Reliability Evaluation of Aging Nigeria Power Distribution System Using Monte Carlo Simulation

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***Abstract* -** *This paper evaluated aging and non-aging effects in the Nigerian distribution system using Monte Carlo approach. It is a known fact around the world that most customer service interruptions are caused due to failure in distribution system. This failure is mostly caused by the aging of the equipment involved. Hence, considering reliability assessments provides an opportunity to incorporate the cost or losses incurred by the utility's customer because of power failure and this must be considered in planning and operating practices. Monte Carlo Simulation method is used in this study and it incorporates different methods used for sampling the age of the equipment. This work is limited specifically to six (6) load points of a selected 11kV feeder in Owerri distribution system network. Aging and Non-aging conditions wereanalyzed, and the reliability indices obtained. Three different methods were used to assess the distribution of failure due to aging of the distribution transformer and they are Interval by Interval Method, Time to Scale Transformation Method and Thinning Algorithm Method. They are modeled with an incremental value of the aging factor, β, of 0.075 starting from the first year with the aging factor of 1. This distribution shows how age affects equipment with increase in the number of years as designed by the bathtub curve. The results show that failure rate increases as number of years increases and the energy lost due to aging in the equipment is also increased. It is observed that after the number of years considered, that is 50 years, the energy lost is almost equal to the rating of the transformer and the unavailability of the transformer is almost one(1). Therefore, for these transformers to last longer, aging should be put into consideration and the things that limit the age of these transformers such as maintenance of the equipment, changing of transformer oil, reducing the load on the transformers or applying load shedding mechanism, etc., should be done on the transformers for longer life.*

Keywords - *Distribution Reliability, Aging factor, Failure rate,Monte Carlo Simulation.*

I. INTRODUCTION

Aging of equipment has been a long-lasting factor in the interruption of power in the Nigerian Power system. Different power equipment such as transformers, overhead cables, circuit breakers, isolators, current and voltage transformers have been installed in the power network. Most of them are long pass their prime and they are still in existence. Due to the number of years these equipment have been in service, the equipment tend to exhibit different types of failures and more frequently as time passes. The reliability of equipment decreases and there is a higher risk of failure [1].

The Nigeria power system is divided into generation, transmission and distribution systems. Performing Reliability on different sections of the power system can be done according to functional zones and the hierarchical level which is shown in figure 1. These levels are [2], [3]:

- Generation Facilities - HL I
- Composite Zone (Generation and Transmission Facilities – HL II)
- Complete Zone (Generation, Transmission and Distribution – HL III)

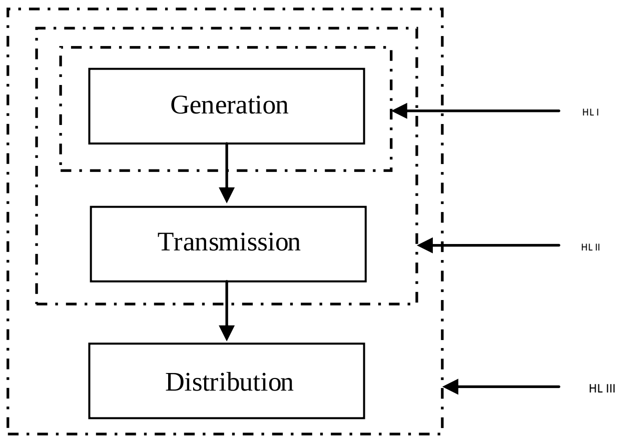

Fig 1: Functional zones and hierarchical levels of power system facilities [2]

Due to largeness of the HL III, it is practically impossible to analyze the reliability of all the systems at once, therefore only distribution systems are put into consideration in the HL III. It is also worthy to note that analyzing the reliability of a distribution system in Nigeria poses more difficulty since most distribution systems do not keep record of outages from their equipment. Also, distribution system has received less attention on reliability evaluation than the generating and transmission systems because the generating system are capital intensive and will have a widespread disaster while the distribution system outages have a localized effect [4]. Hence HL I and HL II reliability are mostly done by reliability engineers.

After the privatization of the power sector in Nigeria, little work had been done in the distribution sector and obsolete equipment are still in use. Most equipment are aged and aging of these equipment are mostly caused due to no repairing of spoilt equipment, lack of timely replacement, overloading of equipment, lack of maintenance etc.These factors contribute to constant outages in the equipment and increase the failure rate of the equipment.

The relationship between the failure rate and the age of equipment can be represented by the bathtub curve as shown in Fig 2. The bathtub curve is divided into three stages namely: The infant stage, Normal operating stage, Wear out stage (Aging stage).

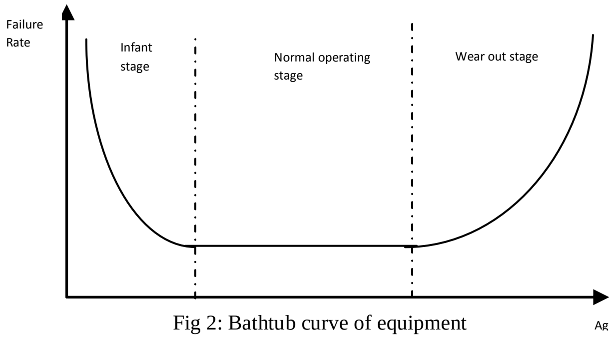

Fig 2: Bathtub curve of equipment

The infant stage is associated with the reduction of failure rate with time, the normal operating stage is the main part of the equipment life, the failure rate is almost constant with time while the wear out stage represents the aging of the equipment where the failure rate increases with time meaning that the equipment is approaching the end of life [5].

In this paper, the aging life of a distribution transformer attached to a load point from an 11kV feeder was considered. The reliability of this transformer is analyzed and its effects on the energy output for a period of 50 years evaluated.

II. DISTRIBUTION SYSTEM RELIABILITY ASSESSMENT

Distribution system reliability is the study of the systems availability over a period in the distribution system. Distribution system reliability indices quantify the system performances, help in identifying the parts of the system that experiences poor reliability and noting the weak equipment in the system. The reliability parameters as defined in [4], [6] and [7] in the distribution system for each load point and they include:

- Average failure rate index of a load point which represents the average number of occurring interruptions at the supplying of the load point, given by

$$\lambda_i = \frac{N_{fi}}{\sum T_{ui} + \sum T_{di}} \qquad 1$$

- Average annual unavailability index that represents the number of hours in a period of one year in which supplying a load point is interrupted, given by

$$U_i = \frac{\sum T_{di}}{\sum T_{ui} + \sum T_{di}} \qquad 2$$

- Average outage time index which represents the average time needed to resolve the interruption at a certain load point, given by

$$r_i = \frac{U_i}{\lambda_i} = \frac{\sum T_{di}}{N_{fi}} \qquad 3$$

where N_{fi} is the number of interruptions occurred in supplying i[th] load in a certain period of time.

$\sum T_{ui}$ is total time in which the i[th] load has been fed in the same period.

$\sum T_{di}$ is the total time in which the ith load has been in interruption mode in the same period of time.

In order to reflect the severity or significance of system outages, additional reliability indices can also be evaluated. The work in [6] developed the reliability indices of the distribution system divided into customer and system-oriented indices.

The Customer-oriented indices include:

- System average interruption frequency index, SAIFI, designed to give information about the average frequency of sustained interruptions per customer over a predefined area.

$$SAIFI = \frac{total number of customer interruptions}{total number of customer sserved} = \frac{\sum \lambda_i N_i}{N_i} (/yr) \qquad 4$$

where λ_i is the failure rate and N_i is the number of customers of load point i.

- System average interruption duration index, SAIDI is commonly referred to as customer minutes of interruption or customer hours and is designed to provide information about the average time that the customers are interrupted.

$$SAIDI = \frac{sum of customer interruption durations}{total number of customerss erved} = \frac{\sum U_i N_i}{\sum N_i} (hr|yr) \qquad 5$$

- Customer Average Interruption Duration Index CAIDI is the average time needed to restore service to the average customer per sustained interruption.

$$CAIDI = \frac{sum of customer interruption durations}{total number of customer interruptions} = \frac{\sum U_i N_i}{\sum \lambda_i N_i} = \frac{SAIDI}{SAIFI} (hr) \qquad 6$$

- Customer average interruption frequency index, CAIFI is designed to show trends in customers interrupted and helps to show the number of customers affected out of whole customer base.

$$CAIFI = \frac{total number of customer interruptions}{total number of customer affected} = \frac{\sum U_i N_i}{N} \qquad 7$$

The Load and energy – oriented indices are given as:

The average load, L_a given by

$$L_a = L_p f \quad 8$$

where L_p = peak load demand and f = load factor

$$L_a = \frac{totalenergydemandedinperiodofinterest}{periodofinterest} = \frac{E_d}{t} \quad 9$$

- Energy not supplied index, ENS

$$ENS = totalenergynotsuppliedbythesystem = \sum L_{a(i)} U_i \quad 10$$

where $L_{a(i)}$ is the average load connected to load point I, U_i is the average outage time.

- Average energy not supplied, AENS or Average system curtailment index, ASCI,

$$AENS = \frac{totalenergynotsupplied}{totalnumberofcustomersserved} = \frac{\sum L_{a(i)} U_i}{\sum N_i} \quad 11$$

- Average Customer Curtailment Index, ACCI

$$ACCI = \frac{totalenergynotsupplied}{totalnumberofcustomersaffected} \quad 12$$

III. RELIABILITY ANALYSIS (MONTE CARLO SIMULATION)

There are different methods to analyze the reliability of distribution power system. They are mostly divided in two categories, namely: Analytical method and the Monte Carlo simulation approach.The most common analytical methods for reliability evaluation are state space method, contingency enumeration method and minimal cut set method [2] involving petri nets, prime number encoding [8].

Monte Carlo simulation involves using statistical component failure and repair data as well as system configuration [6]. Randomly generated samples of failures and repair times based on the probability distribution of the statistical data provided are used to calculate one set of numeric result for reliability indices. By repeating the process with new random values sampled from input probability distribution, new possible values for reliability indices are calculated. After large number of iterations, the expected reliability of the system is calculated.

A modified Monte Carlo Simulation algorithm was used to analyze the reliability of the Nigeria power distribution system incorporating aging sample methods in this paper. It is as follows:

- Generate a random number with uniform distribution for each of the equipment.
- Set aging parameter β = 1 and using the exponential distribution, convert to TTF of the equipment. For aging parameter β > 1, choose an aging sampling Method (either Interval by Interval Method, Time to Scale Transformation or Thinning Algorithm) and using Weibull distribution, convert to TTF of the equipment.
- Produce a random number with uniform distribution and convert it to the TTR of the equipment that has the least amount of TTF
- Save interruption duration of each load point.
- Produce a random number with uniform distribution and convert it to TTF of the equipment that has failed (Equipment that had the lowest TTF).
- Calculate the number and duration of the failure at any load point in the current year.
- Calculate failure rates and failure duration at each load point in the current year.
- Calculate the average values of the indices in the seventh step in the years having been studied so far.
- Input the number of customers served and the number of customers at each load point
- If the number of years under study does not reach to its preset limit or a convergence of all calculated indices is not created, back to the second step and otherwise report the calculated reliability indices consisting of the customer-oriented and the load and energy-oriented indices.

A. NON-AGING CONDITIONS

The mathematical model that is applied in the reliability of distribution power system without considering aging is an exponential distribution process [1] using Monte Carlo Simulation as shown:

If x or TTF = interval time between failures
λ = failure rate (constant value)

then the probability density function f(x) is given as

$$f(x) = \lambda e^{-\lambda x} \quad 13$$

The cumulative distribution function is given as

$$F(x) = 1 - e^{-\lambda x} \quad 14$$

$$TTF = \frac{-lnZ}{\lambda} \quad 15$$

The expected mean or the mean time to failure is

$$E(x) or MTTF = \frac{1}{\lambda} \quad 16$$

B. AGING CONDITIONS

The three methods of sampling Non-Homogenous Poisson Process (NHPP) were analyzed. The Weibull distribution process [1] [9] is used to achieve this. The sampling processes are: Interval by Interval method (IIM), Time to Scale Transformation (TST), and Thinning Algorithm (TA) [10].

1) ***Interval by Interval Method (IIM):*** In this sample process, if we assume k_{th} failure occurs at the time t_k, for k = 1 then,

$$TTF_k = \left(\frac{-\ln(Z)}{\lambda_{eq}}\right)^{\frac{1}{\beta}} \quad 17$$

And for k>1

$$TTF_k = \left\{\left(\sum_{i=1}^{k-1} TTF_i\right)^{\beta} - \frac{\ln(Z)}{\lambda_{eq}}\right\}^{\frac{1}{\beta}} - \sum_{i=1}^{k-1} TTF_i \quad 18$$

2) ***Time to Scale Transform Method (TST):*** This sampling process assumes that for k=1,

$$TTF_k{'} = -\ln(Z) \quad 19$$

$$TTF_k = \left(\frac{TTF_k{'}}{\lambda}\right)^{\frac{1}{\beta}} \quad 20$$

And for k>1:

$$TTF_k{'} = -\ln(Z) \quad 21$$

$$TTF_k = \left[\frac{\sum_{i=1}^{k} TTF_i{'}}{\lambda}\right]^{\frac{1}{\beta}} - \sum_{i=1}^{k-1} TTF_i \quad 22$$

3) ***Thinning Algorithm:*** In this algorithm, using the last time that failure occurred (t_k), next time the failure will occur (t_{k+1}) and thus TTF_{k+1} is determined. Put $t_k = t_{k+1}$ and produce a random number, Z with a uniform distribution

$$t_{k+1} = t_k - \frac{\ln(Z)}{\lambda^H} \quad 23$$

λ^H is defined as follows

$$\lambda^H = \max(\lambda(t))\, where t\ [0,T] \quad 24$$

$$T = 1/\lambda_{eq} \quad 25$$

It can be deduced that

$$\lambda^H = \lambda(t)|_{t=T} = \lambda_{eq}\beta\left(\frac{1}{\lambda_{eq}}\right)^{\beta-1} \quad 26$$

From equation 23,

$$\frac{-\ln(Z)}{\lambda^H} = t_{k+1} - t_k \quad 27$$

$$TTF_{K+1} = t_{k+1} - t_k \quad 28$$

IV. CASE STUDY

A part of Owerri distribution system was used for this study. 11kV feeders in Owerri metropolis are Naze, Township, New Owerri and GRA feeders feed power across the Owerri Distribution system. The New Owerri feeder is the case study feeder and is connected to 70-100 load points. Six different load points are chosen at random and the aging and non-aging reliability of these load points are analyzed. Due to insufficient data from the public utility, certain assumptions were made when evaluating the reliability due to aging of the transformers at each load point. These assumptions included:

- The natural aging of the equipment is considered only.
- The simulation was carried out for the period of 50 years considering in the first year, the transformer is viewed as a new transformer due to uncertainty of the manufacturing year of the transformer. Also, the six load points that are considered in this paper are new transformers.
- The aging factor β is 1 on the first year and has a constant increment of 0.075 for the period of 50 years.
- It is also assumed that maintenance and replacement were not considered on the equipment.

The six load points are Town 1 FHE, Area N Ejinkonye, Claret Area A, Sites and Services, Town 2 FHE and Area L (AG) hereafter referred to as L1, L2, L3, L4, L5 and L6 respectively. The summary of the data used in the analysis for the six load points are shown in Table I.

They include:

- The total number of interruptions at each load point for a period of one year
- The number of customers served at each load point used for this study
- The total number of customers at each load point
- Total time of interruption at each load point T_{dp}
- The total number of time each load point is fed $T_{\mu p}$

Table I: Summary of the Data Collected from the Utility for Outages in the Year 2015

S/No	Load point	Rating of transformer (KVA)	Total no of customers	No of customers served	T_{dp} (hrs)	T_{up} (hrs)	No of inter.
1	Town 1 FHE	500	600	400	950	7560	740
2	Area N Ejinkonye	500	580	350	800	7350	1050
3	Claret Area A	300	450	310	1080	7150	950
4	Sites and Services	500	500	380	1200	7200	1000
5	Town 2 FHE	300	400	280	1000	7000	820
6	Area L (AG)	500	570	400	850	7400	800

V. RESULTS AND DISCUSSIONS

After the simulation, the reliability indices for the year 2015 for the six different load points without considering the age of the equipment are shown in the Table II.

It can be seen from Table II that Claret Area A has the least failure rate (F_R) of 0.09 and therefore has the least energy not served (ENS) in the system as 33.65KVA/hr whereby Area L AG has the highest failure rate of 0.11 and the highest energy not served in the system with a value of 65.72KVA/hr. It can also be seen that the Average System Availability Index (ASAI) is least in Area L AG and Town 2 FHE load points. This shows that much time is needed to restore their transformers into service once it is out. This explains the reason why the two load points also have the highest value of CAIDI as 1.21 and 1.22, respectively. Although F_R and U_P for all the load points were almost the same with deviation ±0.02, the time taken to repair the equipment once it fails differs. These are represented with average outage time index, R_P. R_P was higher in Town 2 FHE load point with an index of 1.22. The indices SAIFI, SAIDI, CAIDI, CAIFI, ASAI and ASUI gave almost the same results with deviations not more than ±0.02. This shows that the energies in those areas are almost supplied at the same time. Considering the Average Energy Not Supplied (AENS) index, it is very clear that though higher energy is lost at Town 2 FHE than Claret Area A load point, more customers are being satisfied at Town 2 FHE (AENS= 0.14) than Claret Area A (AENS= 0.19).

Due to ambiguity in reporting the results of the reliability of the load points considering aging for the period of 50 years for the three methods of sampling, only one load point is presented in this paper, which is the Area L (AG) load point. Table III shows the results of the reliability indices considering the age of the transformer using the Interval by Interval Method (IIM) of sampling for the period of 50 years taking into account the assumptions made in the previous section; while Table IV and V shows the results of the reliability indices considering the age of the transformer using the Time to Scale Transformation (TST) and Thinning Algorithm (TA), respectively. The aging factor β has a constant increment of 0.075 per year starting from 1 in the first year. The value is chosen because the transformer in the second year would have depreciated from the value which it was from the first year. The aging causes such as weather conditions, environmental factors, oil changes and over loading of transformer has been put into consideration, and this would make the transformer to depreciate with a new aging factor greater than the previous year. In this case 1.075 on the second year and 1.15 on the third year and so on. The failure rate, unavailability, and the outage time index also increase as the year increases. This shows that as the year passes, there is a higher tendency that the transformer will be failing more frequently if maintenance is not done on it. Also, it can be seen from the table that unavailability is zero (0) in the first and second year; this is because as a new transformer, it will be readily available, and the unavailability would be minimal or negligible. But as year goes on and age sets in, it becomes unavailable and its unavailability tends to 1. When it gets to 1, the transformer can no longer supply power to its customers. Therefore, maintenance is required to be done on the transformer to improve its life span and reduce both the failure rate and the unavailability.

The Availability index which ranges from 0-1 in reliability evaluation has a perfect index of one (1) at the first year and second year, but then reduces as age sets in on the transformer. This continues to deteriorate while the index keeps tending towards zero if maintenance is neglected on the equipment. Maintaining the equipment improves the availability index and reduces customer interruption frequency. Availability after 50 years of predicted time is very low (0.33 for IIM, 0.06 for the TST and 0.11 for the TA) which shows that at the end of 50 years, the transformer will be minimally available and supplies minimum or no amount of power to its customers. Also, since the rating of Area L AG transformer is 500kVA. This means that the transformer supplies 500kVA of power to its customers at any point in time. At the end of 50 years, the results show that the energy lost will be 324.11kVA/hr for IIM, 461.46kVA/hr for the TST and 438.68kVA/hr for the TA. This is unacceptable because the customers will be out of power for very long period. The IIM shows a slow energy loss in the system as it can be seen more than the other sampling methods.

Table II: Results of the Reliability Indices Without Aging for the Six Load Points

Load Points	F_R	U_P	R_P	SAIFI	SAIDI	CAIDI	CAIFI	ASAI	ASUI	ENS (kVA/hr)	AENS
L1	0.10	0.12	1.18	0.09	0.10	1.18	0.10	0.88	0.12	58.15	0.19
L2	0.10	0.11	1.13	0.08	0.09	1.13	0.09	0.89	0.11	55.56	0.18
L3	0.09	0.11	1.20	0.08	0.09	1.20	0.09	0.89	0.11	33.65	0.19
L4	0.10	0.11	1.13	0.08	0.10	1.13	0.10	0.89	0.11	57.12	0.17
L5	0.10	0.13	1.22	0.07	0.09	1.22	0.09	0.87	0.13	37.94	0.14
L6	0.11	0.13	1.21	0.09	0.11	1.21	0.11	0.87	0.13	65.72	0.19

Table III: Results of the Reliability Indices Considering Aging Using the Interval by Interval Method (IIM)

Years	F_R	U_P	R_P	SAIFI	SAIDI	CAIDI	CAIFI	ASAI	ASUI	ENS	AENS
1	0.15	0.00	0.02	0.13	0.00	0.02	0.00	1.00	0.00	1.36	0.00
10	0.47	0.06	0.12	0.40	0.05	0.12	0.05	0.94	0.06	28.78	0.08
20	0.70	0.22	0.31	0.59	0.18	0.31	0.19	0.77	0.26	107.65	0.31
30	0.82	0.39	0.48	0.69	0.33	0.48	0.35	0.59	0.53	196.58	0.56
40	0.89	0.54	0.61	0.75	0.45	0.61	0.47	0.44	0.76	269.53	0.79
50	0.93	0.65	0.70	0.79	0.55	0.70	0.56	0.33	0.89	324.11	0.93

Table IV: Results of the Reliability Indices Considering Aging Using the Time to Scale Transformation Method (TST)

Years	F_R	U_P	R_P	SAIFI	SAIDI	CAIDI	CAIFI	ASAI	ASUI	ENS	AENS
1	0.17	0.00	0.02	0.14	0.00	0.02	0.00	1.00	0.00	1.35	0.00
10	0.42	0.06	0.14	0.36	0.05	0.14	0.05	0.94	0.06	29.68	0.08
20	0.80	0.25	0.31	0.67	0.21	0.31	0.22	0.74	0.26	124.54	0.36
30	0.95	0.52	0.55	0.80	0.44	0.55	0.46	0.46	0.54	259.34	0.74
40	0.99	0.77	0.78	0.83	0.65	0.78	0.67	0.20	0.80	385.33	1.10
50	1.00	0.92	0.93	0.84	0.78	0.93	0.79	0.06	0.94	461.46	1.32

Table V: Results of the Reliability Indices Considering Aging Using the Thinning Algorithm Method (TA)

Years	F_R	U_P	R_P	SAIFI	SAIDI	CAIDI	CAIFI	ASAI	ASUI	ENS	AENS
1	0.08	0.00	0.03	0.07	0.00	0.02	0.00	1.00	0.00	1.35	0.00
10	0.38	0.06	0.16	0.32	0.05	0.17	0.05	0.94	0.06	29.52	0.08
20	0.65	0.25	0.38	0.55	0.21	0.40	0.22	0.74	0.23	122.74	0.35
30	0.80	0.50	0.63	0.68	0.42	0.66	0.44	0.47	0.41	251.66	0.72
40	0.83	0.73	0.83	0.74	0.62	0.86	0.64	0.24	0.56	367.26	1.05
50	0.93	0.88	0.94	0.78	0.74	0.96	0.75	0.11	0.67	438.68	1.25

VI. CONCLUSION

Aging equipment in the Nigerian power system, especially in the distribution sector has been one of the main reasons of unreliability of power supply in the country. Many transformers are long overdue for a change and they are still in service. This causes a frequent failure of these transformers and constant repairs of these transformers also depreciate its value the more. Aging of transformers are caused by wear and tear of machines, environmental factors, weather conditions, transformer oil etc. when these factors are not managed or maintained properly, it will only quicken the aging process of these transformers. The aging of these transformers also affects the output of the transformers. The output deteriorates as age sets in on the electromechanical machine. Non-aging and aging conditions on six selected load points in Owerri Metropolis are analyzed. The distribution transformers used on these load points are used for the study. The Monte Carlo Simulation method was used to calculate the failure rate and a non-homogenousPoisson process is employed to sample the aging condition using Weibull distribution. The three different aging sampling methods, Interval by Interval Method (IIM), Time to Scale Transformation (TST) and Thinning Algorithm were compared and the result for the reliability indices for the six load points was obtained.

From the results of the failure rates, the failure rate of distribution transformers in Owerri is expected to rise sharply when approaching its 40-50 years in service and closely attain the end of their useful lives. Utilities may have to make significant changes in the way they operate and care for their transformers, otherwise power producers could be hard pressed to meet future demand for electricity and maintain system reliability. Managing these assets will require considerable effort by the utility engineer in the coming years. An optimum strategy includes:

- A condition assessment of the entire distribution transformers
- The development of a dynamic loading/overloading policy.
- A life cycle management program that sets priorities to repair, relocate, refurbish or replace the transformers.
- A maintenance strategy that will always take in to consideration those factors that quicken the age of the transformers.

It is important to note that a limiting factor in the pursuit of this study is lack of historical data to enhance and have a proper distribution and behavior of the equipment. To combat this effect, it was assumed that the distribution transformers on service were new transformers and then the behavior of these transformers after 50 years gives a more accurate explanation of the reliability analysis of these transformers.

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