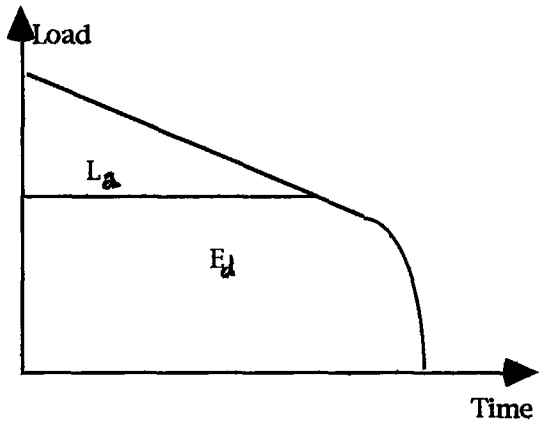


Figure 2.10 Load-duration curve

a) **Energy not Supplied Index, ENS**

ENS = total energy not supplied by the system $\sum L_{a(i)}U_i$

where $L_{a(i)}$ is the average load connected to load point i

b) **Average Energy not Supplied**

$$AENS = \frac{\sum L_{a(i)}U_i}{\sum N_i} \qquad (2.39)$$

The customer and load oriented indices are very useful for assessing the severity of system failures in future reliability prediction analysis. They can also be used, however, as a means of assessing the past performance of a system. In fact these indices are widely used in assessment the past performance than as measures of future performance. Assessment of system performance is a valuable procedure for three reasons:

1) It helps to identify weak areas and the need for reinforcement

2) It establishes existing indices which serve as a guide for acceptable values in future reliability assessment

3) It enables predictions to be compared with actual operating experience.

CHAPTER III
DISTRIBUTION SYSTEM RELIABILITY ANALYSIS

3.1. Historical Background and Basic Terminology

The scope of interest will be reliability analysis of distribution system. The distribution system is portion of the electric power system that links the bulk power source or sources to the customer's facilities. Distribution substation, distribution transformerrs, primary feeders, and customer's connections all form different parts of what can generally be called a distribution system. Distribution system reliability evaluation therefore consist of assessing how adequately the different parts are able to perfor their intended function. As we said distribution system links the bulk system and customer. Their links are radial in nature and therefore susceptible to outage due to a single event. It has been stated that 80% of all interuptions occur due to failures in the distribution system [10].

Why do we have a need to determine the reliability of distribution system? Firstly, it is necessary to ensure a reasonable balance in the reliability of the various constituent parts of a power system (i.e., generation, transmission, distribution). Secondly, a number of alternatives are available to the engineer in order to achive aceptable customer reliability, including reinforcement schemes, improvements in maintenance policy, alternative operating policy etc.. Of course it is not possible to determine the merits of different alternatives without utilizing quantitative reliability evaluation.

In general, the basic activities associated with reliability assessment can be devided into two segments of measuring past performance and predicting future performance. Both applications involve the collection of system outage data. Of course the level of complexity of the outage data collection procedure is entirely dependent upon the use to be made of the data.

The analysis of distribution system reliability analysis may involve two main groups [4]:

a) Total Loss of Continuity (TLOC)

b) Partial Loss of Continuity (PLOC)

The TLOC technique is based on the concept of expected failure rate, and average outage duration method. For each load point, the expeted failure rate, average outage duration and average annual outage time are evaluated. These three basic indices permit a measure of reliability at each load point. The criterion for determining a load point failure events are "loss of continuity", i.e., a load point fails only when all paths between the load point and all sources are disconnected. This assumes that the system is fully redundant and ay branch is capable of arrying all the load demanded of it. For this reason, the previous "loss of continuity" criterion is best described as "Total Loss of Continuity" (TLOC).

However, a system outage or failure event may not lead to TLOC but may cause violation of a network constraints, e.g. overload or voltage violation, which necessitates that the load of some or all of the load points be reduced. If the load and energy indices are to be evaluated, evaluation of PLOC events becomes of great significance, of course, it is necessary to find all events that would lead to disturbance of system constraints (line overloads and voltage violation). A load flow analysis must be used in order to to find whether or not a network constraint has been violated. As the most used criteria for determining PLOC events is line overload. If any of the outage combinations causes a line overload, and according to the accepted load shedding policy, reliability indices for each outage combination can be evaluated [4,7].

Quantitative assessment techniques have been initiated in 1964 with introducing the concept of failure bunching in parallel facilities due to storm-associated failures, together with some basic techniques whih have proven to be useful in many areas of application. Introduction the procedures for calculating failure rate and average duration was a major contribution [8].

The application of Markov processes to transmission system evaluation was considered. Tranmission components are assumed to operate within a 2-state fluctuating environment described by normal and stormy weather conditions. Markov processes are used to determine the system failure rate and the probabilities of failure for simple configurations and to illustrate the bunching effect of storm associated failures on parallel facilities. A set of equations for series/parallel system reduction including adverse weather and permanent, temporary, maintenance failure modes was obtained. Also, concept of utilizing minimal cuts in complex configuration was presented.

The incorporation of switching action in the evaluation of transmission circuits including protective elements was introduced [9,10]. A reliability model was described which more closely simulates the states of power systems during faukts than do the usual "two-state" models. This was achieved by modeling the effects of component failures on the system through three-state cycles, which include a state following the fault and another after the failed device is isolated, through switching, for repair. This was the base for implementing the procedure for evaluating substation and switching station reliability and a quantitative comparison of the reliability of fundamental station configurations. The concept of active and passive failure modes in systems containing protective elements was introduced. The utility of the techniques developed for transmission and distribution system evaluation including all possible failure modes together with active and passive ones were applied to the auxiliary systems of power station.

Distribution system reliability evaluation by incorporating operational constraints was considered [5]. Effect of comon mode failures in parallel and meshed system were considered by using theory of minimal cut sets.

The question of data has always been of concern in quantitative reliability evaluation and although most utilities collect data, in some form, on transmission and distribution system components, there is relatively little generally published material. The approach in collecting transmission outage data and type of data that can be collected was recommended by one utility group [11].

The development of data collection systems and analytical techniques that can be used in optimizing planning, design, and operation of these facilities provide a very important system benefits

Several papers have been published containing algorithms for calculating the reliability of networks. Most of them are based on the minimal cut set theory and proposes equations to calculate three reliability indices,average outage rate,average outage duration and average annual outage time for each minimal cut set. Before it will be explained basic definitions and terms are given.

Minimal Path: A path between the input and the output of a system is a set of operating components required for system success.

Minimal Cut Set: is a set of system components which, when failed, causes failure of the system but when any one component of the set has not failed, does not cause system failure.

3.2. Deducing the Minimal Paths by Conventional Methods

Deducing minimal cut sets requires the determination of minimal paths.One developed method was connection matrix techniques. In this method, a connection matrix (N) is constructed from the system network or reliability diagram that defines which components are connected between the nodes of the network or diagram [2]. Unidirectional (flow is permitted in one direction only) and bidirectional (flow is permitted in either direction) components are included. Connection matrix can be constructed in which zero indicates that there is no connection between two nodes and unity represents a connection between a node and itself, this being the value of the elements on the diagonal. The essence of this method of solution is to transform this basic connection matrix into one which defines the transmission of flow between the input and the output, i.e., between the two nodes of interest. There are two methods that use formed connection matrix.

a)Node Removal: All nodes of the network that are not input or output are removed by sequential reduction of the basic connection matrix until it is reduced to involve only input and output nodes [2]. Of course, in this method only passive nodes can be removed.

b)Matrix Multiplication: In this method the basic connection matrix is multiplied by itself a number of times until the resulting matrix remains unchanged. The advantage of the multiplication method compared with the node removal method is that it gives the transmission between all pairs of nodes

In either method, the nodes are assumed 100% reliable and the network cannot contain pendant nodes.

3.3. Deducing the Minimal Paths by Predecessor Method

In the case of multi-ended components and reliability of nodes not to be 1, conventional method becomes impractical.

The most powerful method for determining minimal paths and minimal cut set is predecessor method. This method has advantages such as:

1) The minimal cut sets can be deduced for every output node of the system from a single description of the system topology without requiring any simplification in the system configuration.

2) The system can have any number of input and output nodes.

3) Any element of the system can be either unidirectional or bidirectional and allows any element to be multi-ended. This is vital if the nodes themselves are not 100% reliable.

4)This is a powerful technique particularly for comparing alternate system design.

The algorithm will be discussed in detail in the following sections. Before the algorithm will be implemented data requirements must be completed. The topology of the system is described by the branches of the network and each branch is defined by the series-connected components in the branch and by its two ends. Each branch end can be either a multi-ended component if it is less than 100% reliable or simply a system node if the branch end is 100% reliable. The input data consist of:

1) branch numbers, component numbers, and numbers of branch ends,

2) all input and output nodes,

3) unidirectional branches,

4) for each component (including the appropriate branch ends), the relevant reliability data such as failure rate, maintenance rate, average repair time, and average maintenance time.

3.3.1. Network Topology

This part of the algorithm prepares the network topology for each output node.

1) Unidirectional branches and those specified in the data must be determined. These additional branches are those connected to the input nodes and to the particular output node being considered.

2) All bidirectional branches are then duplicated so that flows can be considered in both directions.

3) This new set of branches is reordered for each output node; the original branch number is retained.

3.3.2. List of Predecessors

A predecessor of branch k is defined as any branch for which the receiving end coincides with the sending end of branch k. It is necessary to prevent a branch's having a predecessor which has an

original branch number equal to its own original branch number, i.e., a duplicated branch cannot be a predecessor of itself.

The predecessors of a branch are deduced as follows:

1) Consider each branch in turn; identify its sending end number,

2) Detect the branches that have a receiving end number equal to the sending end number of the branch for which the predecessors are being deduced,

3) Repeat 1 and 2 for all branches of the system.

To prevent a duplicated branch being considered a predecessor of itself, the following logic is used in the numbering scheme of the duplicated branches: new number of a bidirectional branch + new number of the corresponding duplicated branch = 2 * new number of the output node branch. So, the array of predecessors is the basis for deducing the minimal paths.

3.3.3. Minimal Paths

The minimal paths from all the input nodes to the output node being considered are evaluated from the array of predecessors. Commencing from the branch representing the output, the paths are traced in terms of branches back to the input nodes. If a loop is established in this process, the path being created is eliminated. When any one of the input points is reached, i.e., (-1) represents the end of the path, minimal path is formed.
The new branch numbers are now replaced by their original numbers and the array of minimal paths is then obtained.

The minimal paths are then obtained in terms of the system components by replacing each branch by its constituent components. During this process it is necessary to prevent a component's being duplicated in the same path. In deducing these paths, unidirectional, bidirectional, multiended components and multi-input nodes have been considered. In the case of multi-ended components, these have been

included by defining them as system nodes and also as system components in the input data. The present algorithm enables both unidirectional and bidirectional branches to be included and also enables multi-ended components to be assessed. Furthermore, tracing paths by means of branches instead of components appreciably reduces the computation time particularly when many components exist in each branch.

3.4. Deducing the Minimal Cut Sets

In a typical system the number of nodal minimal cut sets is considerably greater than the number of associated paths. Computationally, the easiest way of deducing the minimal cut sets is by representing in binary form all the minimal paths as well as the cuts that are subsequently generated.

3.4.1. Minimal Paths in Binary Form

To deduce the minimal cut sets the previous minimal path array is overwritten by the paths represented in a binary form [12]. To deduce the first order minimal cuts it is necessary to search columns in which every element is unity. These are then replaced by zeros to prevent nonminimal cuts which contain first order minimal cuts from being detected. The maximum order of a minimal cut is equal to the number of minimal paths.

The second order minimal cuts are calculated by adding logically two columns at a time of the path array. If any of the resulting columns has every element equal to unity, the combined columns (components) form a second order minimal cut.

This process is continued by logically adding three columns at a time to detect a third order cut and so on until cuts of all required orders are deduced. Each time a cut of order 3 or greater, it is necessary to check whether it includes any minimal cut sets of order between 2 and n-1. If it does, the cut is rejected as a non-minimal cut. To do this the following technique is used.

Consider two cuts, I and J; being a minimal cut set of order n_i and J a cut set of order n_j where $n_i \langle n_j$. Consider the following sets:

$\{I\} = \{a_i, b_i, c_i .....\}$ with n_i elements

$\{J\} = \{a_j, b_j, c_j .....\}$ with n_j elements

Create a set

$\{A\} = \{I\} \cap \{J\}$. If the number of non-zero elements of $\{A\}$ is equal to n_i, then cut J is non-minimal and is rejected.

3.4.2. Minimal Paths in Compact Form

When the number of components is a very large, above discussed algorithm becomes impractical. So, minimal paths expressed in compact form is more practical [12].

To deduce the first order minimal cut sets, every component is considered, one at a time, and checked whether it belongs to every path; if it does it is a first order cut set. This component number is then negated to prevent non-minimal cut sets containing first order minimal cut sets from being detected. If the paths are required for further analyses then the negated components are reset positive after all cut sets of the required order have been deduced.

To deduce the second order minimal cut sets, all combinations of two components $\{i,j\}$ for i=1 to n-1 and j=i+1 to n where n is the total number of system components are considered. If any of these combinations breaks all minimal paths, the combination is a second order minimal cut.

To deduce the third order minimal cut sets, all combinations of three components $\{i,j,k\}$ for i=1 to n-2, j=i+1 to n-1 and k=j+1 to n are considered. If any of these combinations breaks all minimal paths, the combination is a third order cut. It is then necessary to check whether these cuts are minimal cuts using the technique described.

3.5. Evaluation of the System Reliability

In order to evaluate system reliability (or unreliability), the minimal cut sets identified from the reliability network must be combined. From the definition of minimal cut sets it is evident that all components of each cut must fail in order for the system to fail. Consequently, the components of the cut sets are effectively connected in parallel and the failure probabilities of the components in the cut set may be combined using the principle of parallel systems. The system fails if any one of the cut sets occurs and consequently each cut set is effectively in series with all the other cuts.

Although the cut sets are in series, the concept of union does apply and if *i*th cut is designated as C_i and its probability of occurence is designated as $P(C_i)$ then the unreliability of the system is given by:

$$P(F) = P(C_1 + C_2 + \ldots\ldots + C_m) \tag{3.1}$$

Using the priniple of union it can be obtained:

$$P(F) = \sum_{i=1}^{m} P(C_i) - \sum_{j=2}^{m}\sum_{i=1}^{j-1} P(C_iC_j) + \sum_{j=3}^{m}\sum_{k=2}^{j-1}\sum_{i=1}^{k-1} P(C_iC_jC_k) - \ldots + (-1)^m P(C_1C_2..C_m) \tag{3.2}$$

where "+" and "." denote the union and intersection of the sets, respectively.

When the elementary probabilities involved are low, the first term of the expresion (3.2), which provides a conservative evaluation of P(F), is sufficient:

$$P(F) \cong \sum_{i=1}^{m} P(C_i) \tag{3.3}$$

In the next consideration two basic aproximation are made. The first aproximation assumes that Equation (3.2) can be reduced to a summation of unreliabilities. The second aproximation is to neglect cut sets of an order greater then a certain value. This is valid if all components have reliabilities of similar value but can be invalid if a low

order cut set involves components having very high reliabilities while a high order cut set involves components having very low reliabilities.

3.6. Minimal Cut Sets Including Alternative Types of Restorarion

Up to now the subject of interest have been the cut sets when all the components of the cut are out of service, i.e., being maintained or repaired. Service is returned to normal after restoring to service at least one of the components [Figure 3.1].

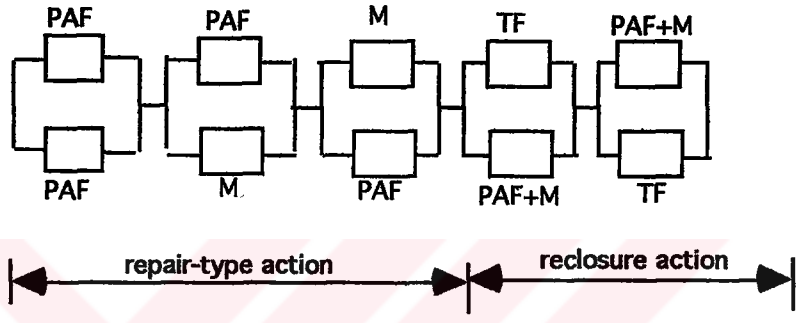


Figure 3.1 Failure modes of 2-nd order cut sets

The second group are those minimal cut sets when all the components of the cut are out of service but service can be restored by closing a normally open path. The reliability indices associated with the second type of cut sets can be calculated using the following approach.

Consider:
event A; a failure event that can be eleiminated by closing any of the normally open paths k,j,1.....m.
event B; an event defined as, "at least one of the normally open paths k,j,1....m, does not fail before restoring to service one component of failure event A".

Using the conditional probability approach, the following equation can be written:

$$P(A) = P(A/B)P(B) + P(A/\bar{B})P(\bar{B}) \qquad (3.4)$$

P(A/B) is the probability of event A given that at least one of the normally open paths is always available and $P(A/\bar{B})$ is the probability of event A given that none of the normally open paths are available to restore service.For each of the events A/B and $A/\bar{B}$ the contribution to the average failure rate, the average outage durationn and average annual outage time due to forced outages and forced outages overlappinf a maintenance outage are evaluated. These indices are:
for A/B λ_1 and λ_1'' , r_1 and r_1'', U_1 and U_1''
for $A/\bar{B}$ λ_2 and λ_2'' , r_2 and r_2'' , U_2 and U_2''

To calculate the same indices for the event represented by $\bar{B}$, the minimal cut sets for the paths k,j,1....m are evaluated. Any of these that are also load point minimal cut sets are eliminated. The minimal cut sets of event $\bar{B}$ are evaluated up to second order if event A is of first order, up to first order if event A is of second order and are not evaluated if event A is of third order.From these minimal cut sets the reliability indices of the "element" equivalent to the normally open paths are evaluated; these being defined as λ_e and λ_e'' , r_e and r_e'' , U_e and U_e''.

The normally open breakers, which are first order cut sets of the minimal paths k,j,1...m are also considered in order to include the stuck breaker probability P_s of this equivalent element.

So, from Equation (3.4) it can be written:

$$U_a = U_1\left[1-(U_e+P_s)\right]+U_2\left(U_e+P_s\right) \tag{3.5}$$

$$U_a'' = U_1''\left(1-U_e''\right)+U_2''U_e'' \tag{3.6}$$

The following equations can also be obtained:

$$\lambda_a = \lambda_2\left(1+\lambda_e r_2\right) \tag{3.7}$$

$$\lambda_a'' = \lambda_2''\left(1+\lambda_e'' r_2''\right) \tag{3.8}$$

$$r_a = \frac{U_a}{\lambda_a} \tag{3.9}$$

$$r_a'' = \frac{U_a''}{\lambda_a''} \tag{3.10}$$

Having calculated the reliability indices of all the independent failure events of each busbar, the overall busbar indices are evaluated by simply adding the expected failure rates and the annual outage times of each failure event.

Previously described method is explained using the following system:

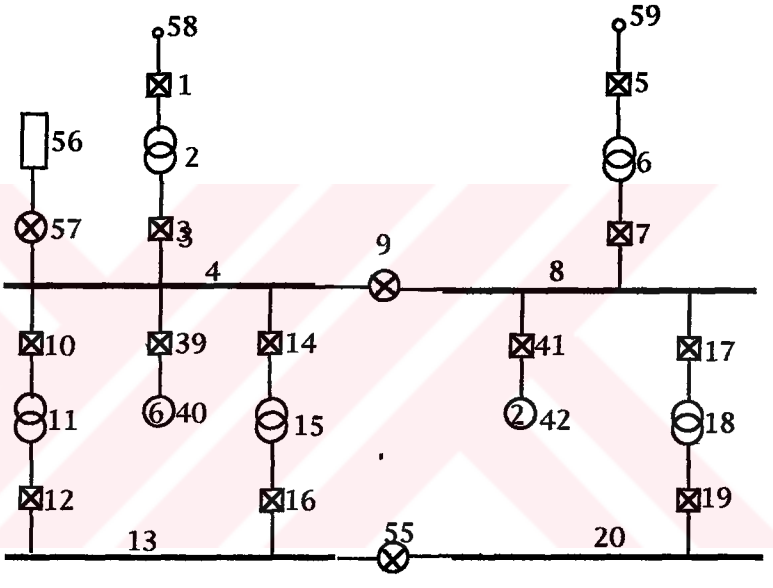


Figure 3.2 Typical auxilary system

All breakers are assumed normally closed, exept encircled ones. Component 56 is a standby generator, normal supply sources are 58 and 59.

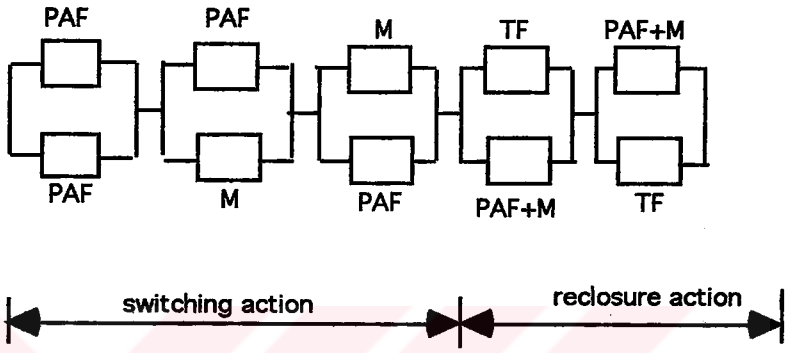
It is evident that there are two normally closed paths from sources 58 and seven normally open paths from sources 56, 58 and 59 through the normally open breakers 9,55 and 57.

Consider the failure of breaker 1 and the subsequent restoration of supply to busbar 13. The failure rate of this event is λ_2 and the outage time if a normally open path was not available would be r_2.

If however at least one normally open path is available then the failure rate remains unchanged but the outage time becomes the switching time for restoring the supply.

λ_e, Ue, $\lambda_e^{"}$, $U_e^{"}$ are found from the minimal cut sets of the normally open paths to busbar 13 that are not already included in the failure modes of busbar 13

So, if there are normally open breakers, failure events restored by closing a normally open paths can be represented as follows:



Fifure3.3 Failure modes of 2-nd order cut sets eliminated by normally open breakers

3.7. Non-Basic Minimal Cut Sets

All minimal cut sets considered up to now have taken under consideration only passive type of failures. These type of minimal cut sets will be called "**basic minimal cut sets**" .

There can be some components in the system which are not on any direct transmission path to the load point under consideration but their active failures can interrupt some or all the direct paths.

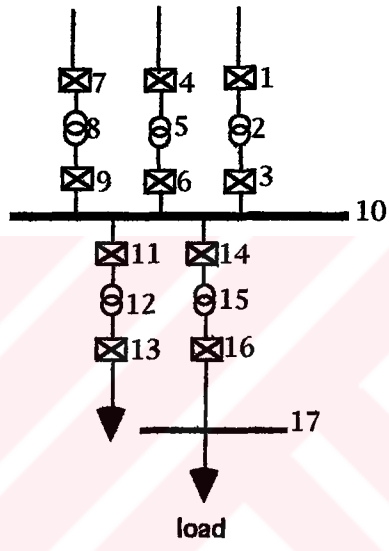


Figure 3.4 Portion of the distribution system

The effect of components 11,12,13 is very important on the reliability indices calculated at busbar17. For such components, the passive outage rates values are assigned zero values. The average outage time is also assigned a zero value. Maintenance outages of such components cannot interrupt the direct transmission paths and thus the maintenance rate and outage time are assigned zero values. The active outage rate and switching time parameters are the actual values associated with the component. If the component cannot be switched out, then switching time is assigned a value equal to component repair time.

Of course,in order to determine the reliability degree of specified bus the effect of active failures must be taken under consideration. In addition, stuck probability of protection breakers must

be incorporated into account. All mentioned realistic situation in distribution systems are represented by adequate minimal cut sets. These type of minimal cut set will be called **"non-basic minimal cut sets".**

"Stuck Probability": This value represents the probability of a breaker or a switch being stuck when called upon to operate. In the case of normally open breakers or switches, this value is the probability of a breaker or switch not closing when called upon to do so. The stuck breaker probability is estimated from the ratio of the number of times the breaker fails to operate when called upon to do so to the total number of times the breaker is called upon to operate.

In order to show procedure for determining the non-basic minimal cut sets, consider the arbitrary selected bus *i* and portion of distribution system associated to given bus, Figure 3.5.

In order to simulate all active failures occurring at various type of system components, i.e., to obtain non-basic minimal cut sets of first, second order and incorporating stuck probabilities of the protection breakers, consider Figure 3.5.

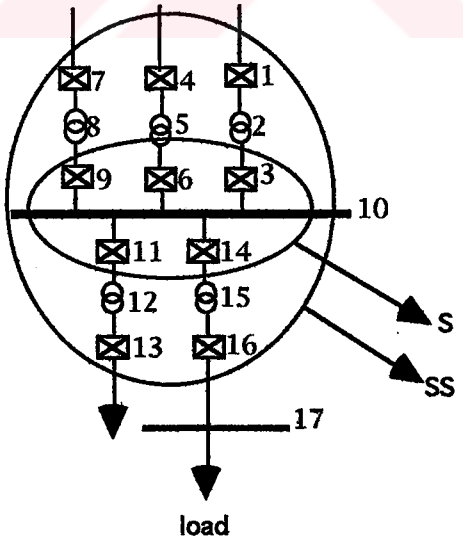


Figure 3 .5 Representation of sel ected groups

For each busbar of the given network it is necessary to define two groups of elements, group S and SS . The first group will include all elements (components) up to first (primary) breakers for all branches connected to the busbar. The second group will include all components up to second breakers for all branches connected to the busbar. From this, it is possible to conclude that probability of simultaneously stuck more than two breakers is negligible.

In order to simulate active failures of components, all elements that belong to S group must be considered(only the busbars presented in basic minimal cut sets and those components connected to those busbars). From these non-basic cut sets only minimal cut sets should be found (non-basic minimal cut set must not be included in basic minimal cut sets).

Components from the SS group and stuck probability of the adequate protection breaker will describe active failures and inadequate operation of the protection system. In the same manner only minimal cut sets should be found.

According to the previous terminology, non-basic minimal cut sets can be classified as non-basic minimal cut sets of first and second order.

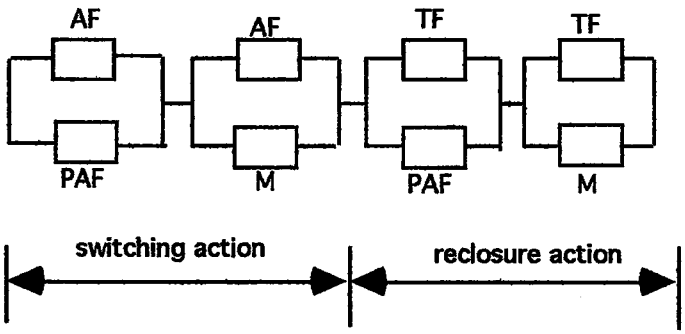


Figure 3.6 Failure modes of 2nd order cut set

CHAPTER IV
SYSTEM STUDY

In order to illustrate previously described algorithm for determining the reliability indices of a given bus, let consider a typical distribution system and adequate component reliability data (Figure 4.1).

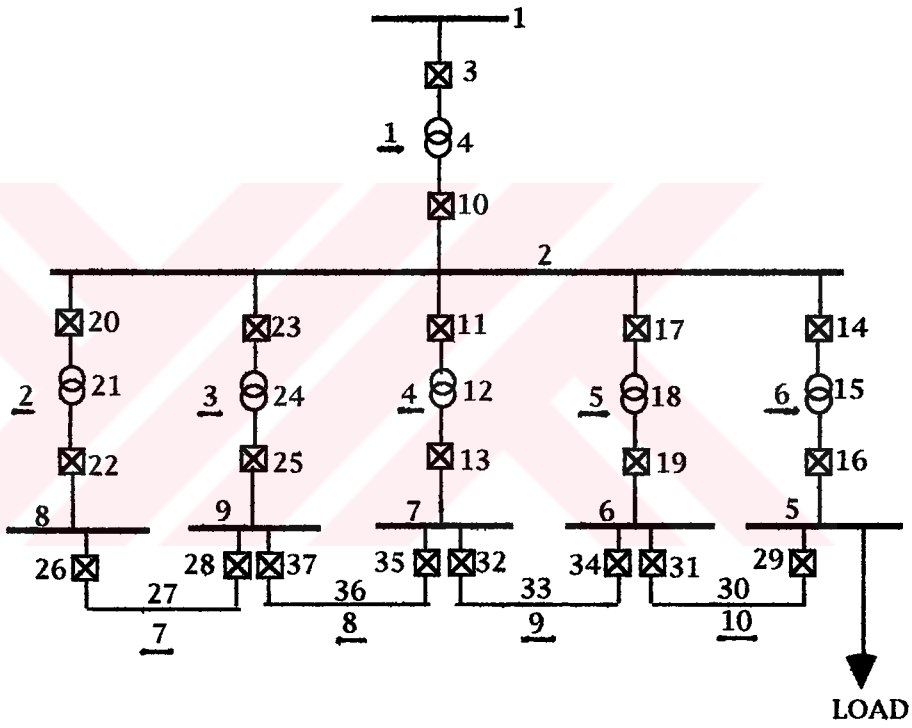


Figure 4.1. Typical distribution network

This system may be considered as a radial distribution network with interconnection between the low voltage busbars. In the Figure 4.1 ⊠ represent a switchgear. At a low voltage side interconnection is performed by the cable ties. The busbar of interest will be busbar 5 and all reliability indices will be determined for that busbar.

In order to perform a complete reliability analyses for the given distribution system, component reliability data must be known. For the given distribution system component reliability data is given in Table 4.1.

Table 4.1 Component reliability data

Component	Annual failure rate		repair time	Switching time	Stuck probability	Maintenance	
	total	active	[h]	[h]		annual rate	time
1,2,5,6, 7,8,9	0.024	0.024	3	2	-	-	-
3,10	0.23	0.10	15	2	0.005	-	-
4	0.10	0.10	24	1	-	-	-
11,13,14,16, 17,19,20,22, 23,25,26,28, 29,31,32,34, 35,37,	0.23	0.10	20	1	0.005	0.4	12
27,30,33,36	0.12	0.12	10	1	-	0.1	2
12,15,18,21, 24.	0.10	0.10	500	1	-	0.5	48

Annual failure rate, maintenance annual rate are given as failure/year and repair/year respectively.

According to the Figure.4.1 a topology of the given distribution system can be represented as follows in Table 4.2., that describes nature of all branches, their ends and components included in each branch.

Table 4.2 System topology

brunch number	branch ends		components	
1	1	2	3,4,10	
2	2	8	20,21,22	unidirectional
3	2	9	23,24,25	unidirectional
4	2	7	11,12,13	unidirectional
5	2	6	17,18,19	unidirectional
6	2	5	14,15,16	
7	9	8	28,27,26	bidirectional
8	9	7	37,36,35	bidirectional
9	6	7	34,33,32	bidirectional
10	6	5	31,30,29	

As a step one in analysis, modified table must be obtained. That table consist of the new branch list for the specified node (in our case node 5). That table can be constructed as follows:

Table 4.3 New branch list for node 5

New branch number	Original branch number	Sending end	Receiving end	Comments
1	2	2	8	Specified unidirectional branches
2	3	2	9	
3	4	2	7	
4	5	2	6	
5	1	1	2	Input node branches-unidirectional
6	6	2	5	Branches connected to output node-unidirectional
7	10	6	5	
8	7	9	8	Bidirectional branches
9	8	9	7	
10	9	6	7	
11	-	5	0	Output node branch
12	9	7	6	Duplicated branches
13	8	7	9	
14	7	8	9	

As a step 2 list of the predecessors must be found. To prevent a duplicated branch being considered a predecessor of itself, the logic described in the previous chapter will be used. So the the array of predecessors for node 5 is as follows in Table 4.4.

Table 4.4 Array of predecessors for node 5

New branch number	Predecessors
1	5
2	5
3	5
4	5
5	-1
6	5
7	4,12
8	2,13
9	2,14
10	4
11	6,7
12	3,9
13	3,10
14	1

In the above table, -1 denotes input node.

As a step 3 minimal paths must be found. The minimal paths are evaluated from the array of predecessors. If a loop is established in this process, the path being created is eliminated. So the minimal paths expressed by the number of branch is listed as follows in Table 4.5.

Table 4.5 Minimal paths expressed by the number of the branches

Minimal paths Number	Branches included in minimal paths
1	(-1),5,6,11
2	(-1),5,4,7,11
3	(-1),5,3,12,7,11
4	(-1),5,2,9,12,7,11
5	(-1)5,1,14,9,12,7,11

The new branch numbers (Table 4.5.) are replaced by their original numbers according to the Table 4.3.

Table 4.6 Minimal paths expressed by the numbers of original branches

Minimal paths Number	Branches included in minimal paths
1	input,1,6,output
2	input,1,5,10,output
3	input,1,4,9,10,output
4	input,1,3,8,9,10,output
5	input,1,2,7,8,9,10,output

The minimal paths are then expressed in terms of the system components including the busbars by replacing each branch by its constituent components according to the Table 4.2.

Table 4.7 Minimal paths expressed by the components

Minimal paths Number	Number of the components in minimal paths
1	1,3,4,10,2,14,15,16,5
2	1,3,4,10,2,17,18,19,6,31,30,29,5
3	1,3,4,10,2,11,12,13,7,32,33,34,6,31,30,29,5
4	1,3,4,10,2,23,24,25,9,37,36,35,7,32,33,34, ,6,31,30,29,5
5	1,3,4,10,2,20,21,22,8,26,27,28,9, ,37,36,35,7,32,33,34,6,31,30,29,5

Previously obtained minimal paths expressed in binary form and using the principle of Boolean algebra, minimal cut sets can be determined. Minimal cut sets up to third order will be considered.

BASIC MINIMAL CUT SETS:

basic minimal cut sets I st order
1
2
3
4
5
10

basic minimal cut sets II nd order
6,14
6,15
6,16
14,29
14,30
14,31
15,29
15,30
15,31
16,29
16,30
16,31

In order to simulate active failures of the components Non-Basic Minimal Cut Sets must be found. Looking at the basic minimal cut sets previously obtained it can be conclude that nodes 1,2,5, and 6 are present in either basic minimal cut of the Ist order or basic minimal cut sets of the IInd order. So, for each node (1,2,5,6) S and SS groups must be formed as follows:

Table 4.8 S and SS groups for adequate node

Node number	1
S	3
SS	4,10

Node number	2					
S	10	20	23	11	17	14
SS	3,4	21,22	24,25	12,13	18,19	15,16

Node number	5	
S	16	29
SS	14,15	30,31

Node number	6		
S	19	31	34
SS	17,18	29,30	32,33

According to the Table 4.8., simulation of active failures is implemented only on the components presented in group S, and simulation of active failures with stuck probability of adequate protection breakers is implemented only on the components presented in the group SS. Satisfying the minimum principle i.e., considering only cut sets that didn't appear as basic minimal cut sets, non basic minimal cut sets were obtained. Of course, non basic minimal cut sets up to third order will be considered. They are listed as follows in Table4.9.

NON BASIC MINIMAL CUT SETS

Non basic minimal cut sets Ist order
11A
14A
16A
17A
20A
23A
29A
12A,11S
13A,11S
15A,14S
15A,16S
18A,17S
19A,17S
21A,20S
22A,20S
24A,23S
25A,23S
30A,29S
31A,29S

Non basic minimal cut sets IInd order
34A,14
34A,15
34A,16
19A,14
19A,15
19A,16
18A,19S,14
18A,19S,15
18A,19S,16
32A,34S,14
32A,34S,15
32A,34S,16
33A,34S,14
33A,34S,15
33A,34S,16

Table4.9. Non basic minimal cut sets(Ist and IInd order)

Where A denotes active failures of corresponding components, and S denotes stuck probability of adequate protection breakers.

After the basic and non basic minimal cut sets were determined, using the reliability data for each component, reliability indices associated with busbar 5 can be determined using the equations developed in the chapter 2. These reliability indices are listed as follows in Table 4.10.

BMCS Ist order	Forced outages		
	yr^{-1}	h	h/yr
1	0.24000E(-01)	3.0000	0.72000E(-01)
2	0.24000E(-01)	3.0000	0.72000E(-01)
3	0.23000E(+00)	15.0000	0.34500E(+01)
4	0.10000E(+00)	24.0000	0.24000E(+01)
5	0.24000E(-01)	3.0000	0.72000E(-01)
10	0.23000E(+00)	15.0000	0.34500E(+01)
Subtotal 1	0.63200E(+00)	15.0570	0.95160E(+01)

BMCS IInd order	Forced outages		
	yr^{-1}	h	h/yr
6,14	0.14493E(-04)	2.6087	0.37808E(-04)
6,15	0.13781E(-03)	2.9821	0.41096E(-03)
6,16	0.14493E(-04)	2.6087	0.37808E(-04)
14,29	0.24155E(-03)	10.0000	0.24155E(-02)
14,30	0.94521E(-04)	6.6667	0.63014E(-03)
14,31	0.24155E(-03)	10.0000	0.24155E(-02)
15,29	0.13653E(-02)	19.2310	0.26256E(-01)
15,30	0.69863E(-03)	9.8039	0.68493E(-02)
15,31	0.13653E(-02)	19.2310	0.26256E(-01)
16,29	0.24155E(-03)	10.0000	0.24155E(-02)
16,30	0.94521E(-04)	6.6667	0.63014E(-03)
16,31	0.24155E(-03)	10.0000	0.24155E(-02)
Subtotal 2	0.47513E(-02)	14.8950	0.70770E(-01)

BMCS IInd order	Maintenance overlapping forced outages		
	yr^{-1}	h	h/yr
6,14	0.13151E(-04)	2.4000	0.31562E(-04)
6,15	0.65753E(-04)	2.8235	0.18566E(-03)
6,16	0.13151E(-04)	2.4000	0.31562E(-04)
14,29	0.25205E(-03)	7.5000	0.18904E(-02)
14,30	0.71005E(-04)	5.1856	0.36820E(-03)
14,31	0.25205E(-03)	7.5000	0.18904E(-02)
15,29	0.68493E(-03)	13.9260	0.95382E(-02)
15,30	0.33105E(-03)	8.2325	0.27254E(-02)
15,31	0.68493E(-03)	13.9260	0.95382E(-02)
16,29	0.25205E(-03)	7.5000	0.18904E(-02)
16,30	0.71005E(-04)	5.1856	0.36820E(-03)
16,31	0.25205E(-03)	7.5000	0.18904E(-02)
Subtotal 3	0.29432E(-02)	10.3120	0.30349E(-01)

NBMCS	Forced outages		
Ist order	yr^{-1}	h	h/yr
11A	0.10000E(+00)	1.0000	0.10000E(+00)
14A	0.10000E(+00)	1.0000	0.10000E(+00)
16A	0.10000E(+00)	1.0000	0.10000E(+00)
17A	0.10000E(+00)	1.0000	0.10000E(+00)
20A	0.10000E(+00)	1.0000	0.10000E(+00)
23A	0.10000E(+00)	1.0000	0.10000E(+00)
29A	0.10000E(+00)	1.0000	0.10000E(+00)
12A,11S	0.50000E(-03)	1.0000	0.50000E(-03)
13A,11S	0.50000E(-03)	1.0000	0.50000E(-03)
15A,14S	0.50000E(-03)	1.0000	0.50000E(-03)
15A,16S	0.50000E(-03)	1.0000	0.50000E(-03)
18A,17S	0.50000E(-03)	1.0000	0.50000E(-03)
19A,17S	0.50000E(-03)	1.0000	0.50000E(-03)
21A,20S	0.50000E(-03)	1.0000	0.50000E(-03)
22A,20S	0.50000E(-03)	1.0000	0.50000E(-03)
24A,23S	0.50000E(-03)	1.0000	0.50000E(-03)
25A,23S	0.50000E(-03)	1.0000	0.50000E(-03)
30A,29S	0.60000E(-03)	1.0000	0.60000E(-03)
31A,29S	0.50000E(-03)	1.0000	0.50000E(-03)
Subtotal 4	0.70610E(+00)	1.0000	0.70610E(+00)

NBMCS IInd order	Forced outages yr^{-1}	h	h/yr
34A,14	0.55137E(-04)	0.95238	0.52511E(-04)
34A,15	0.57192E(-03)	0.99800	0.57078E(-03)
34A,16	0.55137E(-04)	0.95238	0.52511E(-04)
19A,14	0.55137E(-04)	0.95238	0.52511E(-04)
19A,15	0.57192E(-03)	0.99800	0.57078E(-03)
19A,16	0.55137E(-04)	0.95238	0.52511E(-04)
18A,19S,14	0.27568E(-06)	0.95238	0.26256E(-06)
18A,19S,15	0.28596E(-05)	0.99800	0.28539E(-05)
18A,19S,16	0.27568E(-06)	0.95238	0.26256E(-06)
32A,34S,14	0.27568E(-06)	0.95238	0.26256E(-06)
32A,34S,15	0.28596E(-05)	0.99800	0.28539E(-05)
32A,34S,16	0.27568E(-06)	0.95238	0.26256E(-06)
33A,34S,14	0.33082E(-06)	0.95238	0.31507E(-06)
33A,34S,15	0.34315E(-05)	0.99800	0.34247E(-05)
33A,34S,16	0.33082E(-06)	0.95238	0.31507E(-06)
Subtotal 5	0.13753E(-02)	0.99063	0.13624E(-02)

NBMCS IInd order	Maintenance overlapping forced outages		
	yr^{-1}	h	h/yr
34A,14	0.54795E(-04)	0.92308	0.50580E(-04)
34A,15	0.27397E(-03)	0.97959	0.26838E(-03)
34A,16	0.54795E(-04)	0.92308	0.50580E(-04)
19A,14	0.54795E(-04)	0.92308	0.50580E(-04)
19A,15	0.27397E(-03)	0.97959	0.26838E(-03)
19A,16	0.54795E(-04)	0.92308	0.50580E(-04)
18A,19S,14	0.27397E(-06)	0.92308	0.25290E(-06)
18A,19S,15	0.13699E(-05)	0.97959	0.13419E(-05)
18A,19S,16	0.27397E(-06)	0.92308	0.25290E(-06)
32A,34S,14	0.27397E(-06)	0.92308	0.25290E(-06)
32A,34S,15	0.13699E(-05)	0.97959	0.13419E(-05)
32A,34S,16	0.27397E(-06)	0.92308	0.25290E(-06)
33A,34S,14	0.32877E(-06)	0.92308	0.30348E(-06)
33A,34S,15	0.16438E(-05)	0.97959	0.16103E(-05)
33A,34S,16	0.32877E(-06)	0.92308	0.30348E(-06)
Subtotal 6	0.77326E(-03)	0.96438	0.74571E(-03)

Table4.10 Reliability indices associated with busbar 5

where: BMCS represent basic minimal cut sets, and NBMCS represent non basic minimal cut sets.

According to the Table 4.10, i.e., sum of subtotals will give the resultant reliability indices as follows in Table 4.11.

Table 4.11 Reliability indices of busbar 5

yr^{-1}	h	h/yr
1.34794	7.6599	10.325327

CONCLUSION

This study presents a modified method for reliability assessment of a distribution system. The modifications are made in two steps of the evaluation procedure.

First, minimal paths are determined by using the proposed "predecessor method" instead of using conventional methods based on "connection matrix".

Second, active failures and inadequate operation of circuit breakers are encountered by establishing S and SS groups of specified busbars. For the sake of less computation time and memory requirement two zones are assumed to be enough.

The proposed method is applied for a given distribution system. Three basic reliability indices evaluated at a specified busbar are compared with those presented in the literature. It was seen that the same numerical values are attained with less computational effort.

In case of non-redundant branches, system constraints must also be considered. Distribution system reliability assessment including system constraints can be considered as the future step of this study.

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BIOGRAPHY

Fahrudin Mekiç was born in Dyakovica in February 1967. He had completed his primary and secondary education in Priboy in June 1985. After he had completed his military service, he attended to the Electric Department of Electrical Faculty of Sarayevo University. He received the Bachelor of Science degree in April 1991 and attended to Master of Science Program at the same department in October 1991. Since April 1991 he has been working as research assistant at the Electric Department of Electrical Faculty of Sarayevo University. He is married and has got two children. He knows English, Turkish and Russian.