EQUIPMENT CONDITION ASSESSMENT AND ITS IMPORTANCE IN ESTIMATION AND PREDICTION OF POWER SYSTEM RELIABILITY

A Thesis by

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I have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical and Computer Engineering.

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Edwin Sawan, Committee Member

_____
Brian Driessen, Committee Member

DEDICATION

To my Aai, Pappa, Archana, Santosh, and Prashant

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ABSTRACT

Transmission and Distribution Electric Utilities have a vast amount of assets distributed over their system in the form of various equipment. As part of an asset management program, electric utilities keep focusing on the inspection and maintenance activities of these assets to improve system performance, reliability, and to ensure cost-effective expenditures. Therefore methodology that will reflect these inspection and maintenance efforts in terms of overall condition of the equipment is needed. Also techniques are needed to assess the impact of inspection and maintenance activities on the overall reliability of systems performance.

To achieve this, a methodology for the assessment of equipment condition and the estimation of the health index for transformers and circuit breakers was developed. After that, a technique to estimate the failure rate from the equipment health index was used. Then an IEEE test case was selected to demonstrate its impact on system reliability indices with the help of a predictive reliability assessment software tool, Milsoft Utility Solution.

As part of equipment condition assessment method for transformer and circuit breaker, failure modes and maintenance practices for these equipment was reviewed. Based on this review, parameters were selected for condition assessment which will provide significant information about the equipment condition and will also justify the cost and efforts. For each of the parameters, a score and weight were defined, and guidelines were developed to assign them. Also, ways in which online monitoring systems can contribute to equipment condition assessment were presented briefly.

A technique was used to convert the equipment health index into its failure rate. Then an IEEE reliability test case was modeled using the Milsoft software, incorporating this estimated failure rate and studied system's behavior in terms of reliability indices. It was observed that developing such models will provide more realistic information about the system's actual performance and will demonstrate the way in which impact of the inspection and maintenance efforts can be accounted.

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LIST OF ABBREVIATIONS

ALIDI	Average Load Interruption Duration Index
ALIFI	Average Load Interruption Frequency Index
ANSI	American National Standards Institute
ASAI	Average Service Availability Index
CAIDI	Customer Average Interruption Duration Index
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
NEMA	National Electrical Manufacturers Association
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

CHAPTER 1

INTRODUCTION

1.1 Overview

Presently, Transmission and Distribution Electric utility businesses are facing challenges of sectoral reforms, more stringent regulatory norms, increasing customer demands, rising need for customer satisfaction, and growing system reliability requirements. At the same time, electric utilities must ensure that their expenditures are cost effective and that money invested is fully utilized to improve a system's performance and reliability. A quick look at approximate cost of electricity for any electric utility is divided into 50 percent fuel cost, 20 percent Generation Cost, 5% Transmission cost and 25 percent Distribution cost [1], as shown in Figure 1.1. Hence, transmission and distribution systems are being focused to improve the overall performance of the system.

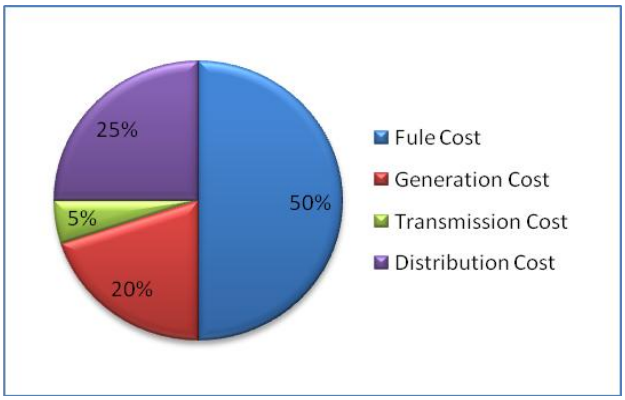

Figure 1.1: Approximate division of electricity costs

The predominant expense in transmission and distribution utilities is the cost of maintaining a system's various assets. With respect to this, as part of an asset management program, utilities keep performing various inspection and maintenance

tasks systemwide. Therefore there is a need to develop the equipment wise condition assessment technique which will utilize the vast amount of equipment inspection and maintenance related data. From the condition of equipment, health indices are derived which will provide basis for assessing the overall health of the asset. Once these equipment wise condition assessment models are developed, there is a need to integrate these condition assessment data into equipment failure rate estimation and further can be utilized in the system reliability prediction studies. Use of such system-specific failure rates will help to improve the accuracy of the system reliability studies. This approach will develop a procedure that will take into account the inspection and maintenance efforts and will assess its impact in terms of system reliability. Equipment condition assessment is a data intensive process and appears at first to be resource consuming, but with the use of data management systems and computerized maintenance management systems, it can be made more efficient and simplified.

This research work is part of an ongoing research project titled, “Integration of Asset Management and Outage Management Tasks for Distribution Systems,” sponsored by Power System Engineering Research Center (PSERC). Here, developing an equipment condition assessment technique is approached as a part of an asset management program, and its use in the estimation and prediction of a system reliability study will ultimately help to improve the outage management task.

1.2 Scope

Transmission and distribution systems are built up from various equipment, such as transformers, circuit breakers, reclosures, overhead and underground transmission and distribution lines, cables, capacitor banks, etc. To develop a technique for condition

assessment of all these equipments is very vital aspect of a utility asset management program. As a part of this research work focus on transformers and circuit breakers and have developed condition assessment technique for its various components and subsystems.

The next step is to estimate the health index and integrate it with the failure rate for each of the equipment. Figure 1.2 indicates the various steps involved in the equipment condition assessment, health index estimation and failure rate estimation.

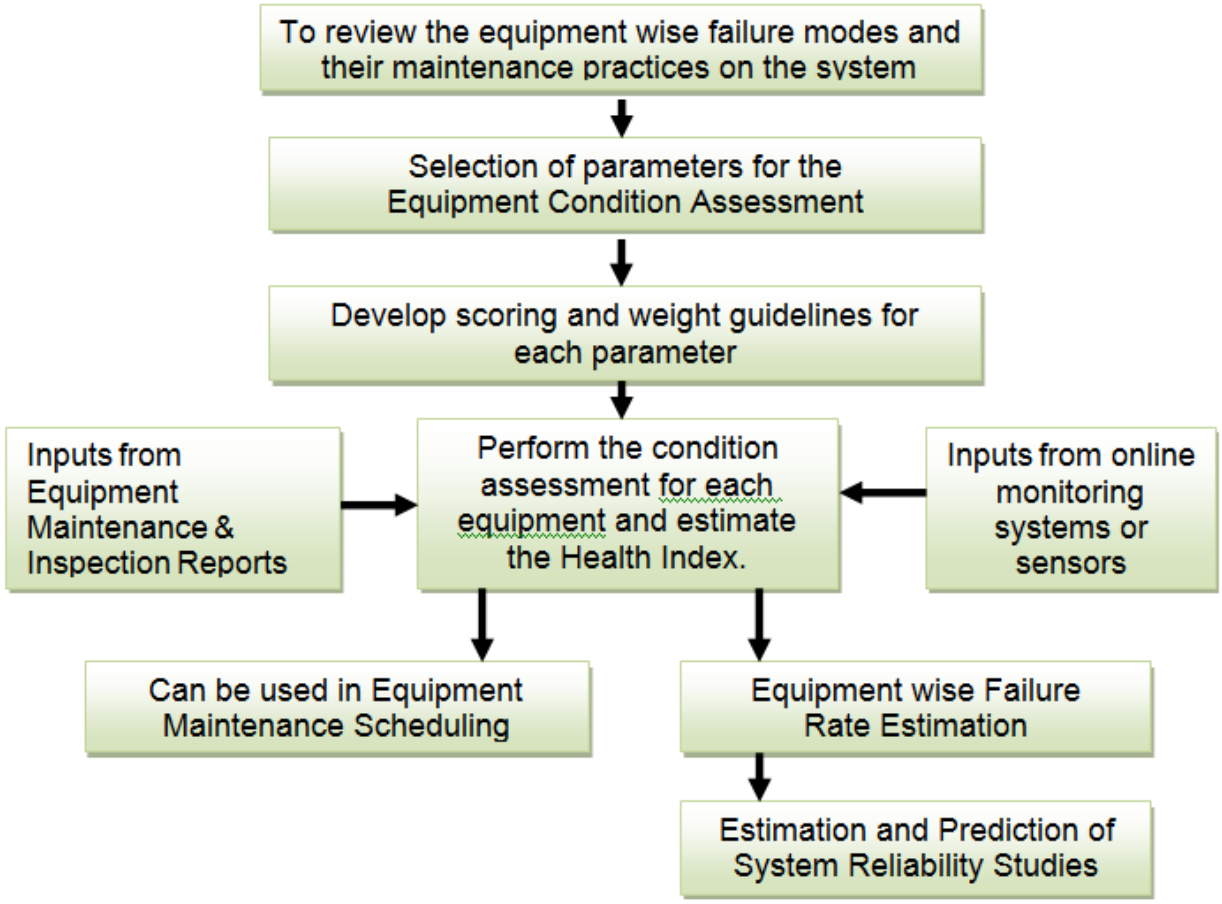

Figure 1.2: Steps involved in equipment condition assessment

First, historical failures causes and maintenance activities were reviewed for this equipment. Based on that, various parameters were finalized for equipment condition assessment. Then for each parameter, scoring and weighting guidelines were developed. Then examples were demonstrated for the condition and assessment of transformers and circuit breakers and then equipment wise health index was obtained. After this step, we have used a technique developed in reference [2] to convert the health index score into failure for that particular equipment. Then once such health index scores and failures rates were available for a system, its importance is demonstrated with an IEEE test case for a system reliability study.

1.3 Thesis Organization

The remainder of the thesis is organized as follows: Chapter 2 will discuss, in detail, about the condition assessment for a transformer. It will include a review of the observed historical failures, details of maintenance activities, parameters for equipment condition assessment, equipment failure rate estimation and the importance of online monitoring systems in condition assessment. Similarly, Chapter 3 will focus on condition assessment for a circuit breaker. Chapter 4 demonstrates the importance of system-specific failure rates in system reliability models. Chapter 5 is dedicated to discussion and conclusions on the proposed techniques, and also highlights future work in this area.

CHAPTER 2

TRANSFORMERS: CONDITION ASSESSMENT AND FAILURE RATE ESTIMATION

2.1 Introduction

Transformers are the building blocks of the power distribution system. They are available in many types, sizes, and voltage levels, and are a vital component for the operation of a distribution system. This chapter reviews the failure modes associated with power and distribution transformers along with the maintenance tasks associated to address their failure modes. Later, the overall transformer condition assessment sheet to estimate the overall health index of the transformer is developed. Then, scores from the conditions assessment sheet are used for the estimation of the failure of the transformer.

2.2 Transformers Failure Modes

Transformers are reliable devices and can provide service for a long period of time. But with age, their internal components degrade, which increases their risk of failure. In-service failure of transformers causes system outages, costly repairs, long downtime, and significant loss of revenue. Therefore, analyzing the failure modes and developing policies for monitoring and assessing transformer condition are vital tasks.

Transformer failure can occur due to various causes and conditions:

- Any forced outage due to transformer damage in service (e.g., winding damage, tap-changer failure).

- Trouble that requires removal of the transformer for repair, either in the field or at a repair facility (e.g., excessive gas production, high moisture levels, etc.).

2.2.1 Transformer Failure Statistics

Transformer failures are broadly classified as electrical, mechanical or thermal. The causes of failure can be internal or external [3], as shown in Table 2.1.

TABLE 2.1

CAUSES OF TRANSFORMER FAILURE

Causes of Transformer Failure	
Internal Causes	Insulation Deterioration, Loss of Winding Clamping, Overheating, Oxygen, Gases and Moisture in Oil, Oil Contamination, Partial Discharge, Design and Manufacturing Defects.
External Causes	Lightning Strokes, Overloads, Systems faults

The survey on transformer failure presented by International Council on Large Electric Systems (CIGRE) on failure of power transformer shows that 41 percent failures are due to on load tap changer and 19 percent are due to windings [3]. The percentage of transformer failures is shown in Figure 2.1.

For transformers without on load tap changer, 26.6 percent failures are due to windings, 6.4 percent are due to magnetic circuits, 33.3 percent are due to terminals, 17.4 percent are due to tanks and 4.6 percent are due to tap changers and 11 percent are due to other accessories [3], as shown in Figure 2.2.

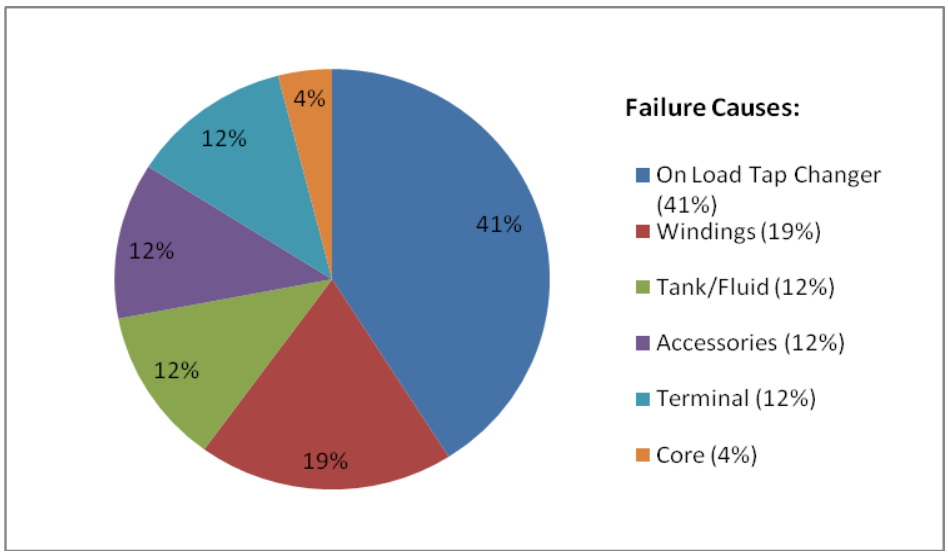

Figure 2.1: Failiure modes of transformer with load tap changer

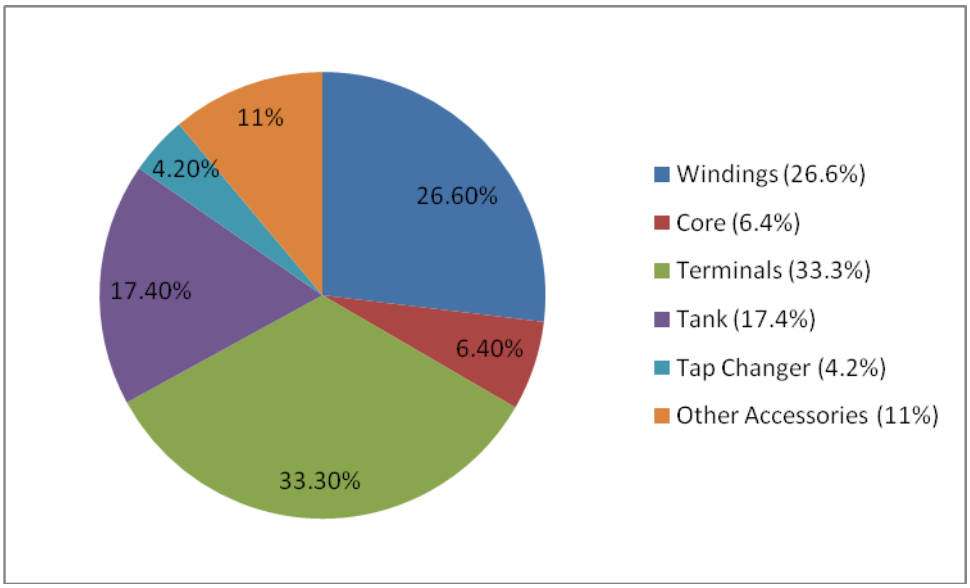

Figure 2.2: Failure modes of transformer with no load tap changer

2.2.2 Transformer Failure Causes

Transformer failure may take place due to various causes:

- **Winding Insulation and Conductor Failure**

Winding insulation and conductor failure can be caused by short circuit, overload condition, lightning, or transformer liquid contamination because of moisture and other

contaminants. A large amount of short circuit currents produces mechanical stress on the conductor's windings which deforms and destroys conductor orientation and sometimes melts them.

- **Insulation Decomposition and Degradation**

For an oil-immersed transformer, cellulose and mineral oil are the widely used insulation materials. Both decompose and degrade under electrical and thermal stress faced by the transformer. Cellulose is made up of fiber and carbohydrate. Under electrical and thermal stress their molecular structure gets damaged, reducing their strength and making them brittle. Mineral oil is made up of different hydrocarbons. These hydrocarbons undergo decomposition due to electrical and thermal stresses forming various gases. Gases are sometimes flammable, causing danger to the transformer life. Also, oxidation of oil results in formation of acids, which causes carbon and sludge formation, thus reducing the heat transfer capacity of the inner surface of the transformer.

- **Partial Discharge**

Partial discharge is a type of electrical discharge that partially bridges the insulation between conductors. Partial discharge activity may initiate due to over-voltage or voids in the insulation that are present at the time of manufacturing [4]. Partial discharge is undesirable because it deteriorates the insulation with the formation of gases.

- **Bushing Failure**

Bushing failure is caused by the flashover due to dirt accumulation and/or lightning strike. Also, bushings are subject to high mechanical stresses due to a connectors and

bus supports. Bushings deteriorate due to combination of cracking, corrosion, wear and contamination [4].

- **Internal Arcing**

Internal arcing is caused by a low liquid level, thus exposing live parts of the transformer, and a loose connection. Internal arcing is usually audible and causes radio interference.

- **Core Failure**

Core failure occurs due to failure of core laminations, core bolts, and clamps.

- **Over Temperature**

Over temperature occurs due to overcurrent, overvoltage, insufficient cooling, low liquid levels, and high ambient temperatures. In a dry type of transformer this condition occurs due to clogging of ducts.

- **Pressure Relief Diaphragm Broken**

This occurs due to internal excessive pressure, which takes place due to internal faults or high liquid levels in the transformer, or due to excessive loading of the transformer.

- **Transformer Auxiliary Equipment Troubles**

There are some other auxiliary equipments such as on-load and off-load tap changers, transformer cooling system which are required for reliable and efficient operation of the transformer. Failure of such auxiliary systems are responsible for the failure of transformers.

2.2.3 Transformer Maintenance Practices

Periodic maintenance of transformers is needed to safeguard against the various failures causes as discussed above. Transformer maintenance scheduling is an important aspect, which mainly depends upon the critical and non-critical nature of the transformer and the load connected to it. Proper maintenance of a transformer should include routine inspection and repair. Also, any special maintenance aspect as mentioned by the manufacturer should be considered.

2.3 Selection of Criteria for Condition Assessment Sheet

A review of specific system wise failure modes, restoration practices, and maintenance activities are helpful in selecting condition assessment criteria. Selection of parameters for condition assessment of a transformer depends upon its type, size, and application. Parameter selection should provide significant information about the equipment condition and also justify cost and efforts. Various techniques are available in the market for monitoring various parameters of transformer and its subsystems. Attempt here is to select the parameters which will be realistic, be more significant in representing equipment condition, and reflect the results obtained from the advanced monitoring systems.

2.3.1 Condition Assessment Sheet for Transformer

A condition assessment sheet for a transformer is presented as shown in Table 2.2.

TABLE 2.2

CONDITION ASSESSMENT SHEET FOR TRANSFORMER

	Sr. No.	Criteria		Weight	Score
GENERAL	1	**I**	Age of the Transformer		
	2	**I**	Experience with Transformer Type		
	3	**I, M**	Noise level		
	4	**I, M**	Transformer Loading Condition		
	5	**O**	Core & Winding losses		
WINDING CONDITION	6	**O**	Winding Turns Ratio		
	7	**O**	Condition of Winding		
	8	**O**	Condition of Solid insulation		
	9	**I,M**	Partial Discharge (PD) Test		
OIL CONDITION	10	**I,M**	Gas in Oil		
	11	**I,M**	Water In Oil		
	12	**I,M**	Acid in Oil		
	13	**I,M**	Oil Power Factor		
PHYSICAL CONDITION	14	**I,M**	Condition of Tank		
	15	**I,M**	Condition of Cooling System		
	16	**I,M**	Condition of Tap Changer		
	17	**I,M**	Condition of Bushings		
	18				
Sum					
Weighted Average					

I: Energized and In-service testing
M: On line monitoring & measurement is possible.
O: De-energized and isolated

2.3.2 Discussion on Condition Assessment Criteria and Their Scoring

Discussion on transformer condition assessment criteria are broadly categorized as General Condition, Winding condition, Oil Condition and Physical Condition.

2.3.2.1 General Criteria

- **Age of Transformer (years of operation)**

The life of a transformer is often defined as the time required for the mechanical strength of the insulation material to lose 50 percent of its mechanical strength. Normally transformers are not loaded to their nameplate rating, which results in an average life of around 30 years [1]. The guideline for scoring this parameter is presented in Table 2.3.

TABLE 2.3

SCORING CRITERIA FOR TRANSFORMER AGE

Age of Transformer	Score
Less than 1	0.00
1-10	0.05
11-20	0.10
21-25	0.25
26-29	0.40
30-31	0.50
32-35	0.60
36-40	0.80
Greater than 40	1

- **Experience with Transformer Type**

In practice, there are a variety of transformers of different types, rating from different manufacturers. Utility engineers need to review the history of the failure of

transformer on the system. Then conclusions need to be drawn regarding the reliable operation of the transformer as per their types, rating and manufacturer. This will serve for developing the scoring guideline for this criterion. A score of '0' indicates the satisfactory performance while a score of '1' indicates the poor performance with the particular transformer type.

- **Noise Level**

All transformers hum and create noise when they are energized. Noise is generated by the vibration of the core. Hence, in one way, noise monitoring indicates the condition of the core assembly. Typical ratings for a distribution transformer and its average noise level as per NEMA are listed in Table 2.4 [5].

TABLE 2.4

TRANSFORMER NOISE LEVELS AS PER NEMA

Transformer Rating in KVA	**Noise Level dB**
0 – 9 kVA	40
10 – 50 kVA	48
51 – 100 kVA	51
101 – 300 kVA	55
301 – 500 kVA	56

Also the average noise level for the oil fill and dry type power transformers are mentioned in the NEMA standard [6]. Noise level for a power transformer ranges from 57dB to 91dB. The transformer manufacturer will also specify the limiting noise level for each transformer. In case that information is not available, the noise level as per NEMA standard should be followed.

Noise level limits mentioned in NEMA standard are useful in developing the scoring criterion for this parameter, as shown in Table 2.5.

TABLE 2.5

SCORING CRITERIA FOR TRANSFORMER NOISE

Limits on Noise Level	Scoring
If noise level is well below NEMA standards	0
If noise level is as per NEMA standards	0.5
If noise level exceeding NEMA standards	1

- **Transformer Loading Condition**

Transformer loading has a significant effect on transformer life. Loading a transformer in excess of the nameplate rating involves some degree of risk. Mechanical deterioration of the winding insulation has been the basis for the loading the transformer. Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. With modern oil preservation techniques, the effect of moisture and oxygen content are minimized. Hence, insulation temperature is the main controlling parameter. Therefore, the transformer loading condition can be reflected by the effect of the highest (hottest spot) temperature on the loss of insulation life.

IEEE Standard C57.91-1995 presents the procedure for the percent loss of insulation life for an oil-immersed transformer, which is mentioned in equation (2.1) [7],

$$\%\ Loss\ of\ Insulation\ life = \frac{F_{EQA} * t * 100}{Normal\ Insulation\ Life} \quad (2.1)$$

where F_{EQA} = Equivalent aging factor for the total time period. Refer equation (2.2)

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} * \Delta t_n}{\sum_{n=1}^{N} \Delta tn} \quad (2.2)$$

N = Total Number of time interval

$F_{AA,n}$ = Aging accelerator factor for the temperature which exists during the time interval Δtn. Aging acceleration can be determined from graph shown in Figure 2.3.

Δtn = Time interval in hours

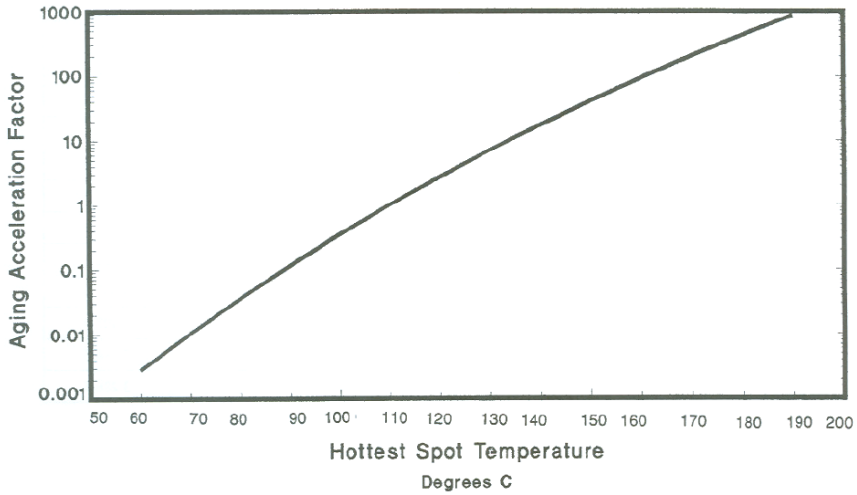

Figure 2.3: Ageing acceleration factor

Table 2.6 gives the percent loss of life based on a nominal life of 180,000 hours for various hot spot temperatures [7]. Also note that percent loss of life is presented only for time durations up to 24 hours. The formula for percent loss of life shown in equation (2.1) needs to be used for time duration not mentioned in the Table 2.6.

TABLE 2.6

TIME DURATIONS IN HOURS FOR CONTINUOUS OPERATION ABOVE RATED HOTTEST-SPOT TEMPERATURE FOR DIFFERENT LOSS-OF-LIFE VALUES

Hot Spot Temp °C	**FAA**	**Percent loss of life ***						
		0.0133t	**0.02**	**0.05**	**1**	**2**	**3**	**4**
110	1.00	24	-	-	-	-	-	-
120	2.71	8.86	13.3	-	-	-	-	-
130	6.98	3.44	5.1	12.9	-	-	-	-
140	17.2	1.39	2.1	5.2	10.5	20.9	-	-
150	40.6	0.59	0.89	2.2	4.4	8.8	13.3	17.7
160	92.1	0.26	0.39	0.98	1.96	3.9	5.9	7.8
170	201.2	0.12	0.18	0.45	0.89	1.8	2.7	3.6
180	424.9	0.06	0.08	0.21	0.42	0.84	1.27	1.7
190	868.8	0.028	0.04	0.10	0.21	0.41	0.83	1.66
200	1723	0.014	0.02	0.05	0.10	0.21	0.31	0.42

*Based on a normal life of 180 000 h. Time durations not shown are in excess of 24 h.

With reference to the above discussion, scoring guideline is developed as below,

Score = 1 – (% loss of insulation life)

A Score of “0” indicates the full insulation life and as the score increases towards 1, it indicating reduced insulation life.

- **Core and Winding Losses**

Transformer losses consist of no-load losses and load losses. No-load losses consists of hysteresis loss ($W_h = K_h * f * B_m^{1.6}$) and eddy current ($W_e = K_e * f^2 * K_f^2 * B_m^2$) losses. As the core flux in the transformer remains practically constant, the core loss should be constant for all loads. Load losses are mainly due to the ohmic resistance (I^2r losses) of the transformer winding. They also include the stray losses occurring in the mechanical structure and winding conductors. Monitoring core and winding

losses gives the information about the transformer performance. To assess this parameter, total losses (sum of no-load and load losses) are considered. As per IEEE Standard C57.123 [8] recommends the maximum tolerance of 6% total losses. Based on this criterion, a scoring guide line is developed as shown in Table 2.7.

TABLE 2.7

SCORING CRITERIA FOR TRANSFORMER LOSSES

Percent (%) Increase in Total Losses	**Scoring**
No increase in total losses	0
(Percent increase in total losses) < 3 %	0.5
(Percent increase in total losses) < 6 %	0.75
(Percent increase in total losses) ≥ 6 %	1.0

When the total loss limits from the manufacturer are available, they should be used for developing this scoring criterion.

2.3.2.2 Winding Condition

- **Transformer Turns Ratio**

The transformer turns test is useful to assess the condition of transformer winding. It measures the number of turns of the primary winding with reference to the number of secondary turns. But for this test transformer needs to be isolated from the service. As per ANSI 57.12-00 [5], results of this test should be within 0.5 percent of the nameplate marking of the transformer [5]. With reference to this, a scoring guideline for this criterion can be developed as shown in Table 2.8.

TABLE 2.8

SCORING CRITERION FOR TRANSFORMER TURNS RATIO

Percent change in Transformer Turns Ratio (TTR)	Assigned Score
(Percent change in TTR) < 0.1 %	0
0.1 % ≤ (Percent change in TTR) < 0.3 %	0.5
0.3 % ≤ (Percent change in TTR) < 0.5 %	0.75
(Percent change in TTR) ≥ 0.5	1

- **Condition of Solid Insulation**

The condition of solid insulation is generally assessed by the Insulation Resistance Test. In this test, insulation between winding and the ground or between two windings is tested. Two tests are widely used for this measurement, the megohmmeter test and polarization index test.

In the megaohm test, insulation resistance is measured as the function of leakage current that passes through the volume of the insulation upon the application of dc voltage. Commonly used dc test voltages are 500V, 1000V, and 2500V. Minimum resistance value for a one-minute resistance measurement for a transformer is determined as per equation (2.3) [9]:

$$IR = \frac{C * E}{\sqrt{(KVA)}} \qquad (2.3)$$

Where IR= Insulation resistance in MΩ

C = 1.5 at 20^0C, Constant for Oil-filled transformer

= 30 at 20^0C, Constant for Dry-type transformer

E = Voltage rating in V. (Phase-to-phase voltage for delta connected winding and phase to neutral voltage for star connected winding)

kVA = Rated capacity of winding under test

Megohm test results below this minimum value would indicate probable insulation breakdown. A Megaohm test that indicates zero or a very low value in ohms indicates grounded windings, winding-to-winding short circuit, or heavy carbon tracking. The minimum acceptable insulation resistance for 2.3kV to 13.2kV is 800 MΩ and for above 13.2kV voltage is 1600 MΩ. Based on this discussion, scoring guidelines for this parameter are developed as shown in Table 2.9.

TABLE 2.9

SCORING CRITERION FOR TRANSFORMER INSULATION RESISTANCE

Limits on Insulation Resistance	**Assigned Scoring**
Insulation resistance higher than *IR* *	0
Insulation resistance equal to *IR* *	0.5
Insulation resistance less than *IR**	1

** where IR is defined as*

$$IR = \frac{C * E}{\sqrt{(KVA)}}$$

The polarization index test is also used to assess the condition of the insulation. The polarization index is the ratio of the megohm resistance at the end of a ten minute test to that of a one minute test at constant voltage. A polarization index less than 1 is considered very dangerous and indicates very poor condition of the insulation. A polarization index greater than 2 is considered as very good insulation health [9]. Based on this, a scoring guideline for this parameters with reference to polarization index is developed as shown in Table 2.10.

TABLE 2.10

SCORING CRITERION FOR TRANSFORMER POLARIZATION INDEX

Polarization Index	Assigned Scoring
(Polarization Index) < 1 *Dangerous insulation condition*	1
1 ≤ (Polarization Index) < 1.1 *Poor insulation condition*	0.75
1.1 ≤ (Polarization Index) < 1.25 *Questionable insulation condition*	0.50
1.25 ≤ (Polarization Index) < 2 *Fair insulation condition*	0.25
(Polarization Index) > 2 *Very good insulation condition*	0

- **Partial Discharge (PD) Test**

Partial discharge had very detrimental effects on the transformer insulation. Partial discharge is basically an electrical discharge between the conductors' insulations. Because of the partial discharge, insulation loses its strength gradually due to effects of cracking and erosion. As outputs of this diagnostic technique can provide information about partial discharge activity, such as source of failure, safety and reliability of the transformer unit can be discussed and replacement/maintenance activities can be planned. Generally, Partial discharge takes place due tracking of insulation, voids in solid insulation, and also due to gas bubbles generated due to some fault location. Partial discharge activity reduces the transformer's healthy life, but there is no rule for this correlation.

Partial discharge can be detected by the two methods: detection of acoustic signals and measurement of electrical signal produced by the partial discharge [3]. Partial discharge can also be detected indirectly, using chemical techniques such as measurement of degradation products (C_2H_2, C_2H_4) produced by partial discharge [3,

10]. Acceptable limits of partial discharge depend upon the size of the transformer and normally range between 100pC to 500pC [3]. Based on the above discussion scoring guidelines for this parameter is developed as shown in Table 2.11.

TABLE 2.11

SCORING CRITERION FOR PARTIAL DISCHARGE

Partial Discharge	**Assigned Score**
No presence of partial discharge activity	0
Partial discharge less than 50% of limiting value mentioned by the transformer manufacturer	0.25
Partial discharge is 50% to 75% of limiting value mentioned by the transformer manufacturer	0.50
Partial discharge is greater than 75% but below limiting value	0.80
Partial discharge exceeding limiting value mentioned by the transformer manufacturer	1

- **Winding Resistance**

The winding resistance test measures the DC resistance of the transformer leads and windings. A low-resistance ohm meter is used for this test. For delta-connected winding, phase-to-phase measurements are made, and for start-connected winding, phase-to-neutral measurement is done. All test values are converted to the common temperature base such as 75^0C. The temperature corrected resistance value should be within 2% of the factory values of the transformer [5]. This is used for developing the scoring guidelines, as shown in Table 2.12.

TABLE 2.12

SCORING CRITERION FOR TRANSFORMER RESISTANCE

Percent Change in Winding DC Resistance Value	Assigned Score
No change is winding resistance	0
< 1%	0.5
≤1% to < 2%	0.75
≥ 2%	1

2.3.2.3 Oil Condition

- **Gas in Oil**

For oil-filled transformer, the insulation system consists of oil and cellulose (paper) material. Under normal operating conditions, transformer insulation deteriorates and generates certain combustible and non-combustible gases. The main cause of gas formation in the transformer is the heating of paper and oil insulation due to electrical problems such as corona (low energy phenomenon) and electric arc (high energy phenomenon) inside the transformer. Detection, analysis, and identification of these gases can be very helpful in determining the condition of the transformer. Dissolved gas analysis is widely been used in the industry for the detection of gases in oil.

Detailed evaluation information on the concentration of separate gases as well as the total concentration of all combustible gases is provided in IEEE Standard C57.104-1991 [5]. In this standard, four level criteria are specified to classify risk for a transformer. These IEEE criteria are presented in Table 2.13. An increasing gas generating rate indicates a problem in the transformer oil, and hence, a short sampling interval is needed to check the gas levels in the oil.

TABLE 2.13

DISSOLVED KEY GAS CONCENTRATION LIMITS AS PER IEEE

Status	Dissolved Key Gas Concentration Limits (ppm)							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG[4]
Condition 1	<100	<120	<35	<50	<65	<350	<2500	<720
Condition 2	101-700	121-400	36-50	51-100	66-100	351-570	2500-4000	721-1920
Condition 3	701-1800	401-1000	51-80	101-200	101-150	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>80	>200	>150	>1400	>10000	>4630

Based on the Total Dissolved Combustible Gases (TDCG) column from Table 2.13, a scoring guideline is developed for this parameter, as shown in Table 2.14.

TABLE 2.14

SCORING CRITERIA FOR GAS IN OIL

Total Dissolved Combustible Gases (TDCG) Level in ppm	**Assigned Score**	**Remark**
(TDCG Level) ≤ 720	0.25	Represents normal aging of the oil and oil analysis needs to be done in six months.
721 < (TDCG Level) ≤ 1920	0.50	Indicates decomposition and excess oil aging, oil analysis is recommended every three months.
1921 < (TDCG Level) ≤ 4630	0.75	Indicates excessive decomposition and oil analysis is recommended every month.
(TDCG Level) > 4630	1.0	Indicates very poor condition of the oil and oil analysis is recommended every week.

- **Water in Oil**

Water can be present in the oil in a dissolved form, as tiny droplets. The presence of water in oil is harmful for both the solid paper insulation and the oil. Paper insulation, being porous, absorbs water. This reduces the insulation strength of the solid

paper. Free water in the oil reduces the dielectric strength of the oil. An excessive amount of water can accelerate the insulation degradation process and ultimately the age of the transformer. The Karl Fischer method is being widely used for water content testing. Accepted levels of water content in the mineral insulating oil, according to various voltage levels and operating temperatures, are mentioned in IEEE C57.106.200 and is presented in Table 2.15 [11].

TABLE 2.15

LIMITS ON WATER CONTENT IN OIL

	Accepted Maximum Water Content (In ppm and percentage figures)					
	50^0C		**60^0C**		**70^0C**	
Voltage Level	Water content in ppm	Water content in %	Water content in ppm	Water content in %	Water content in ppm	Water content in %
≤ 69 kV	27	15	35	15	55	15
> 69 kV to ≤ 230 kV	12	8	20	8	13	8
230kV and greater	10	5	12	5	15	5

The above mentioned maximum acceptable limits are further used for developing the scoring criterion for this parameter. For a transformer below 69kV and average oil temperature of 50^0C, a scoring guideline can be developed based on the percent of water content in the oil as shown in Table 2.16.

TABLE 2.16

SCORING CRITERIA FOR WATER CONTENT IN OIL

Percent Water Content in Oil	Assigned Score
≤ 1%	0
2% to ≤ 5%	0.25
6% to ≤ 10%	0.5
11% to ≤ 15%	0.75
≥ 15 %	1

With reference to the scoring guideline, as shown in table 2.16, scoring criteria can be developed for transformers of various voltage ratings and according to the average oil temperature.

Percentage of water in insulation oil is calculated as per equations (2.4) and (2.5),

$$\log_{10} S_0 = (-1567/T) + 7.0895 \tag{2.4}$$

Where S_0 is the solubility of water in oil, and T is the absolute temperature in Kelvin

$$Percentage\ of\ water\ content = 100 * \frac{(ppm\ of\ water\ in\ oil)}{S_o} \tag{2.5}$$

- **Acid in Oil**

Acids are formed in the transformer oil by the oxidation process. Acids are directly responsible for sludge formation. They also interact with the transformer metal body causing another form of sludge formation. For field testing to determine total acid

value in the oil, titration methods, such as D664, D974 methods are used [5]. The acid number in an oil is a measure of the amount of acidic materials present. The acidity, and therefore the acid number, increases with the age of the oil in service. A high acid number indicates that the oil is either oxidized or contaminated with materials such as varnish, paint, or other foreign matter. It is very important to monitor the content of acid in oil to assess the oil condition in transformers.

Acid in oil is measured in terms of a neutralization number. Neutralization number is the milligrams of potassium hydroxide required to neutralize the acid contain in one gram of transformer liquid [5]. A neutralization number below 0.4 is considered satisfactory, while a neutralization number between 0.4 and 1 indicates regular reconditioning of the oil [5]. Based on the above discussion, a scoring guideline for this parameter can be developed, as presented in Table 2.17.

TABLE 2.17

SCORING CRITERION FOR ACID IN OIL

Neutralization number (acidity)	**Assigned Score**
(Neutralization number) < 0.4	0
0.4 ≤ (Neutralization number) < 0.7	0.5
0.8 ≤ (Neutralization number) < 1.0	0.75
(Neutralization number) ≥ 1.0	1

- **Oil Power Factor**

The oil power factor indicates the dielectric loss of oil and its dielectric heating. Oil power factor test is very useful and widely used to assess the oil condition. Oil power factor testing at the field can be done with portable equipment. Oil in excellent condition

has a power factor less than 0.05 at 20^0C [5]. A higher power factor indicates deterioration and contamination. The oil power factor is the cosine of the phase angle between applied sinusoidal voltage and resulting current. Guide for grading oil by power factor test says that oil power factor less than 0.5 percent indicates satisfactory performance, 0.5 to 2 percent indicates doubtful oil condition, and poor oil condition is indicated by power factor over 2 percent [5]. Based on this, a scoring guideline for this criterion can be developed, as shown in Table 2.18.

TABLE 2.18

SCORING CRITERION FOR OIL POWER FACTOR

Power Factor in Percent	**Assigned Score**
(Power factor) < 0.05	0
0.05 ≤ (Power factor) < 0.5	0.25
0.5 ≤ (Power factor) < 1	0.50
1 ≤ (Power factor) < 2	0.75
(Power factor) ≥ 2	1

2.3.2.4 Physical Condition of Transformer

Along with the above mentioned specific parameters, there are various other auxiliary components/systems whose satisfactory operation is very important for reliability of the transformer. Cooling system and tap changer assembly are crucial. Also, there are other auxiliary components, such as bushings, pressure relief valves, breathers and outer transformer body, which need to be inspected for reliable operation.

Transformer cooling system consists of fans, oil pumps, valves, and other control devices. Same should be inspected, cleaned, and maintained regularly.

Also, the transformer's outer body should be inspected regularly. This checking should include tank, radiators, gasket leakages, and metal parts for corrosion. Electrical connection should be checked for tightness and overheating.

Transformer bushings should be checked for mechanical damage, cleanness and leakage. Bushings should be cleaned regularly to avoid flashovers.

For all of these physical inspections, scoring criteria need to be developed by the maintenance personnel based on experience. This will provide more realistic criteria for these parameters. The scoring guideline will then be a score of 0 for excellent condition, 0.5 for satisfactory condition, and 1 for poor physical condition.

2.3.3 Weight Assignment for Each Parameter

The assignment of weight to each parameter is a very important stage in the equipment condition assessment process. Weight assignment procedure is more system specific and also need inputs from the maintenance people and equipment manufacturers. The weight selection criterion for each parameter should be selected in such a way that it will highlight the criticality of particular parameter in the overall equipment's condition assessment. The following are the guidelines for deciding and selecting the weights:

- In weight selection criteria, the combined opinion of maintenance personnel and equipment manufacturers shall be considered.
- If a particular utility is having detailed information regarding the historical failures and maintenance activities of the transformers on the system, e.g., causes and frequency of various transformer failures or details of maintenance activities performed frequently, these shall be categorized as per the parameters

mentioned in the condition assessment sheet. This will provide guidelines for giving importance to a particular parameter.

- The weight assignment of particular parameters shall be selected with respect to the score of a particular parameter. This procedure will help in emphasizing the criticality of that parameter in the overall failure rate estimation of the equipment, e.g., for a parameter such as oil condition, winding condition such method shall be developed.
- With respect to the above discussion, a sample weight assignment sheet was developed for the transformer. This condition assessment sheet needs to developed and finalized for a particular utility, which will be helpful in uniform condition assessment of transformer across the system.

2.3.3.1 Sample Weight Assignment / selection sheet:

Sample weight assignment / selection sheet is presented in Table 2.19.

TABLE 2.19

SAMPLE WEIGHT ASSIGNMENT / SELECTION SHEET

	SR. NO.	CRITERIA		WEIGHT SELECTION			
				Score 0-0.25	Score 0.26-0.5	Score 0.51 – 0.75	Score 0.76-1
GENERAL CONDITION	1	**I**	Age of the Transformer	10			
	2	**I,M**	Experience with Transformer Type	5			
	3	**I,M**	Noise Level	5			
	4	**I**	Transformer Loading Condition	10			
	5	**O**	Core & Winding Losses	10			
WINDING CONDITION	6	**O**	Winding Turns Ratio	10	15	20	25
	7	**O**	Condition of Winding	10	15	20	25
	8	**O**	Condition of Solid Insulation	10	15	20	25
	9	**I,M**	Partial Discharge (PD) Test	10	15	20	25
OIL CONDITION	10	**I,M**	Gas in Oil	10	15	20	25
	11	**I,M**	Water In Oil	10	15	20	25
	12	**I,M**	Acid in Oil	10	15	20	25
	13	**I,M**	Oil Power factor	10	15	20	25
PHYSICAL CONDITION	14	**I,M**	Condition of Tank	10			
	15	**I,M**	Condition of Cooling System	10	15	20	25
	16	**I,M**	Condition of Tap Changer	15	20	25	30
	17	**I,M**	Condition of Bushings	10			
	18						

2.4 Failure Rate Estimation:

Based on Information from the periodic inspection and maintenance activities performed on the equipment, available parameters of the condition assessment sheet for transformer shall be filled and scores shall be assigned as per the developed guideline. Also, data obtained from the online monitoring systems is of vital use in this procedure. The available condition assessment data is then processed for the failure rate estimation for that equipment based upon the guidelines developed by R. Brown in the reference [2]. In reference [2], exponential model is used to describe the relationship between the normalized equipment condition score and failure rate of the equipment.

- Score for each parameter in the condition assessment sheet is interpreted as below:

  Score = *0*, Indicates the best equipment condition and all the inspection results are well within the limits as specified the manufacturer.

  Score = *0.5*, Indicates the average equipment condition

  Score = *1*, Indicates the worst equipment condition and immediate attention is required.

- With the help of the weight and score assigned for each of the parameter, weighted average/condition score for the particular transformer is determined as per equation (2.6),

$$Weighted\ Score = \sum_{\substack{for\ all \\ parameters}} (Weight * Score) \div \sum_{\substack{for\ all \\ parameters}} Weight \qquad (2.6)$$

- The above calculated transformer condition score/weighted score is then required to relate to the failure rate. For this purpose the historical failure rates for

transformer as mention in the reference [1] and [2] are used. As per this data, Best, Average and Worst transformer failure rates are as follows,

For power transformers less than 25MVA :

λ(0) = 0.0075 (Best)
λ(1/ 2) = 0.040 (Average)
λ(1) = 0.140 (Worst)

For power transformer bigger than 25MVA:

λ(0) = 0.0050 (Best)
λ(1/ 2) = 0.030 (Average)
λ(1) = 0.120 (Worst)

For pole mounted distribution transformer:

λ(0) = 0.0020 (Best)
λ(1/ 2) = 0.010 (Average)
λ(1) = 0.030 (Worst)

- With the help of the best, average and lowest failure rates, coefficients A, B and C are calculated as per the following equations (2.7), (2.8) and (2.9) [2].

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \tag{2.7}$$

$$B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right) \tag{2.8}$$

$$C = \lambda(0) - A \tag{2.9}$$

- From the condition score (*x*) and above mentioned parameters A,B and C, the failure rate of the equipment can be predicted as per equation (2.10) [2].

$$\lambda(x) = Ae^{B*x} + C \tag{2.10}$$

2.5 Transformer Online Monitoring Systems

Many transformer monitoring systems have been developed over the years. Such systems monitor the various components/subsystems of a transformer. Also, there are new sensors available for various parameter measurements. Figure 2.4, shows a typical transformer monitoring system. Data obtained from monitoring systems can be integrated with the condition assessment of the equipment. In Table 2.20, shows the way that data from such monitoring systems fits into the condition assessment sheet.

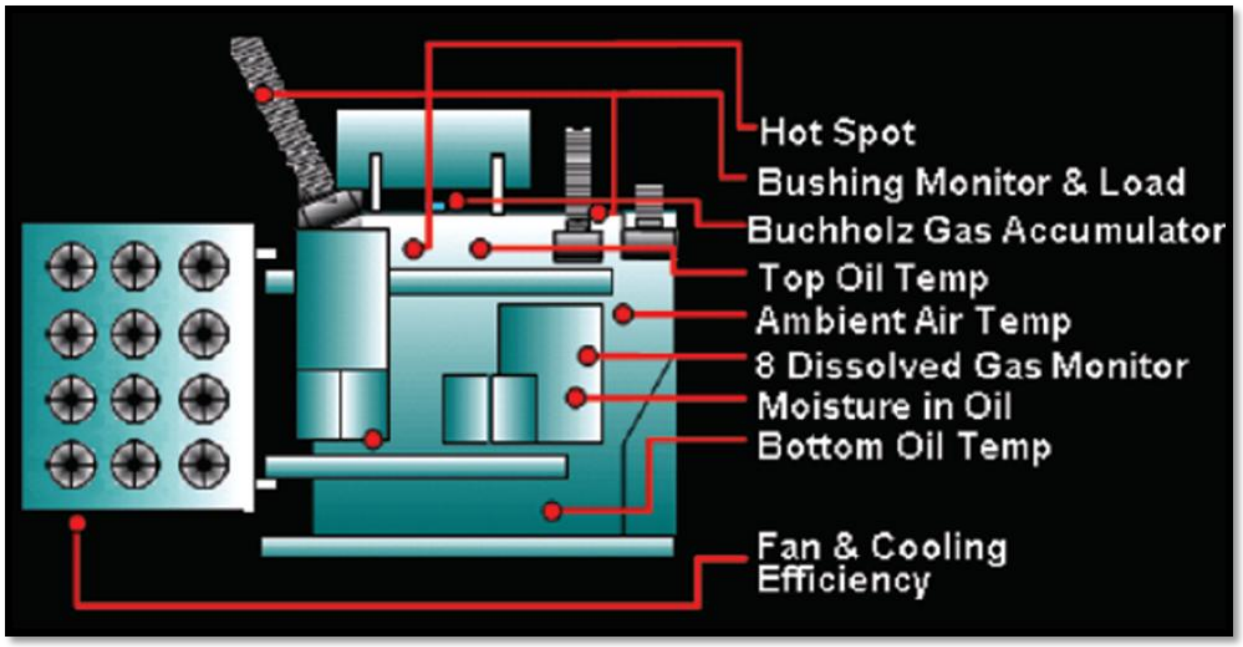

Figure 2.4: Typical transformer monitoring system

TABLE 2.20

INPUT TO TRANSFORMER CONDITION ASSESSMENT FROM ONLINE MONITORING SYSTEMS

Online monitoring for Transformer			**Condition Assessment for Transformer**	
System/ Component	**Monitoring Points with Sensors**		**Criteria**	**Parameter to be Assessed**
Core	• Vibration	→	Criterion No. 3	To assess the noise level
Loading History	• Load Current and Voltage Monitoring	→	Criterion No. 4	To assess Transformer Loading History
Winding	• Partial Discharge • Winding Temperature	→	Criterion No. 9, 4	To assess partial discharge in the winding & Transformer loading history.
Transformer Oil	• Dissolved Gas Monitoring • Oil Temperature at the Top and Bottom • Moisture in Oil • Oil Level	→	Criterion No. 10, 11,12	To assess oil condition
Transformer Tank	• Pressure in the tank • Mechanical Pressure Relief Valve Switch	→	Criterion No. 14	To assess the condition of the tank
Cooling System	• Fan / Pump Motor's Running Current • Fan / Pump Motor's Highest Current • Number of Operations	→	Criterion No. 15	To assess the condition of the cooling system
Tap Changer	• Temperature • Dissolved Gas Monitoring • Oil Level	→	Criterion No. 16	To assess the condition of the Tap Changer
Bushing	• Bushing Leakage Current	→	Criterion No. 17	To Assess the condition of Bushing

2.6 Example

Three and half years of outage data is obtained from an Electric utility in the Midwest region. From the outage data, the total number of substation transformer failed during last 3.5 years is obtained. A total of 15 numbers of substation transformer failed. From the single line diagrams of various substations, total number of substation transformers installed on the system are found out. It was found that total 176 numbers of substation transformers are installed on the system. From this data, we can find out the average failure rate λ(1/2) of the transformer as below,

$$\lambda(1/2) = (15) / (176 * 3.5) = 0.02435$$

Best and worst failure rates for the transformer, λ(0) and λ(1), respectively, are then calculated. Each breaker failed either zero times or one time during the last 3.5 years. This will give best and worst failure rates as below,

Best failure rate, λ(1/2) = 0 failure / 3.5 years = 0.0000

Worst failure rate, λ(1/2) = 1 failure / 3.5 years = 0.2857

The best and worst failures rates obtained above are either too law or too high, respectively [12]. Hence the following published failure rates for substation transformer (less than 25MVA) are used in from reference [2]. The same are listed below.

λ(0) = 0.0075 λ(1/2) = 0.02435 λ(1) = 0.0.120

Then, next step is calculation of A, B and C coefficient as defined earlier. The calculated values are mentioned below,

A = 0.003603 B = 2.604008 C = 0.003879

With above data, equation for failure rate estimation can be presented as below,

$$\lambda(x) = (0.003603 * e^{2.604008 * x}) + (-0.003879)$$

Above equation can be plotted in terms of failure rate λ(x) and equipment condition score x as shown in Figure 2.5.

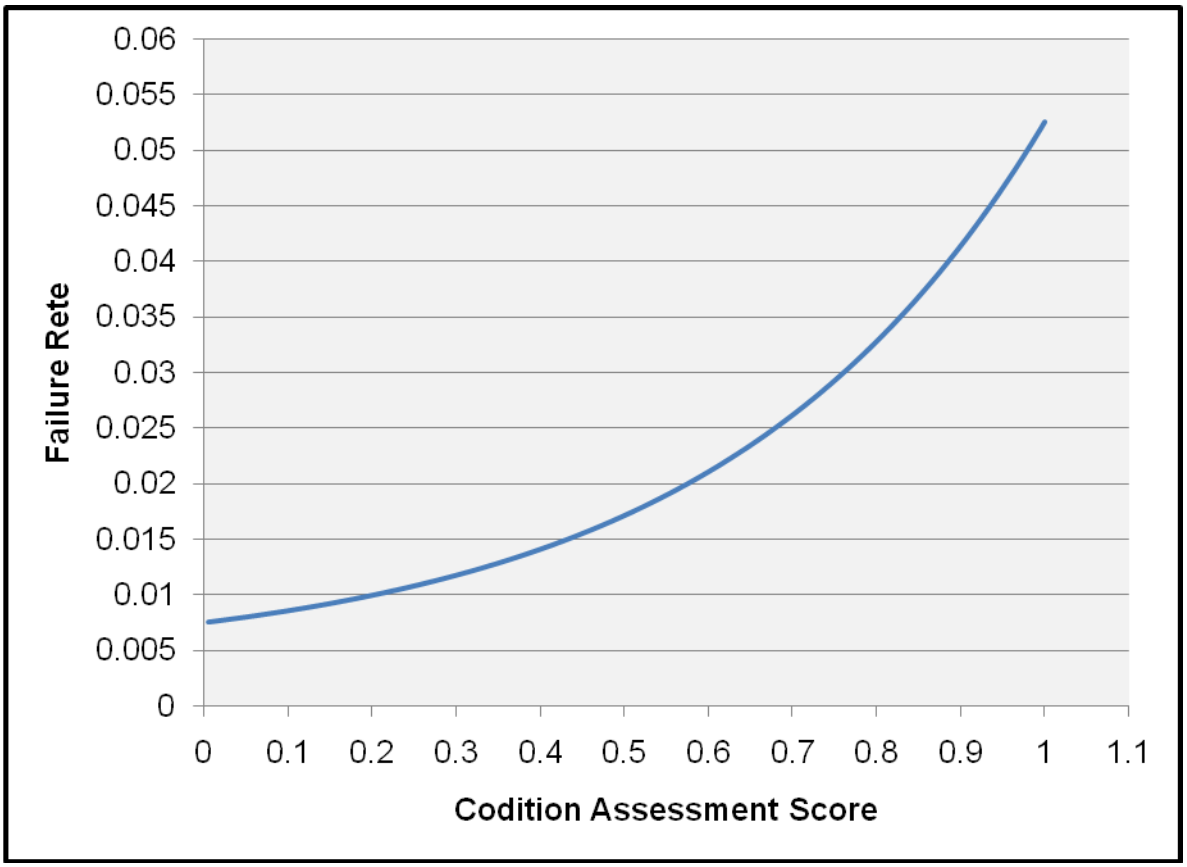

Figure 2.5: Transformer condition assessment score vs estimated failure rate

CHAPTER 3

CIRCUIT BREAKERS: CONDITION ASSESSMENT AND FAILURE RATE ESTIMATION

3.1 Introduction

Circuit breakers are vital components of the power system operation and play an important role in the protection of other equipments. The circuit breaker is an electrical switch designed to interrupt a large load current and large fault currents on the system, under a specified set of conditions. Several methods are employed for current interruption in circuit breaker. Current interruption is a significant property of circuit breaker. Since current interruption occurs in oil, air, vacuum and SF6, name such as bulk oil, air blast, air break, vacuum, and SF6 puffer circuit breakers are widely used. Also, operating mechanisms (energy storage devices and systems) are classified by their method of energy storage. Springs, solenoids, pneumatics, or hydraulics are widely used for circuit breaker operating mechanism.

A circuit breaker should not be considered a single component but rather a system consisting of several components, including control circuit, interrupters, drive mechanism, insulation, and a wide range of ancillary equipment.

There are various technologies used in the circuit breaker design for various voltage levels and applications. Air break/blast circuit breakers, oil circuit breaker, vacuum circuit breakers and SF6 circuit breakers are widely used in power system where breaking of high currents at higher voltages is required.

3.2 Circuit Breaker Failure Modes and Causes of Failure

Circuit breakers are complicated devices that can fail in many different ways. Most circuit breaker failures are observed in the fields have failed due to mechanical problems and problems in auxiliary control circuit. Circuit breaker failure statistics as presented by CIGRE, provide information on the failure statistics of the components of a circuit breaker [13]. The CIGRE report shows that 70% of major failures in circuit breakers are mechanical in nature, 19% are related to auxiliary and control circuits, and 11% are attributed to the electric problems involving interrupter and current path of the circuit breaker [13]. The same is presented in the Figure 3.1.

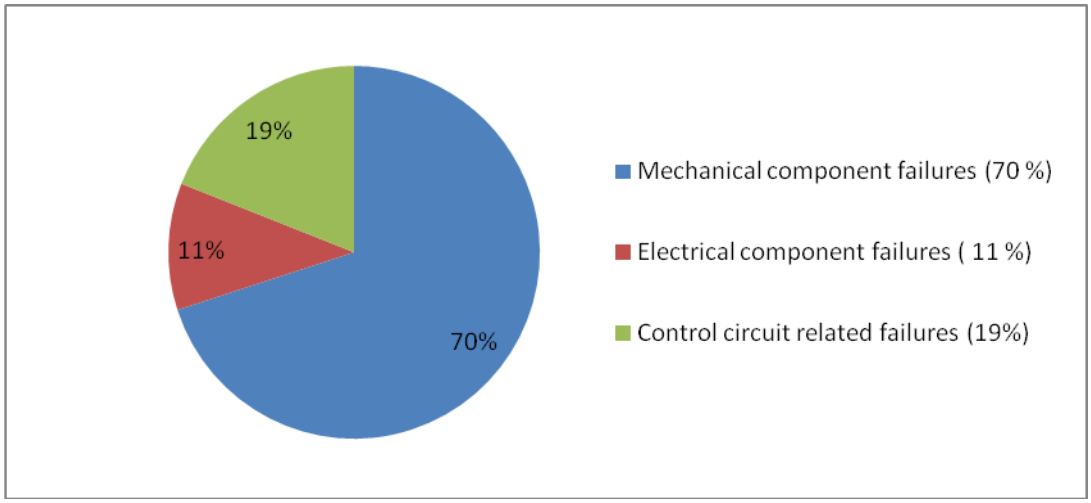

Figure 3.1: Failure statistics for circuit breaker as presented by CIGRE

Mechanical component failure involves the failure of many auxiliary components such as compressors, motors, energy storage elements, and actuators. Control circuit related failures involve failures due to trip and close command, auxiliary switches, contactors, and defects in monitoring components. Whereas electrical component failures mainly involve the failures due to the insulation of interrupters. The percentage wise failures observed for all these causes are presented in Table 3.1 [13, 14].

TABLE 3.1

PERCENTAGE FAILURE OF VARIOUS CIRCUIT BREAKER COMPONENTS

Circuit Breaker Component	**Percentage Failures Observed**
Mechanical Component Failures:	
Compressors, pumps and motors	13.6 to 18.7%
Energy Storage elements	7.2 to 7.6%
Control components	9.3 to 11.6 %
Actuators, shock absorbers	5.1 to 8.9 %
Failure of rods and other components	1.4 to 3.8 %
Control Circuit Related Failures:	
Failure to respond to trip and close commands	6 to 10 %
Faulty operation of auxiliary switches	2.1 to 7.4%
Contactor and heater problem	5.4 to 7.6%
Deficiencies in monitoring equipments	9.4 to 10.7%
Electrical Component Failures	
Failures of insulation	5.7 to 20 %
Failures of interrupters	9.4 to 14 %
Failures due to grading resistors & capacitors	o.6 to 1.3 %

Above presented circuit breaker failure modes and their failure statistics is very helpful for selection of condition assessment parameters for circuit breakers.

3.3 Maintenance Practices for Circuit Breakers

Circuit breakers are the line of defense on the power system network, hence reliable operation of circuit breakers is highly recommended. To ensure the reliable operation of this equipment, comprehensive maintenance programs are undertaken.

Maintenance practices for circuit breaker vary as per their types and design. Routine maintenance practices for power circuit breaker consists of testing of operating mechanism, insulation integrity, quality of contacts and testing of associated trip unit and control circuit.

Maintenance of the operating mechanism consists of lubrication of operating mechanism, cleaning of insulating parts, alignment of breaker operating mechanism, tightening of breaker accessories, checking breaker's power and auxiliary contact operation and inspecting the current carrying parts for evidence of overheating.

Breaker contacts are tested as per Millivolt drop test to verify the condition of the contact such as erosion and contamination. Same can also be assessed by measurement of breaker contact resistance. Also the travel time of contacts is also verified as per the manufacture's specification. Checking the condition of insulating medium, insulation resisting testing for verifying insulation integrity is carried out.

Following are the steps in circuit breaker maintenance:

- **General Inspection:** Circuit breaker is visually inspected for cleanliness of terminals, earth connections, level/pressure of arc quenching medium.
- **Cleaning and Drying:** Internal dust and moisture in the circuit breaker causes the gradual deposits on internal surface resulting in increase of leakage currents and internal flashover due to tracking. Hence cleaning and drying is very important. For cleaning, fluid recommended by the manufacturer is used or air pressure jets are also been used.
- **Insulation Surface:** Insulation surface is inspected visually for signs of cracks, tracking or any other possible defects. Cleaning and drying of the external insulation material is done. To assess the health of the insulation, insulation resistance measurement is done. For oil and SF6 circuit breakers, more care needs to be taken maintain insulation surface.

- **Interrupter Maintenance:** Interrupter maintenance include observation, cleaning, replacement of main and arcing contact, removal of decomposed products, cleaning of terminals and sliding contacts, cleaning of vent system.
- **Operating Mechanism:** Checking the operation for open/close command thoroughly. Noting the reading of operation counter and condition of spring. For oil circuit breaker and SF6 circuit breaker poles, Time-Travel characteristic of moving contact is observed critically. This characteristic gives indication about the health of the operating mechanism linkage.
- **Measurement of Contact Resistance:** The resistance between each interrupter and each pole is measured by means of micro-ohm meter. Contact resistance is inversely proportional to the contact pressure. Low contact pressure is because of weak springs or worn out contacts. High contact resistance is also not desirable as it causes excessive heating of contacts while carrying normal currents.
- Also the busbar chamber and its assembly are checked for cleanliness of insulators, tightness of joints. Proper working of auxiliary switches, indicating devices and interlocks are verified. Routing checking of associated protection devices, control relays, pressures gauges are carried out.

3.4 Selection of Criteria for Condition Assessment Sheet:

Selection of parameters for condition assessment of circuit breaker depends upon circuit breaker technology, type and application. Parameter selection should provide significant information about the equipment condition and also justify cost and efforts. Various techniques are available in the market for monitoring various parameters of circuit breaker and its subsystems. This work attempts to select those parameters that will be realistic, be more significant in representing equipment condition and reflect the results obtained from the advanced monitoring systems.

3.4.1 Condition Assessment Sheet for Circuit Breaker

Based on the above review of circuit breaker failure modes and their statistics, we have selected following parameters for condition assessment of circuit breaker. Refer the table 3.2 for Condition assessment sheet for circuit breaker.

TABLE 3.2
CONDITION ASSESSMENT FOR CIRCUIT BREAKER

	Sr. No			Criteria	Weight	Score
GENERAL	1	I		Age of the Circuit Breaker		
	2	I		Experience with Circuit Breaker Type		
	3	I, M		Number of Breaker Operation		
	4	I		Environmental Factors		
POWER CONTACTS	5	O		Contact Resistance		
	6	I		Contact & Conductor Temperature		
	7	I		Bushing Terminal Temperature		
	8	O		Contact Erosion		
OPERATING MECHNISM	9	I, M		Condition of Release Mechanism		
	10	I		Indication Status		
	11	O		Time for Main & Auxiliary Contact Status Operation		
	12					
INSULATIONS	13	O		Voltage withstand of insulation		
	14	I		Audible Noise		
	15	I, M		Bushing Condition		
	16	O		Breaker Loss Index		
SPECIFIC PARAMETERS	17	O	AIR	Arc Chute Condition		
	18	O		Puffer Condition		
	19					
	20	I, M	VACUUM	Vacuum Interrupter Condition		
	21					
	22					
	23	O	SF6	SF6 Gas Level		
	24	O		Moisture in SF6		
CONTROL CIRCUIT	25	I, M		Trip & Close Coil Operation		
	26	I, M		Condition of Charging Motor		
	27	I, M		Control Circuit function		
	28	I, M		Condition of Charging Motor, Relay & Auxiliary Contact, Heater.		
	Sum					
	Weighted Average					

I: Energized and In-service testing
M: Online Monitoring & measurement is possible
O: De-energized and isolated

3.4.2 Discussion on Condition Assessment Criteria and Their Scoring

3.4.2.1 General

- **Age of Circuit Breaker**

Circuit breaker designing is becoming more robust day by day. They are designed to work satisfactorily for many years. But as with the any other device, circuit breaker gets less reliable, more prone to faults, and faces more failures withage. Age of the circuit breaker is not an indicator of its tendency to fail, but still breaker age monitoring is recommended. This will be also helpful for observing the trends of various types of circuit breakers installed in the system, with increasing age. Utility needs to check with their historical data for information about the service life for circuit breakers of various types and make. This will be helpful in assigning more realistic scores. Scoring guideline can be developed for this parameter, as presented in Table 3.3.

TABLE 3.3

SCORING CRITERIA FOR CIRCUIT BREAKER AGE

Circuit Breaker Age (In-service years of equipment)	**Assigned Score**
Less than 5 years	0
6 to 10 years	0.25
11 to 20 years	0.5
21 to 30 years	0.75
Above 30 years	1

- **Experience with Circuit Breaker Type**

In any electric utility power system, breakers of various types, rating and of different manufactures are being used over the period of type. Each breaker type shows different behavioral and operational characteristics. This criterion helps in accounting such behavioral aspects in deriving circuit breakers condition assessment. For this, utility needs to review the historical data about the failure of circuit breakers and need to come up with the statistical figures giving information about the circuit breakers failure, such as the types of circuit breakers failed, their manufacturers and their mounting such as indoor/outdoor. With reference to this data scoring criteria for this parameter can be developed. A score of “0” indicates satisfactory performance and a score of “1” indicates poor performance, of the particular circuit breaker type.

- **Number of Breaker Operation**

This parameter can be directly measured from the operation counter. Although this criterion does not relate directly to the failure rate of a circuit breaker, it provides an idea of the breaker mechanism operation and eventually indicates its wear and tear over the long period of time. It also indicates the number of faulty conditions on a particular feeder. Generally, a circuit breaker is rated for around 2000 operations for its rated current and around 50 operations for its rated short circuit current [5]. Based on this, scoring criteria is developed, as shown in Table 3.4.

TABLE 3.4

SCORING CRITERIA FOR NUMBER OF BREAKER OPERATION

Number of Breaker operations in %	Assigned Score
Less than 25 % of breaker operations at rated current and short circuit current	0.25
25 % to 50% Breaker operations at rated current and short circuit current	0.5
More than 50% of breaker operations at rated current and short circuit current	1

- **Environmental Factors**

Circuit breaker installation can be either indoor or outdoor. This criterion can be used to assess the causes of breaker failures and maintenance efforts needed for indoor and outdoor circuit breaker installation, and also the effect of geographical conditions on them. Scoring criteria for this parameter will depend on the utilitie's geographic condition. Minimum score of "0" indicates satisfactory performance and maximum score of "1" indicates poor performance for this parameter.

3.4.2.2 Power Contacts

- **Contact Resistance**

The circuit breaker contact resistance varies with its type and voltage range. An increase in contact resistance usually signifies loose joints, corroded and misaligned contact surfaces. Measurement of contact resistance is used to monitor the condition of beaker contact, and its wear and tear. Breaker contact resistance test is used to measure the contact resistance. In this, contact resistance is measured by applying DC Current and then observing the voltage drop. Contact resistance is measured in micro-ohms. Each manufacturer specify the range of healthy contact resistance. Generally, 200 – 250 micro-ohm is normal contact resistance for a circuit breaker [4]. Tested

values of circuit breaker should not exceed the range specified by the circuit breaker manufacturer. A difference of more than 50% in the contact resistance value is considered serious and immediate attention is required [5]. Measuring the contact resistance helps in monitoring the trend in contacts deterioration and can take corrective action before significant degradation of contacts occurs. Based on this discussion, scoring guideline can be developed as presented in Table 3.5.

TABLE 3.5

SCORING CRITERIA FOR BREAKER CONTACT RESISTANCE

Percent (%) Change in Contact Resistance (ΔR)	**Assigned Score**
(ΔR %) ≤ 10 %	0
11% < (ΔR %) ≤ 30%	0.5
31 % < (ΔR %) ≤ 40%	0.75
(ΔR %) > 41%	1

- **Temperature of Contacts and Bushing Terminals**

It is desirable to have temperature rise at the contacts and bushing terminal within the temperature rise limit. Monitoring the temperature helps to verify the same. Excessive temperature rise indicates the degradation and deterioration of contacts and material of bushing terminals. Temperature rise shall be referred with respect to ambient temperature. Now day's infrared temperature monitoring techniques are widely used. These are portable tools and don't need any experimental setup. They are very handy, easy to use and more reliable in measurement.

IEC 294 provides the guidelines for the temperature limits for circuit breaker contacts. In this, temperature limits are given in terms of total temperature, and

temperature rise over ambient temperature, as shown in Table 3.6. Following are the temperature limits for bare copper contacts. The temperature limit increases with the plating of copper contact with silver, nickel or tin.

TABLE 3.6

TEMPERATURE LIMITS FOR CIRCUIT BREAKER CONTACTS
AS PER IEC 294

Contact Description	**Maximum Temperature**	
	Total Temp (^{0}C)	**Temp Rise (^{0}C)**
Bare copper contact in Air	75	35
Bare copper contact in SF6	90	50
Bare copper contact in Oil	80	40

With reference to the above IEC 294 temperature rise limits and temperature rise limits as mentioned by the circuit breaker manufacturer, guidelines for scoring can be established as shown in Table 3.7.

TABLE 3.7

SCORING CRITERION FOR TEMPERATURE OF CONTACT TERMINAL

Limits on temperature rise	**Assigned Score**
If temperature rise is as per manufacturers limits	0
If temperature rise is exceeding manufactures limits but below the 50% of IEC 294 temperature rise limits	0.5
If temperature rise is 51% to 75% of IEC 294 temperature rise limits	0.75
If temperature rise above the 75% of IEC 294 temperature rise limits	1

- **Contact Erosion**

Contact erosion takes place due to the vaporization of electrodes during the current interruption process. Contact erosion results in binding of contacts and ultimately breaker failure. This criterion is important to monitor the condition of contact. Erosion rate is expressed as vaporization rate in cubic centimeters of contact material lost per kA of current. Observed Rate of erosion of copper in air is approximately 0.8 c.c. per KA-sec. Observed Rate of erosion of copper in SF6 is approximately 0.85 c.c. per KA-sec [13]. Contact erosion rate can be estimated as per equation (3.1) [13],

$$R = 1000 (E_C+E_A) / \rho JH \qquad (3.1)$$

where, R = Contact erosion rate, cc per kA-sec.
E_C, E_A = Cathode and anode voltage drop in Volts.
J = Heat equivalent, 4.18 joules per calories
H = Heat of vaporization, calories per gram
ρ= Density of contact material

Based on above discussion, a guideline for scoring criterion for copper contact erosion is developed as shown in Table 3.8.

TABLE 3.8

SCORING CRITERIA FOR CONTACT EROSION

Estimated Erosion Rated (R) for Copper (cc per kA-sec)	Assigned Score
R < 0.6	0.25
0.6 ≤ R < 0.8	0.75
R ≥ 0.8	1

3.4.2.3 Operating Mechanism

- **Performance of Operating Mechanism and Indication Status**

Most of the circuit breakers are either in closed position or open position for long period of time. So, when they are called for open/close operation, they must do so reliably without any added delays and sluggishness. To ensure this, breaker operating mechanism testing should be done periodically and its performance needs to be verified. Today's electronic time-travel analyzer are very handy in the measurement of parameters such as total opening and closing time, contact bounce, trip operation, close operation, trip-close operation etc. For this criterion, a score of "0" indicates satisfactory performance and maximum a score of "1" indicates poor performance for this parameter.

- **Opening /Closing Speed and Travel Distance of Main Contacts**

Opening speed and total travel distance are the basic characteristics of the opening operation. Opening speed is very crucial as it controls the fault duration and limits the contact erosion. Contact travel distance is also important from the current interruption point of view and to withstand the normal dielectric stress and the lightning impulse wave that may appear across the contacts of circuit breaker when it is connected to a circuit in open position. Also high closing speeds are desired as it indicates the reduction in mechanism energy requirement and reduction in total contact erosion [13]. Now days, electronic time-travel analyzer are available to easily measure above these parameters. Measured parameters are then compared with the manufacturer's figures to verify the breaker performance.

These are vital parameters for breaker operation as they indicate overall performance of breaker operating condition. If these parameters are as per the manufacturer's catalogue then a score "0" shall be assigned else a score "1".

3.4.2.4. Electrical Insulation Feature

- **Voltage Withstand of Insulation**

Voltage withstand capacity has to be equal or higher than that specified in the manufacturer's catalogue. Low voltage withstand capacity indicates contamination in the insulation or also to figure out the inadequate line-to-line or line-to-ground insulation. A score of "0" shall be assigned if the circuit breaker passes voltage withstand test else score of "1".

- **Audible Noise**

Circuit breaker should be observed for the presence of unusual audible noise, corona or vibration. Presence of such phenomenon indicates the arcing insulation or loose bushing etc. Immediate corrective action should be taken during such situation. Score for this shall be assigned as per the experience of the maintenance personnel. A score of "0" indicates presence of no such audible noise while a score of "1" indicates presence of high noise inside the breaker and immediate attention is required to identify its cause and necessary corrective action.

- **Bushing Condition**

Bushing condition shall be assessed as it is important component of circuit breaker. Now days online bushing monitoring systems are available for leakage current and acoustic activity monitoring. Also, physical condition of bushing shall be observed for any damage and dust accumulation. For this criterion, score of "0" indicates satisfactory condition and maximum score of "1" indicates poor condition of the bushings.

- **Breaker Loss Index**

In this, insulation power factor is measured for entire breaker, this helps in assessing the condition of all line to ground insulation system. The power factor of the system is essentially the measurement of the leakage current through the equivalent insulation system resistance. Lower the leakage current, lower the power factor and the better the insulation system. A negative power factor is the indication of tacking across the insulation system [15]. Power factor measurement also detects the voids in the insulation system. Generally, insulation power factor will be mentioned by the manufacturer. Based on that information, scoring guideline can be developed as shown in Table 3.9.

TABLE 3.9

SCORING CRITERIA FOR BREAKER LOSS INDEX

Breaker Loss Index	Assigned Score
If breaker loss index is below the manufacturer's figures	0
If breaker loss index is as per the manufacturer's allowable figures	0.25
If breaker loss index is higher than the manufacturer's allowable figures	1

3.4.2.5 Specific Parameters

- **Arc chute condition (Air Circuit Breaker)**

Arc chute is a collection of insulating barriers in a circuit breaker for confining the arc and preventing it from causing damage. Arc chutes are made up of soft steel for low voltage application and zirconium/aluminum oxide for high voltage application. Because of the high temperature of the arc, arc spots and erosion of the arc chute material takes place. These adversely affect the plate's life and arc quenching ability of the arc chutes.

Hence, physical and magnetic properties of the arc chute shall be monitored. This helps in verifying the integrity of all arc chute parts to control the arc by physical and magnetic means. Visual inspection of the arc chute plates shall be done and score shall be assigned based on the judgment of the maintenance personnel. A score of “0” indicates good Arc chute condition and score of “1” indicates poor arc chute condition.

- **Puffer Operation (Air Circuit Breaker)**

In puffer operation, air flow rate and air volume on close/open operation shall be monitored. Proper operation of air flow ensures the quick arc quenching. So puffer operating condition shall be assessed regularly. For this criterion, score of ‘0’ indicates satisfactory performance and maximum score of ‘1’ indicates poor performance of the puffer operation.

- **Vacuum Interrupter Condition (Vacuum Circuit Breaker)**

Vacuum interrupter is the important component of the vacuum circuit breaker. Generally vacuum interrupters are single phase units. Vacuum interrupter is a sealed component that does not require replacement of contact for several thousand of load operation and about 50 operations at rated short circuit current. But it needs periodic inspection and cleaning as per manufacturer. Also, checking of vacuum in the interrupter at site is very crucial aspect. Loss of vacuum i.e. internal pressure exceeding a certain threshold value 10^{-2} to 10^{-1} causes loss in current switching capacity and electric insulating properties [16]. Vacuum in the range of 10^{-4} to 10^{-6} Torr is sufficient for current interruption and for withstanding impulse test voltage. If the vacuum level is found not sufficient, then that vacuum interrupter needs to be replaced for avoiding any further failure. Now days, real time status monitoring units are mounted in the vacuum

interrupter. Such unit notifies the loss of vacuum in the interrupter. Based on the internal pressure diagnostic presented in reference [16], scoring guideline as shown in Table 3.10 is developed for assessing the condition of vacuum interrupter.

TABLE 3.10

SCORING CRITERION FOR VACUUM INTERRUPTER CONDITION

Pressure Inside Vacuum Interrupter (in Torr)	**Assigned Score**
Pressure ≤ 10^{-4} Torr (As per the manufacturer's standards)	0
10^{-4} Torr < Pressure < 10^{-2} Torr (Exceeding manufacturers standards but below 10^{-2} Torr)	0.75
Pressure ≥ 10^{-2}	1

- **SF6 Gas Level:** In the SF6 circuit breaker, SF6 gas level shall be monitored continuously. For monitoring the SF6 Gas level, on-board pressure and temperature compensated pressure switches are implemented for giving alarm and trip signals. SF6 gas level indicates the pressure and density of the SF6 in the breaker module. This condition can be assessed in terms of percentage gas leakage per year. As per IEC 62227.1, maximum leakage is 0.5% per year is allowed [17]. This criterion is used for developing the scoring guideline for this parameter and same is presented in Table 3.11.

TABLE 3.11

SCORING GUIDELINE FOR SF6 GAS LEVEL

% SF 6 gas Leakage / year	**Assigned Score**
(% SF 6 gas Leakage / year) < 0.1 %	0
0.1% ≤ (% SF 6 gas Leakage / year) < 0.5 %	0.75
(% SF 6 gas Leakage / year) ≥ 0.5 %	1

- **Moisture in SF6 (SF6 Circuit Breaker)**

Moisture in SF6 degrades the SF6 gas reducing the dielectric strength and affects the current interruption capability of the circuit breaker. Presence of moisture leads to arcing or corona which quickly degrades many types of solid insulations. Hence, monitoring or periodic checking of moisture content is very vital aspect. As per the guideline mentioned in the reference [18], upper limit on moisture level is 20ppm. Now day's portable Hygrometers are available in the market for such measurement. e.g. GE-Portable Hygrometer, PM880. This PM880 system consists of the battery-powered moisture analyzer, moisture probes, battery charger, cables and accessories [19]. Based on the above discussion scoring guideline for this parameter can be developed as shown in Table 3.12.

TABLE 3.12

SCORING CRITERIA FOR MOISTURE IN SF6

Moisture Content in SF6 (ppm)	Assigned Score
(Moisture Content in SF6) < 5 ppm	0.25
5 ppm ≤ (Moisture Content in SF6) < 10 ppm	0.5
10ppm ≤ (Moisture Content in SF6) < 15 ppm	0.75
(Moisture Content in SF6) ≥ 15 ppm	1

3.4.2.6 Control Circuit Operation:

- **Control Circuit Operation:** Control circuit operation shall be checked regularly to ensure its reliable operation. In control circuit operation, trip & close coil operation, auxiliary contacts, relay contacts, motor current, trip & close command initiation and breaker control supply are measured. With this information response of TC & CC are

derived, need for lubrication is verified and need for adjustment of auxiliary contact is checked. Also monitoring the breaker control supply voltage is useful to detect the adjustment of battery charger setting, battery problem and to ensure the supply circuit integrity.

Score assignment for these parameters shall be given as per the experience of maintenance personnel. A score of “0” indicates the satisfactory performance and condition of the circuit breaker. Whereas, score of “1” indicates the need of frequent attention to the control circuit and related components.

3.4.3 Discussion on Weight Assignment for Selected Criterion:

Weight assignment to each parameter is very important stage in this equipment condition assessment sheet. Weight assignment procedure is more system specific and also need inputs from the maintenance people and equipment manufacturers. Weight selection criterion for each parameter shall be selected in such a way that it will highlight the criticality of particular parameter in the overall equipment’s condition assessment. Following are the guidelines for deciding and selecting the weights.

- In weight selection criteria combined opinion from the maintenance personnel and equipment manufacturers shall be considered.
- If particular Utility is having detail information regarding the historical failures and maintenance activities of the circuit breakers on the system. e.g. causes and frequency of various circuit breaker failures or details of maintenance activities performed frequently shall be categorized as per the parameters mentioned in the condition assessment sheet. This will provide guideline for giving importance to particular parameter.

- Weight assignment of particular parameters shall also be selected with respect to score of particular parameter. This procedure will help in emphasizing the criticality of that parameter in overall failure rate estimation of the equipment. e.g. for parameter such as oil condition, winding condition such method shall be developed.
- With respect to the above discussion, a sample weight assignment sheet for circuit breaker is developed as shown in Table 3.13. Such condition assessment sheet needs to developed and finalized for a particular utility which will be helpful in uniform condition assessment of circuit breaker across the system.

3.4.3.1 Sample Weight Assignment / Selection Sheet

Sample weight assignment / selection sheet for circuit breaker is presented in Table 3.13.

TABLE 3.13

SAMPLE WEIGHT ASSIGNMENT / SELECTION SHEET

	Sr. No		Criteria	Weight Selection			
				Score 0-0.25	Score 0.26- 0.5	Score 0.51-0.75	Score 0.76-1
GENERAL	1	I	Age of the Circuit Breaker	10			
	2	I	Experience with Circuit Breaker type	10			
	3	I, M	Number of breaker operation	10		15	
	4	I	Environmental factors	10			
POWER CONTACTS	5	O	Contact resistance	10	15	20	25
	6	I	Contact & conductor temperature	5			
	7	I	Bushing terminal temperature	5			
	8	O	Contact Erosion	10	15	20	25
OPERATING MECHNISM	9	I, M	Condition of release mechanism	15	20	25	30
	10	I	Indication Status	5			
	11	O	Time for Main & Auxiliary Contact Status Operation	10	15	20	25

TABLE 3.13 (continued)

	Sr. No		Criteria		Weight Selection			
					Score 0-0.25	Score 0.26- 0.5	Score 0.51-0.75	Score 0.76-1
INSULATIONS	13	O	Voltage withstand of insulation		20			
	14	I	Audible Noise		10			
	15	I, M	Bushing Condition		10		20	
	16	O	Breaker loss index		10	15	20	25
SPECIFIC PARAMETERS	17	O	AIR	Arc Chute Condition	10			
	18	O		Puffer condition	10			
	19							
	20	I, M	VACUUM	Vacuum interrupter condition	20			
	21							
	22							
	23	O	SF6	SF6 Gas Level	10			
	24	O		Moisture in SF6	10			
CONTROL CIRCUIT	25	I, M	Trip & Close coil operation		5	10	15	20
	26	I, M	Condition of charging motor		5	10	15	20
	27	I, M	Control Circuit function		5	10	15	20
	28	I, M	Condition of charging motor, relay & auxiliary contact, heater.		5	10	15	20

3.5 Failure Rate Estimation

Based on the information from the periodic inspection & maintenance activities performed on the equipment and equipment operational data obtained from the online monitoring systems, available parameters of the Condition Assessment Sheet for circuit breaker shall be filled and scores shall be assigned as per the developed guideline. Then the available condition assessment data is then processed for the failure rate estimation for that equipment based upon the guidelines developed in the reference [2].

In reference [2], exponential model is used to describe relationship between normalized equipment condition score and failure rate of the equipment.

- Score for each parameter in the condition assessment sheet is interpreted as below:

  Score = 0, Indicates the best equipment condition and all the inspection results are well within the limits as specified the manufacturer.

  Score = 0.5, Indicates the average equipment condition

  Score = 1, Indicates the worst equipment condition and immediate attention is required.

- With the help of the weight and score assigned for each of the parameter, weighted average/condition score for the particular circuit breaker is determined as per equation (3.2).

$$Weighted\ Score = \sum_{\substack{for\ all \\ parameters}} (Weight * Score) \div \sum_{\substack{for\ all \\ parameters}} Weight \qquad (3.2)$$

- Above calculated circuit breaker condition score/weighted score is then required to relate with the failure rate. For this purpose the historical failure rates for circuit breakers as mention in the reference [1] & [2] are used. As per this data, Best, Average and Worst circuit breaker failure rates are as follows,

λ (0) = 0.0005 (Best)
λ (1/ 2) = 0.010 (Average)
λ (1) = 0.060 (Worst)

- With the help of Best, Average and lowest failure rates, coefficient A, B and C are calculated as per the following equations (3.3), (3.4) and (3.5) [2]:

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \tag{3.3}$$

$$B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right) \tag{3.4}$$

$$C = \lambda(0) - A \tag{3.5}$$

- From the condition score and above mentioned parameters A, B & C, failure rate of the equipment can be predicted as per equation (3.6) [2].

$$\lambda(x) = Ae^{B*x} + C \tag{3.6}$$

3.6 Circuit breaker Online Monitoring Systems

For circuit breaker, various monitoring system are been developed over the years. Some on them are as mentioned below:

- ABB-C*stat* Circuit Breaker Monitor (www.abb.com/electricutilities)
- Varmaster Vacuum Interrupter - Monitor (www.joslynhivoltage.com)
- Hathaway Power Instrumentation – Circuit Breaker Testing and Condition Monitoring System
- GE-TM1800 Circuit Breaker Analyzer Systems – (http://www.gepower.com/prod_serv/products/electrical_test/en/downloads_new/down_en/test_cir_break/tm1800_e.pdf)
- Digital Resistance Meters :

Data collected by such Circuit Breaker Monitoring systems and sophisticates measuring instruments can be easily analyzed as per the scoring criteria developed and then reflected in the overall equipment condition assessment sheet. Table 3.14 represents the way data from monitoring systems can be utilized for circuit breaker condition assessment.

TABLE 3.14

INPUT TO CIRCUIT BREAKER CONDITION ASSESSMENT FROM ONLINE MONITORING SYSTEMS

Online Monitoring for Circuit Breaker		→	**Condition Assessment for Circuit Breaker**	
System/ Component	**Information available from the Circuit Breaker**		**Criteria**	**Parameter to be Assessed**
Breaker Operating mechanism	• Number of Breaker operations • Air compressor pressure, current and charge time • Hydraulic pumps operations, pressure and current • Loss of speed indication • Loss of safety factor calculation	→	Criterion No. 3 Criterion No. 10	To assess the number of breaker operations. To assess the movement of release mechanism.
Breaker Power Contacts	• Contact resistance • Contact travel time	→	Criteria No. 5 &12	To assess the condition of contact resistance and travel time.
Bushing	• Leakage current • Acoustic activity	→	Criterion No. 18	To assess Bushing condition.
Vacuum Interrupter	• Loss of vacuum detection	→	Criterion No. 23	To assess the condition of Vacuum Interrupter

TABLE 3.14 (continued)

Online Monitoring for Circuit Breaker		→	Condition Assessment for Circuit Breaker	
System/ Component	**Information available from the Circuit Breaker**		**Criteria**	**Parameter to be Assessed**
Breaker Control Circuit	• Overall trip/close time • Current at each phase at time of Trip/close event • Phase Time Differential During trip and close • Current in each phase • Voltage of trip/close coil	→	Criteria Nos. 29 to 32	To assess the condition of Control Circuit.
SF6 Breaker	• Portable Hygrometers (equipped with moisture measurement sensor) can be used for moisture content measurement.	→	Criteria No. 27	To assess the condition of SF6 Gas

3.7 Example

Three and half years of outage data is obtained from an Electric utility in the mid west region. From the outage data, total number of circuit breakers failed during last 3.5 years is obtained. Total 63 numbers of circuit breakers failed. From the substation single line diagrams and feeder numbers, total number of circuit breaker installed on the system are found out. It was found that total 727 numbers of circuit breakers are installed on the system. From this data, we can find out the average failure rate λ(1/2) of circuit breaker as below,

$$\lambda(1/2) = (63) / (727 * 3.5) = 0.02475$$

Best and worst failure rates for the circuit breaker, λ(0) and λ(1), respectively, are then calculated. Each breaker failed either zero times or one time during the last 3.5 years. This will give best and worst failure rate as below,

Best failure rate, λ(1/2) = 0 failure / 3.5 years = 0.0000

Worst failure rate, λ(1/2) = 1 failure / 3.5 years = 0.2857

The best and worst failures rates obtained above are either too law or too high, respectively. Hence the following published failure rates are used in from reference [2]. The same are listed below.

λ(0) = 0.0005 λ(1/2) = 0.010 λ(1) = 0.060

Then, next step is calculation of A, B & C coefficient as defined earlier. The calculated values are mentioned below,

A = 0.00223 B = 3.3214624 C = -0.0017283

With above data, equation for failure rate estimation can be presented as below,

$$\lambda\,(x) = (\,0.00223 * \,e^{3.3214642 * x}\,) + (\,-0.0017283\,)$$

Above equation can be plotted in termer of failure rate λ(0) and equipment condition score x as shown in Figure 3.2.

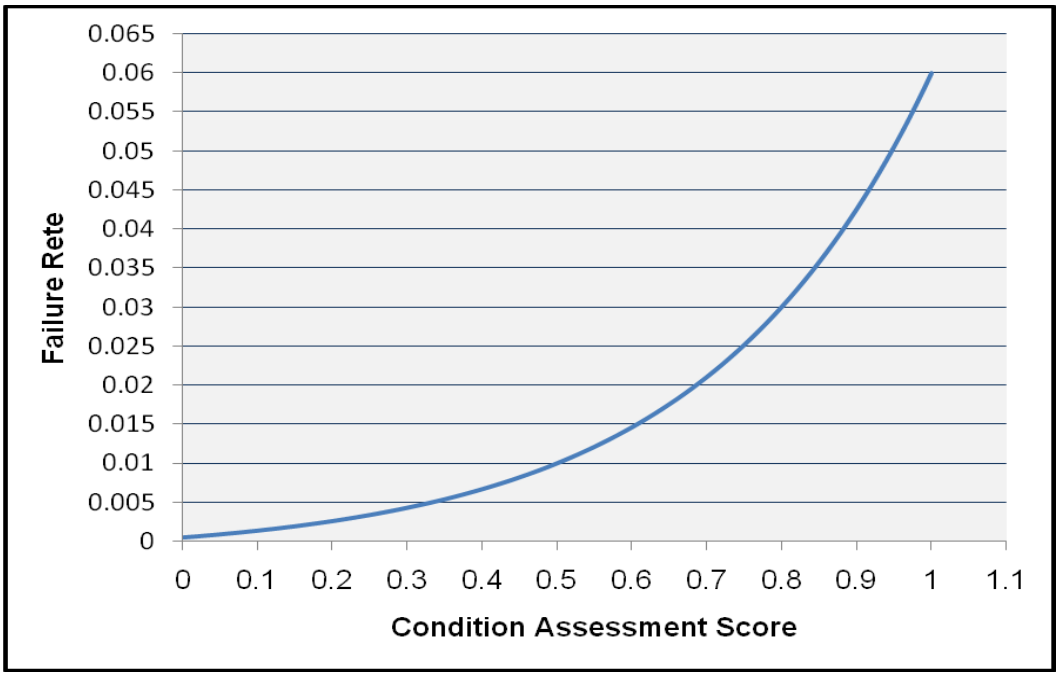

Figure 3.2: Circuit breaker condition assessent score Vs estimated failure rate

CHAPTER 4

RELIBILITY PREDICTION FOR IEEE TEST SYSTEM

4.1 Introduction

An IEEE Test case is selected to demonstrate the importance of system reliability study done with the equipment failure rate obtained the from the condition assessment sheet. This test case is taken from the Reliability test system for educational purpose from reference [20]. Selected test case has 4 feeders, 1908 customers, 12.29 MVA load. This test case is useful as it is designed as per the general distribution utility principle and practice.

4.2 Assumptions

Following assumptions are considered regarding the test feeder:

- All the feeders are operated as radial feeders but connected as mesh through normally open sectionalizing switches.
- All 11kV feeder and laterals are considered as overhead line.
- Commercial, residential and government loads are metered on low voltage side and transformer is utility property and is considered in the analysis.
- All breakers in the system are identified.
- Each of the 11kV feeder and lateral is either 0.6km, 0.75km or 0.8km.

4.3 System Data

Various system related data such as Load Point Data, Feeder Wise Loading Data, Feeder Data, Component Reliability Data, Load Point Reliability Data and System Configuration is presented as below.

4.3.1 Load Point Data

Given system has 22 Load Points (LP) across the four feeders. Total load and customers connected at each load point is mentioned in the table 4.1 below.

TABLE 4.1

SYSTEM LOAD DATA

Number of load points	Load Points	Customer Type	Load in kW	No of Customers
5	1-3, 10, 11	Residential	535	210
4	12, 17-19	Residential	450	200
1	8	Small user	1000	1
1	9	Small user	1150	1
6	4, 5, 13, 14, 20, 21	Govt./inst	566	1
5	6, 7, 15, 16, 22	commercial	454	10
Total			**12291**	**1980**

4.3.2 Feeder Wise Loading Data:

Feeder wise loading data and total number of customers connected at each load point is presented in Table 4.2.

TABLE 4.2

FEEDER WISE LOADING DATA

Feeder No.	Load Points	Load in kW	Number of customers
Feeder 1	1-7	3645	652
Feeder 2	8-9	2150	2
Feeder 3	10-15	3106	632
Feeder 4	16-22	3390	622

4.3.3 Feeder Data

Three types of feeders (0.60km, 0.75km and 0.80km) are mentioned for the given system. Detail for each feeder length data is mentioned in the Table 4.3.

TABLE 4.3

FEEDER WISE LENGTH DATA

Feeder Type	Length in km	Feeder Section number
1	0.60	2, 6, 10, 14, 17, 21, 25, 28, 30, 34
2	0.75	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35
3	0.80	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36

4.3.4 Component Reliability Data:

Given system have many components such as transformer, circuit breaker, busbar and overhead line. All these components have different reliability data. Same is mentioned in the Table 4.4.

TABLE 4.4

COMPONENT RELIABILITY DATA

Component	Permanent Failure rate (λ)	Repair Time in Hours	Switching time in Hours
Transformer			
33/11 kV	0.015	200	--
11kV	0.015 / 0.03	200	--
Circuit Breaker			
33kV	0.0020	4	1
11kV	0.0060 / 0.012	4	1
Busbar			
11 kV	0.0010	2	--
OH Lines			
11 kV	0.065	5	--
Cables			
11kV	0.040	30	--

4.3.4 Load Point Reliability Data

Load point reliability data is required at each load point for the system study. The same is mentioned in the Table 4.5.

TABLE 4.5

LOAD POINT RELIABILITY DATA

Load point	**Failure Rate (λ) In failures/year**	**Repair Time (r) in hours**	**Failure Hours (U) in hours/year**
Feeder 1			
1	0.240	14.90	3.58
2	0.253	14.40	3.64
3	0.253	14.40	3.64
4	0.240	14.90	3.58
5	0.253	14.40	3.64
6	0.250	14.51	3.63
7	0.253	14.24	3.60
Feeder 2			
8	0.140	3.89	0.54
9	0.140	3.60	0.50
Feeder 3			
10	0.243	14.73	3.58
11	0.253	14.40	3.64
12	0.256	14.29	3.66
13	0.253	14.19	3.59
14	0.256	14.08	3.61
15	0.243	14.73	3.58
Feeder 4			
16	0.253	14.40	3.64
17	0.243	14.48	3.59
18	0.243	14.73	3.58
19	0.256	14.24	3.65
20	0.256	14.24	3.65
21	0.253	14.19	3.59
22	0.256	14.08	3.61

4.3.5: System Configuration

System configuration is presented in Figure 4.1.

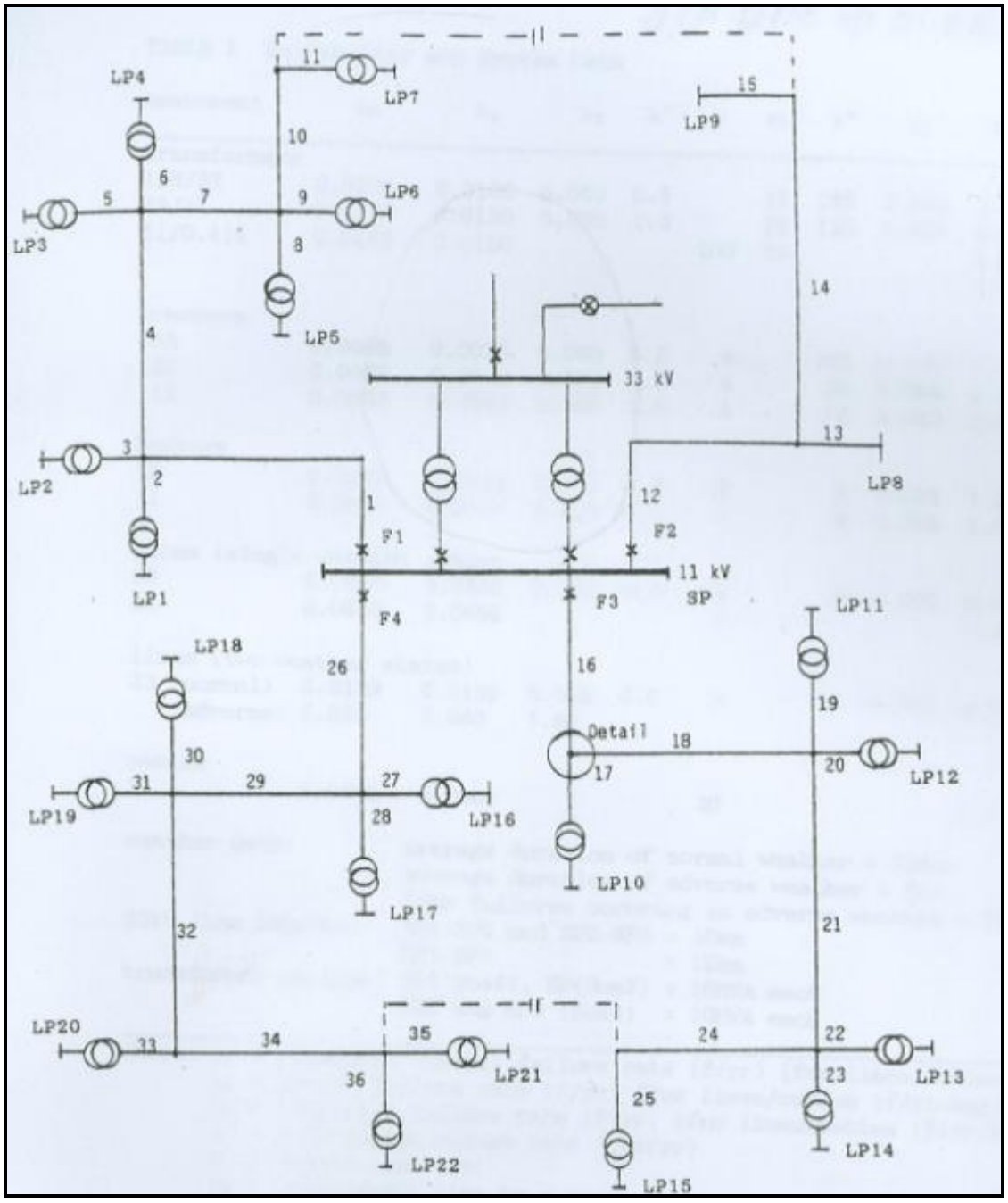

Figure 4.1: System configuration of the IEEE test case

4.4 IEEE Test Case Simulations:

Above system is simulated in software, MilSoft Utility Solution [21, 22] for reliability analysis. Reliability of the system is studied in terms of the reliability indices.

SAIFI: System Average Interruption Frequency Index

SAIDI: System Average Interruption Duration Index

CAIDI: Customer Average Interruption Duration Index

ASAI: Average Service Availability Index

ALIFI: Average Load Interruption Frequency Index

ALIDI: Average Load Interruption Duration Index

4.4.1 System Simulation in MilSoft Utility Solution

Pictorial representation of the system simulation in MilSoft is presented in Figure 4.2.

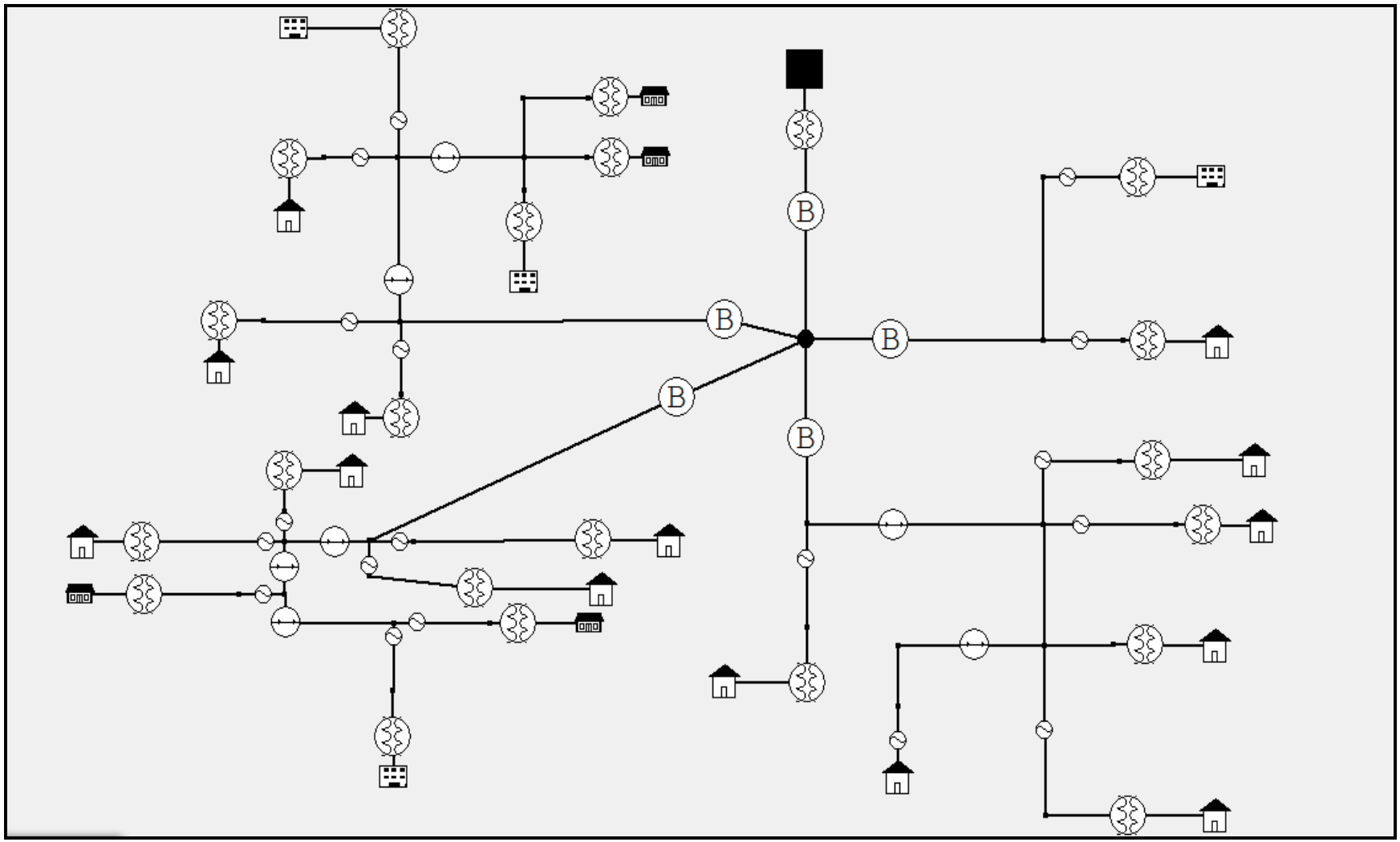

Figure 4.2: System imulation in MilSoft Utility Soltuion

4.4.2 IEEE System Simulation CASE -1

System reliability indices are calculated with the standard reliability data given in the IEEE System. The same are presented in Table 4.6.

TABLE 4.6

SYSTEM RELIABILITY INDICES FOR CASE-1

	SAIFI	SAIDI	CAIDI	ASAI	ALIFI
Feeder-1	1.6938	14.3656	8.4815	0.9982	1.5671
Feeder-2	0.4300	10.0525	23.4013	0.9984	0.4300
Feeder-3	1.0802	19.9495	18.4653	0.9977	1.0113
Feeder-4	0.6673	13.3865	20.0608	0.9985	0.6692
System	1.1546	15.8903	13.7630	0.9982	0.9789

4.4.3 IEEE System Simulation CASE-2

In case-2, system reliability indices are calculated with standard equipment failure rate except for transformer and circuit breaker. For transformer and circuit breaker, failure rates are drawn from the respective equipment condition assessment technique. For this step we have assumed the condition assessment data for each transformer and breaker, the same is presented in Table 4.7 and Table 4.8. Then this condition assessment score is converted into the failure rate for respective equipment and then used for system reliability study.

TABLE 4.7

FAILURE RATE FOR TRANSFORMER BEFORE MAINTENANCE

Transformers	Condition Score Before maintenance	Failure Rate Before Maintenance
Trafo at LP1	0.567	0.047832589
Trafo at LP2	0.634	0.056931657
Trafo at LP3	0.556	0.046465357
Trafo at LP4	0.678	0.063697507

TABLE 4.7 (continued)

Transformers	Condition Score Before maintenance	Failure Rate Before Maintenance
Trafo at LP5	0.546	0.045251416
Trafo at LP6	0.675	0.06321464
Trafo at LP7	0.612	0.053791554
Trafo at LP8	0.5234	0.042606386
Trafo at LP9	0.5786	0.049311494
Trafo at LP10	0.6897	0.065612111
Trafo at LP11	0.655	0.060077417
Trafo at LP12	0.5324	0.043643644
Trafo at LP13	0.5783	0.049272759
Trafo at LP14	0.6987	0.067119533
Trafo at LP15	0.6324	0.056698013
Trafo at LP16	0.567	0.047832589
Trafo at LP17	0.643	0.058261678
Trafo at LP18	0.654	0.059924228
Trafo at LP19	0.546	0.045251416
Trafo at LP20	0.587	0.050406757
Trafo at LP21	0.712	0.069403751
Trafo at LP22	0.582	0.049752325

TABLE 4.8

FAILURE RATES FOR CIRCUIT BREAKER BEFORE MAINTENANCE

Circuit Breakers	Condition Score Before Maintenance	Failure Rate Before Maintenance
CB at Feeder 1	0.643	0.017144031
CB at Feeder 2	0.745	0.024754289
CB at Feeder 3	0.721	0.022725169
CB at Feeder 4	0.646	0.017333023

With the above presented failure rate for transformer and circuit, system reliability study is performed. Results of the same are presented in Table 4.9.

TABLE 4.9

SYSTEM RELIABILITY INDICES FOR CASE-2

	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI
Feeder-1	1.8246	20.0327	10.9792	0.9977	1.6897	32.0246
Feeder-2	0.4800	13.3866	27.888	0.9985	0.4802	13.4258
Feeder-3	1.1648	28.3866	24.8763	0.9967	1.0964	28.0348
Feeder-4	0.7252	18.2928	26.0253	0.9979	0.7277	18.6800
System	1.2462	22.4206	17.9909	0.9974	1.0603	23.9309

4.4.4 IEEE System Simulation CASE-3

In case-3, it is assumed that the all the maintenance activity is done on all the transformer and circuit breakers of the system. This resulted in improved condition scores for these equipments. The same are presented in Table 4.10. With the use of this condition score, new failure rates are estimated from the technique developed in earlier chapters.

TABLE 4.10

FAILURE RATE OF TRANSFORMER AFTER MAINTENANCE

	Condition Score After Maintenance	Failure rate before Maintenance
Trafo at LP1	0.156	0.014075059
Trafo at LP2	0.1876	0.015711043
Trafo at LP3	0.2654	0.020270712
Trafo at LP4	0.1456	0.013561556
Trafo at LP5	0.243	0.018875192
Trafo at LP6	0.1856	0.015604019
Trafo at LP7	0.2345	0.018363764
Trafo at LP8	0.1567	0.014110055
Trafo at LP9	0.235	0.018393578
Trafo at LP10	0.328	0.024564738
Trafo at LP11	0.321	0.024054028
Trafo at LP12	0.234	0.018333983
Trafo at LP13	0.183	0.015465606
Trafo at LP14	0.132	0.012907913

TABLE 4.10 (Continued)

	Condition Score After Maintenance	Failure rate before Maintenance
Trafo at LP15	0.1987	0.016313848
Trafo at LP16	0.274	0.020825439
Trafo at LP17	0.165	0.01452923
Trafo at LP18	0.124	0.012532649
Trafo at LP19	0.187	0.015678885
Trafo at LP20	0.154	0.013975374
Trafo at LP21	0.256	0.019676525
Trafo at LP22	0.342	0.025610584

TABLE 4.11

FAILURE RATE OF CIRCUIT BREAKER AFTER MAINTENANCE

Circuit Breakers	Condition Score After Maintenance	Failure Rate After Maintenance
CB at Feeder 1	0.231	0.003074695
CB at Feeder 2	0.341	0.005193020
CB at Feeder 3	0.261	0.003577950
CB at Feeder 4	0.206	0.002691973

With these new failure rates for the transformer and circuit breaker, system reliability studies are performed. Results of the same are presented in Table 4.12.

TABLE 4.12

SYSTEM RELIABILITY INDICES FOR CASE-3

	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI
Feeder-1	1.6153	12.3655	7.6554	0.9986	1.4906	18.2811
Feeder-2	0.3826	7.1600	18.7141	0.9992	0.3827	7.1854
Feeder-3	1.0288	17.2379	16.7554	0.9980	0.9576	16.0267
Feeder-4	0.6188	10.2699	16.5954	0.9988	0.6233	11.0453
System	1.0949	13.2908	12.1389	0.9985	0.9216	13.6885

4.5 Results and Discussion:

Here, system reliability performance for three different cases is obatined. In Case-1, system performance is obtained with the standards equipment failure rates. In case-2 and case-3, system performance is obtained with the transformer and circuit breaker reliability data derived from the condition assessment before and after maintenance activity respectively. As expected, the system performance is poor in case-2 and the same is improved in case-3. Such assessment of system reliability performance is possible only due to the equipment condition assessment technique and failure rate estimation technique which is developed earlier. In Figure 4.3, 4.4 and 4.5 system performance in terms of SAIFI, SAIDI and CADIA is presented respectively.

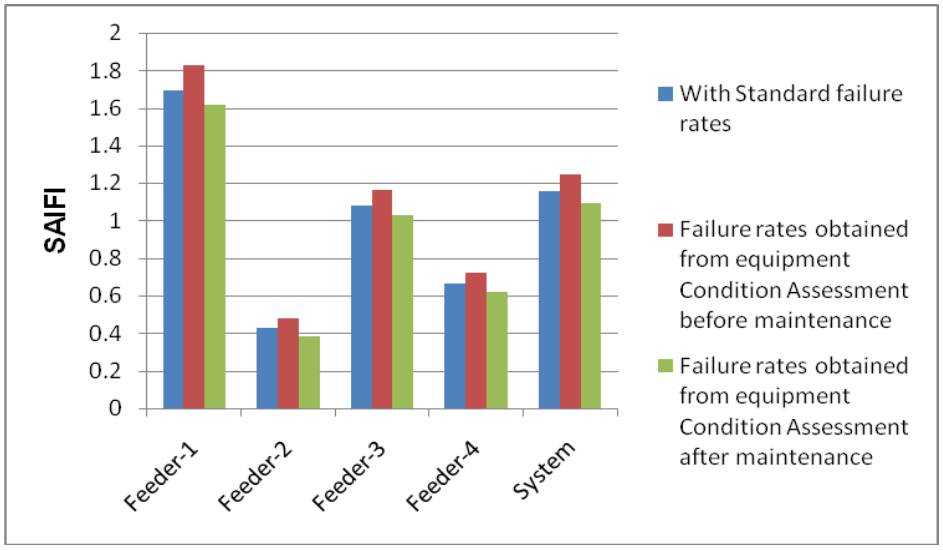

Figure 4.3: System performance in terms of SAIFI

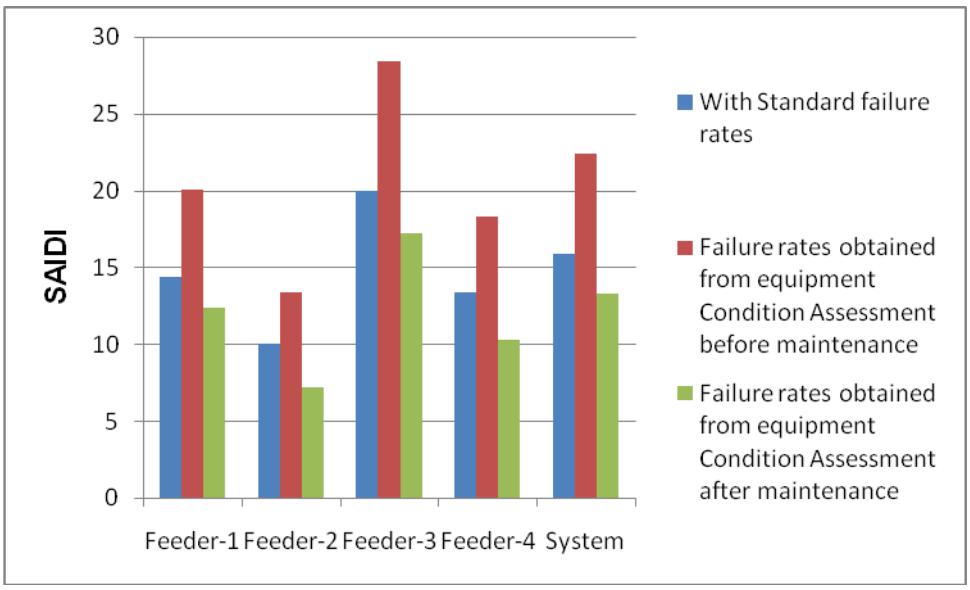

Figure 4.4: System performance in terms of SAIDI

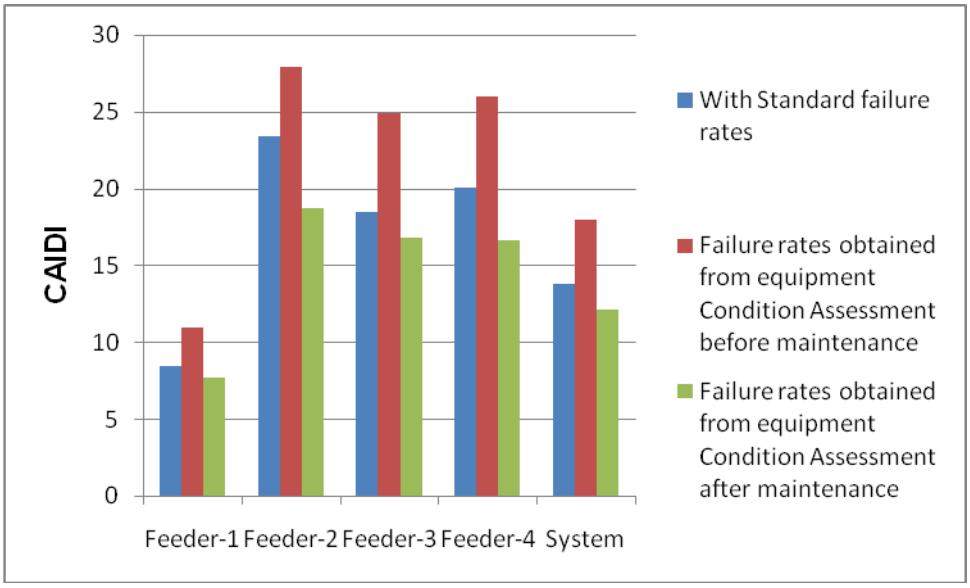

Figure 4.5: System perforamance in terms of CAIDI

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Discussion and Conclusions

A method is need to justify the maintenance expenditure on various distribution assets based on their physical and operational condition. Also, there is a need to systematically relate the system wide maintenance activities and to assess their impact on the overall system reliability performance. This research work focused on transformers and circuit breakers and develops the technique for condition assessment and health index estimation. Then, a method was used to convert the equipment health index score into estimation of failure rate based on best, average, and worst historical failure rates.

The equipment condition assessment technique developed was based on the parameters that assess equipment's various components and subsystems. So impact of performance of each component and subsystem is reflected into overall condition assessment for that equipment. Also, scoring criteria helps to quantify the condition of each parameter and weighting criteria helped to quantify the impact of that parameter in the overall health of the equipment. Also, the way in which data from online monitoring systems can be incorporated into the equipment condition assessment is presents for transformers and circuit breakers.

In Chapter - 4, the results of the reliability study of an IEEE test case shows that system models using component failure rates obtained from equipment condition assessment techniques give more realistic and system specific results, rather than using the standard failure rates. It shows a method to take into account the asset

maintenance activities, reflect those in the equipment condition assessment and estimate component specific failure rate, and assess its impact on system reliability.

5.2 Future Work

The equipment condition assessment technique developed for transformer and circuit breaker could be further developed for other system components. Once, such models are developed for all the components in the system, its impact on the performance of system reliability shall be studied. Also, the scoring and weighing criteria developed for various parameters of each equipment could be tested in different systems to ensure their validity and need for further improvement.

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APPENDIX

APPENDIX – A

PREDICTIVE RELIABILITY ANALYSIS FOR IEEE TEST CASES

CASE- 1: Predictive Reliability Analysis – With all standard failure rates for all the equipment.

Summary

Predictive Reliability Analysis Settings
Source:

Database: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\FEEDER WITH STANDARD DATA.WM\
Title:
Case: 01/20/2008 21:15 Page 1

Reliability Analysis Settings:
Do Upline Fault Isolation
Do Downline Fault Isolation
Include Coordination Failure
If Fix Time is less than 1.00 hours then do not consider switching.
Do switching only if outage hour improvement is greater than 30.00 percent.
1 Crew is avaliable to work each outage.
Time to find trouble is 1.00 hours.
Travel Time is fixed at 0.17 hours per trip.
If calculated travel distance is less than 0.25 miles then travel time is set to 0.0 hours.

Source Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.1546	15.8903	13.7630	0.9982	0.9789	17.1035	1908.0	11837.5
Total System	1.1546	15.8903	13.7630	0.9982	0.9789	17.1035	1908.0	11837.5

Detail

Predictive Reliability Analysis Report
Source: SRC16

Database: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\FEEDER WITH STANDARD DATA.WM\
Title:
Case: 01/20/2008 21:15 Page 2

Element Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.1546	15.8903	13.7630	0.9982	0.9789	17.1035	1908.0	11837.5
Incomer OCD55	1.1546	15.8903	13.7630	0.9982	0.9789	17.1035	1908.0	11837.5
Feeder 3_OCD17	1.0802	19.9459	18.4653	0.9977	1.0113	19.6070	632.0	2652.5
OCD29	1.0770	21.4763	19.9409	0.9975	1.0770	21.4763	200.0	450.0
OCD27	1.0890	24.5403	22.5347	0.9972	1.0890	24.5403	210.0	535.0
OCD51	1.0160	24.7433	24.3536	0.9972	1.0160	24.7433	10.0	0.5
OCD42	1.0920	24.5051	22.4405	0.9972	1.0920	24.5051	1.0	566.0
OCD19	1.0790	13.6712	12.6703	0.9984	1.0790	13.6712	210.0	535.0
Feeder 4_OCD58	0.6673	13.3865	20.0608	0.9985	0.6692	13.6449	622.0	3390.0
OCD64	0.6630	13.1287	19.8020	0.9985	0.6630	13.1287	200.0	450.0
OCD61	0.6550	12.9118	19.7127	0.9985	0.6550	12.9118	10.0	454.0
OCD75	0.6760	13.5444	20.0362	0.9985	0.6760	13.5444	200.0	450.0
OCD71	0.6630	13.4632	20.3065	0.9985	0.6630	13.4632	200.0	450.0
OCD112	0.6730	14.1789	21.0682	0.9984	0.6730	14.1789	1.0	566.0
OCD109	0.6760	14.1968	21.0012	0.9984	0.6760	14.1968	10.0	454.0
OCD103	0.6760	13.8911	20.5490	0.9984	0.6760	13.8911	1.0	566.0
Feeder 2_OCD119	0.4300	10.0625	23.4013	0.9989	0.4300	10.0598	2.0	2150.0
OCD121	0.4300	10.1024	23.4940	0.9988	0.4300	10.1024	1.0	1000.0
OCD127	0.4300	10.0227	23.3085	0.9989	0.4300	10.0227	1.0	1150.0
Feeder 1_OCD101	1.6938	14.3656	8.4815	0.9984	1.5671	22.6530	652.0	3645.0
OCD128	1.7010	14.8443	8.7268	0.9983	1.7010	14.8443	1.0	566.0
OCD124	1.7140	14.9267	8.7087	0.9983	1.7140	14.9267	210.0	535.0
OCD113	1.6990	11.5625	6.8055	0.9987	1.6990	11.5625	210.0	535.0
OCD107	1.7010	14.4977	8.5230	0.9983	1.7010	14.4977	210.0	535.0

CASE- 2: Predictive Reliability Analysis – With failure rates of transformer and circuit breaker before maintenance.

Summary

Predictive Reliability Analysis Settings
Source:

Database: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\TEST CASE WITH CONDITION ASSESSMENT DATA B4 MAINTENNACE.WM\
Title:
Case: 01/20/2008 21:01 Page 1

Reliability Analysis Settings:
Do Upline Fault Isolation
Do Downline Fault Isolation
Include Coordination Failure
If Fix Time is less than 1.00 hours then do not consider switching.
Do switching only if outage hour improvement is greater than 30.00 percent.
1 Crew is avaliable to work each outage.
Time to find trouble is 1.00 hours.
Travel Time is fixed at 0.17 hours per trip.
If calculated travel distance is less than 0.25 miles then travel time is set to 0.0 hours.

Source Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.2462	22.4206	17.9909	0.9974	1.0603	23.9309	1908.0	11837.5
Total System	1.2462	22.4206	17.9909	0.9974	1.0603	23.9309	1908.0	11837.5

Detail

Predictive Reliability Analysis Report
Source: SRC16

atabase: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\TEST CASE WITH CONDITION ASSESSMENT DATA B4 MAINTENNACE.WM\
itle:
ase: 01/20/2008 21:01 Page 2

lement Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.2462	22.4206	17.9909	0.9974	1.0603	23.9309	1908.0	11837.5
Incomer OCD55	1.2462	22.4206	17.9909	0.9974	1.0603	23.9309	1908.0	11837.5
Feeder 3_OCD17	1.1648	28.9752	24.8763	0.9967	1.0904	28.0348	632.0	2652.5
OCD29	1.1590	31.2488	26.9619	0.9964	1.1590	31.2488	200.0	450.0
OCD27	1.1720	34.5139	29.4488	0.9961	1.1720	34.5139	210.0	535.0
OCD51	1.0960	34.1089	31.1213	0.9961	1.0960	34.1089	10.0	0.5
OCD42	1.1820	35.8869	30.3612	0.9959	1.1820	35.8869	1.0	566.0
OCD19	1.1680	21.0456	18.0185	0.9976	1.1680	21.0456	210.0	535.0
Feeder 4_OCD58	0.7252	18.2928	25.2260	0.9979	0.7277	18.6800	622.0	3390.0
OCD64	0.7250	18.8684	26.0253	0.9978	0.7250	18.8684	200.0	450.0
OCD61	0.7070	16.6398	23.5358	0.9981	0.7070	16.6398	10.0	454.0
OCD75	0.7250	16.6689	22.9916	0.9981	0.7250	16.6689	200.0	450.0
OCD71	0.7260	19.4041	26.7274	0.9978	0.7260	19.4041	200.0	450.0
OCD112	0.7460	22.1314	29.6668	0.9975	0.7460	22.1314	1.0	566.0
OCD109	0.7300	18.3271	25.1057	0.9979	0.7300	18.3271	10.0	454.0
OCD103	0.7300	18.0214	24.6869	0.9979	0.7300	18.0214	1.0	566.0
Feeder 2_OCD119	0.4800	13.3866	27.8888	0.9985	0.4802	13.4258	2.0	2150.0
OCD121	0.4770	12.8246	26.8860	0.9985	0.4770	12.8246	1.0	1000.0
OCD127	0.4830	13.9487	28.8792	0.9984	0.4830	13.9487	1.0	1150.0
Feeder 1_OCD101	1.8246	20.0327	10.9792	0.9977	1.6897	32.0246	652.0	3645.0
OCD128	1.8410	21.8870	11.8886	0.9975	1.8410	21.8870	1.0	566.0
OCD124	1.8370	18.5495	10.0977	0.9979	1.8370	18.5495	210.0	535.0
OCD113	1.8470	20.2145	10.9445	0.9977	1.8470	20.2145	210.0	535.0
OCD107	1.8250	18.3217	10.0393	0.9979	1.8250	18.3217	210.0	535.0

CASE- 3: Predictive Reliability Analysis – With failure rates of transformer and circuit breaker after maintenance.

Summary

Predictive Reliability Analysis Settings
Source:

Database: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\WITH CONDITION ASSESSMENT DATA AFTER MAINTENANCE.WM\
Title:
Case: 01/20/2008 21:22 Page 1

Reliability Analysis Settings:
Do Upline Fault Isolation
Do Downline Fault Isolation
Include Coordination Failure
If Fix Time is less than 1.00 hours then do not consider switching.
Do switching only if outage hour improvement is greater than 30.00 percent.
1 Crew is avaliable to work each outage.
Time to find trouble is 1.00 hours.
Travel Time is fixed at 0.17 hours per trip.
If calculated travel distance is less than 0.25 miles then travel time is set to 0.0 hours.

Source Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.0949	13.2908	12.1389	0.9985	0.9216	13.6885	1908.0	11837.5
Total System	1.0949	13.2908	12.1389	0.9985	0.9216	13.6885	1908.0	11837.5

Detail

Predictive Reliability Analysis Report
Source: SRC16

Database: C:\MILSOFT\EXAMPLES\PRASAD PRACTICE\WITH CONDITION ASSESSMENT DATA AFTER MAINTENANCE.WM\
Title:
Case: 01/20/2008 21:22 Page 2

Element Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC16	1.0949	13.2908	12.1389	0.9985	0.9216	13.6885	1908.0	11837.5
Incomer OCD55	1.0949	13.2908	12.1389	0.9985	0.9216	13.6885	1908.0	11837.5
Feeder 3_OCD17	1.0288	17.2379	16.7550	0.9980	0.9576	16.0267	632.0	2652.5
OCD29	1.0316	18.9676	18.3866	0.9978	1.0316	18.9676	200.0	450.0
OCD27	1.0346	20.2211	19.5448	0.9977	1.0346	20.2211	210.0	535.0
OCD51	0.9536	18.8171	19.7327	0.9979	0.9536	18.8171	10.0	0.5
OCD42	1.0266	17.9730	17.5073	0.9979	1.0266	17.9730	1.0	566.0
OCD19	1.0256	12.5582	12.2447	0.9986	1.0256	12.5582	210.0	535.0
Feeder 4_OCD58	0.6188	10.2699	16.5954	0.9988	0.6233	11.0453	622.0	3390.0
OCD64	0.6146	10.0240	16.3098	0.9989	0.6146	10.0240	200.0	450.0
OCD61	0.6126	11.0141	17.9793	0.9987	0.6126	11.0141	10.0	454.0
OCD75	0.6286	10.6409	16.9279	0.9988	0.6286	10.6409	200.0	450.0
OCD71	0.6126	9.9562	16.2524	0.9989	0.6126	9.9562	200.0	450.0
OCD112	0.6286	11.8789	18.8973	0.9986	0.6286	11.8789	1.0	566.0
OCD109	0.6376	13.1038	20.5517	0.9985	0.6376	13.1038	10.0	454.0
OCD103	0.6266	10.5852	16.8931	0.9988	0.6266	10.5852	1.0	566.0
Feeder 2_OCD119	0.3826	7.1600	18.7141	0.9992	0.3827	7.1854	2.0	2150.0
OCD121	0.3806	6.7966	17.8575	0.9992	0.3806	6.7966	1.0	1000.0
OCD127	0.3846	7.5235	19.5618	0.9991	0.3846	7.5235	1.0	1150.0
Feeder 1_OCD101	1.6153	12.3655	7.6554	0.9986	1.4906	18.2811	652.0	3645.0
OCD128	1.6146	11.4891	7.1158	0.9987	1.6146	11.4891	1.0	566.0
OCD124	1.6336	12.7785	7.8223	0.9985	1.6336	12.7785	210.0	535.0
OCD113	1.6296	11.6272	7.1350	0.9987	1.6296	11.6272	210.0	535.0
OCD107	1.6146	11.1425	6.9011	0.9987	1.6146	11.1425	210.0	535.0