*Advanced Materials Research Vol. 367 (2012) pp 117-123*
*© (2012) Trans Tech Publications, Switzerland*
*doi:10.4028/www.scientific.net/AMR.367.117*



# Modeling Distribution Component Deterioration: An application to Transformer Insulation.

A.U. Adoghe[1, a], C.O.A. Awosope[2,b] and S.A. Daramola[3,c]

[1, 3] Department of Electrical and Information, College of Science and Technology, Covenant University, Ota, Nigeria.
[2] Department of Electrical/Electronics, Faculty of Engineering, University of Lagos, Lagos, Nigeria

[a]tony.adoghe@covenantuniversity.edu.ng, [b]coaawosope@yahoo.co.uk, [c]dabaslectcu@yahoo.com.

**Keywords:** Transformer insulation, Reliability-centred maintenance, Deterioration, Distribution transformer, Maintenance model..

**Abstract.** The two most critical components in a typical Power System are the circuit breakers and transformers. Failure of any of these components will result in high cost due to component replacement and associated load loss. Reliability Centred Maintenance (RCM) may reduce this cost in the long run by extending the component lifetime and increasing availability. This will be possible, since the adopted RCM will balance carrying out too much maintenance which will increase maintenance cost or too little maintenance that will result in catastrophic failure and hence increases the cost of maintenance and repair. A Markov model that relates probability of failure to maintenance activity is developed for distribution transformers. This model incorporates various levels of insulation deterioration and minor maintenance state. It was applied to one of the distribution transformers in Abule-Egba Business unit network of Power Holding Company of Nigeria. The result obtained from model simulation agrees with the one obtained from the mathematical analysis of the developed model. With an adjustment in the inspection parameter, this probabilistic deterioration model for a distribution transformer can also be applied to predict the performance of circuit breakers.

## Introduction

Failure of power transformers can greatly affect electric power delivery. The “remaining life” of power components and maintenance cost are two most important aspects, which affects the maintenance policies of many power system utilities. Various maintenance strategies are reported in reference **[1].** Several authors have also reported that power component service availability and replacement **cost** should be balanced in order to get an optimal maintenance strategy. Failure due to deterioration has a long term accumulated effect, which may cause major failures if no related maintenance action is taken. In reference **[2],** deterioration process of circuit breakers using three discrete stages are described as Markov processes and optimal maintenance intervals are discussed in detail. Based on this concept, a maintenance model for circuit breaker is presented in **[3].**
In this paper, a similar idea is applied to distribution transformer. In order to build the Markov model for estimating distribution transformer failure rate, the deterioration process, inspection tests, and maintenance actions are discussed. Then, a comparison between the simulated results of the maintenance model and that of the mathematical analysis of the segmented model of the transformers regarding operating conditions, inspection tests and maintenance actions is carried out.
In this paper, a state - based stochastic deterioration model for evaluating the performance of a distribution transformer in its deteriorating state is developed.
The transformer failure statistics of Abule-Egba distribution network in Lagos, Nigeria is presented, a Markov – chain model for evaluating the performance of the distribution transformer is developed.

**Transformer Failure Statistics in Abule-Egba**

The analysis of the outage data obtained from Abule – Egba business unit revealed that the leading cause of transformer failures is "Insulation failure". This category of failure includes substandard or defective installation, insulation deterioration, and short circuits, note that voltage surges, lightning and line faults are excluded. Table 1 lists the number of failures for each cause of failure investigated. The frequency and the severity of transformer failure are the major risk that affect power availability in most Utilities. A description of the cause of each category is given in detail in reference [4]

Table 1 Number of transformer failures for each cause of failure

| CAUSES OF FAILURE | NUMBER OF TRANSFORMER FAILURE |
|---|---|
| Insulation Failures | 28 |
| Design / Material / Workmanship | 27 |
| Oil Contaminations | 9 |
| Overloadings | 5 |
| Fire /Explosions | 1 |
| Line Surges | 4 |
| Improper Maintenance | 6 |
| Loose Connections | 2 |
| Lightning strikes | 2 |
| Moisture | 1 |
| Unknown | 17 |
| Total | 102 |

**Transformer Ageing:** In Table 1, we did not add "age" as a cause of failure. Ageing of insulation system reduces both the mechanical and dielectric-withstand strength of the transformer. As the transformer ages, it is subjected to faults that result in high radial and compressive forces. As the load increases, with system growth, the operating stresses increase. In an ageing transformer failure, typically the conductor insulation is weakened to the point where it can no longer sustain mechanical stresses of a fault. Turn – to - turn insulation then suffers a dielectric failure, or a fault causes a loosening of winding clamping pressure, which reduces the transformer's ability to withstand future short - circuit forces.

Table 2 displays the distribution of transformer failure by age. The age of transformers deserves special attention, because most of these transformers may have been installed 35 years ago and hence in its ageing part of its life cycle.

**Transformer Maintenance model**

A Markov model of the impact of maintenance on reliability developed in this paper is applied to the transformer as shown below.

**Table 2 Distribution of transformer failure by age**

| Age at Failure | No of Failures |
|---|---|
| 0 to 6 years | 8 |
| 7 to 11 years | 6 |
| 12 to 16 years | 12 |
| 17 to 21 years | 12 |
| Over 21 years | 24 |
| Unknown | 35 |

The model represents the deterioration process in a distribution transformer using discrete stages. In Figure 1, deterioration process of a transformer is approximated by three discrete stages: $D_1$, $D_2$, and $D_3$. At each state, oil is inspected to determine its condition. After the inspection, oil condition is determined by some defined criteria as indicated in reference [5]. Table 2.2 Lists of the distribution of transformer failure by age.

The criteria categorize oil condition into three groups as follows:
Condition $C_1$ means - Satisfactory
Condition $C_2$ means – Should be reconditioned for further use.
Condition $C_3$ means – Poor condition, dispose off and replace.

Each oil condition has a corresponding maintenance action assigned to it. For example, if oil condition is $C_1$, nothing is done, if oil condition is $C_2$ or $C_3$, two options are available and are assigned with different probabilities: oil filtering or oil replacement. If for example, the present stage is $D_2$ with oil condition $C_2$, the probability of oil filtering will be higher than oil replacement. On the other hand, if the present state is $D_2$ with oil condition $C_3$, the probability of oil replacement will be higher. After maintenance, the device will have three options: going to state $D_1$ or $D_2$ or $D_3$. The probability of transferring to other states depends on the present state and the maintenance strategy adopted. Further, the maintenance process is divided into three levels namely: Do nothing, Basic Maintenance and Replacement. Once the suggested maintenance action is taken, the subsequent condition of the transformer is determined.

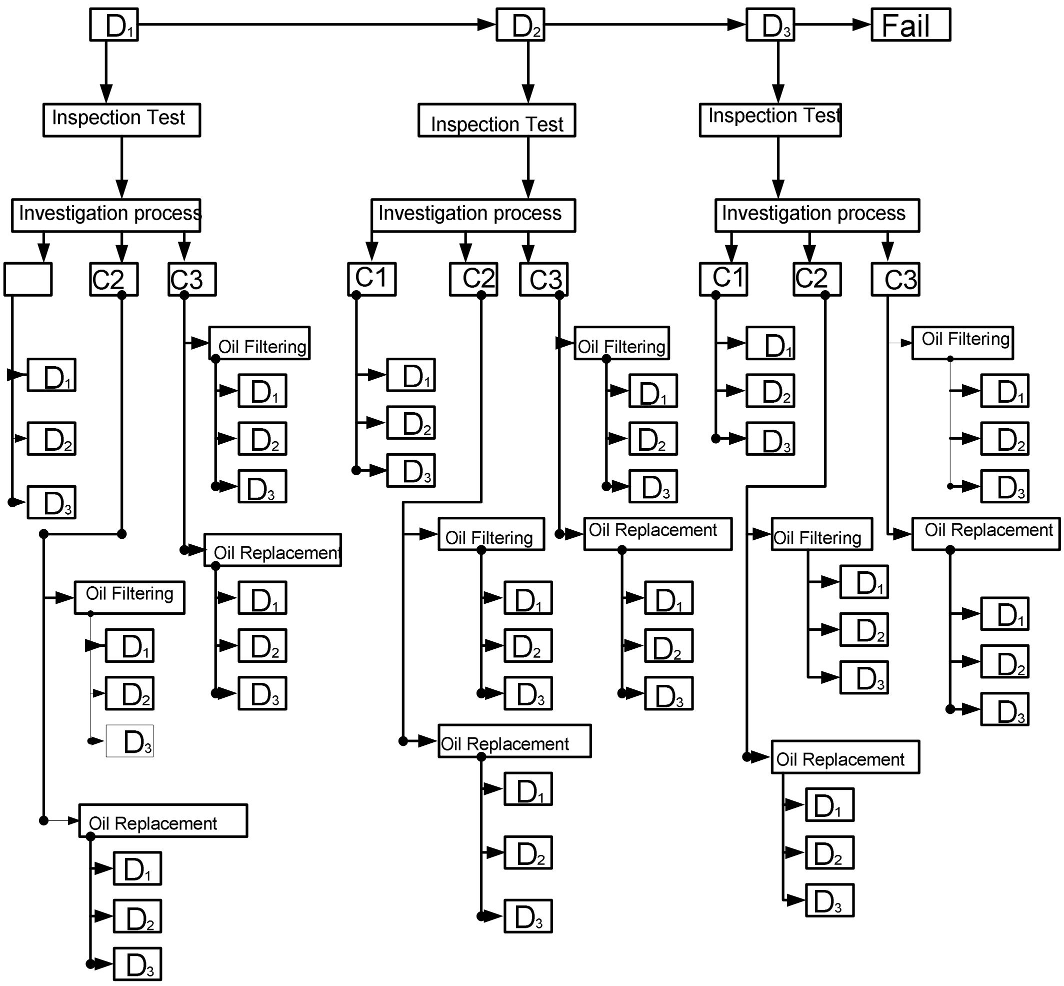


Figure 1 Transformer Maintenance Model

The model takes data from various inspection and maintenance tasks of the distribution transformers in Abule – Egba unit and the frequency of performing this tasks of inspection and maintenance is taken as inputs and gives the failure rates as output. The changes in the "mean time to failure" indicator can be observed by considering different inspection and maintenance actions. This model can help asset managers to evaluate the performance of a distribution transformer in obtaining optimum maintenance intervals such that both the transformer availability and the life span are balanced. Various inspection tests and maintenance actions considered in the model are shown in Table 3 and Table 4 respectively.
The rating of the transformers range from 300 – 1000kVA and their high voltage rating ranges from 13.8 – 34.5kV. The units were manufactured between 1985 and 1995 by different transformer'manufacturers and the oil used in all units was mineral oil provided from different suppliers. The unit was taken from Abule-Egba distribution network to conduct routine maintenance to evaluate its working conditions.

**Table 3 Transformer maintenance tasks**

| Transformer Activity task | Standard Checklist to ensure transformer availability. |
|---|---|
| Main Components. | Winding, Cooling agent (for example, oil, gas, or air), Bushing, Tap Changer. |
| Operating Mechanism. | Transforms voltage from one level to another, preserving the same voltage frequency. |
| Deterioration process | Insulation paper in the winding, oxidation of oil. |
| Particles produced by aging process | Sludge, water, fiber, Gases (CO, CO2 etc), Furfural, partial Discharge. |
| Failure mode | - Themal related faults<br>- Dielectric related faults<br>- General degradation related faults<br>- Mechanical related faults |
| Inspection tests | - Dielectric strength, resistivity, acidity, moisture content<br>- Routine oil sampling test,<br>- Dissolved gas analysis<br>- Furfural analysis<br>- Partial discharge monitoring. |
| Maintenance | <u>For oil Immersed transformer</u><br>- Oil filtering (online/offline<br>- Oil replacement. |

Stated limits for Service- Aged oils for Transformers [6].

Various inspection tests are considered in developing the model. Oil filled transformer are considered in this study. The underlisted items form the basis for the inspection tasks. In particular, the following tests were considered in this model.

- Dielectric strength verification,
- Resistivity, acidity and moisture content analysis,
- Routine oil sampling test,
- Dissolved gas analysis, and
- Furfural analysis

**Table 4 Rated limit for values of transformer oil for voltage class [7]**

| Test | BS / ASTM Standard | Accepted value for aged oil |
|---|---|---|
| Dielectric breakdown (kV)(Min.) | D – 877 | 26 |
| Interfacial tension, (Mn/m or dynes/cm)(Min.) | D – 971 | 24 |
| Water Content, (ppm)(Max.) | D – 1583 | 35 |
| Total Acidity (Mg KOH/g oil)(Max) | D – 644 | 0.3 |

The condition of the transformer can be obtained by comparing the measured values with the working stardard. In the case of the transformer oil, Table 4 could be regarded as the working standard.

**Equivalent Mathematical models for transformer maintenance:** Two equivalent models are used to simplify the transformer maintenance model shown in Figure 1. The equivalent models have three discrete staages representing the deterioration processes. We assume that decision is taken at the end of every inspection. Decision for maintenance and inspection rate of each stage are considered to be an equivalent repair rate. The mathematical formulation of the model is shown in Figure 2 [7].

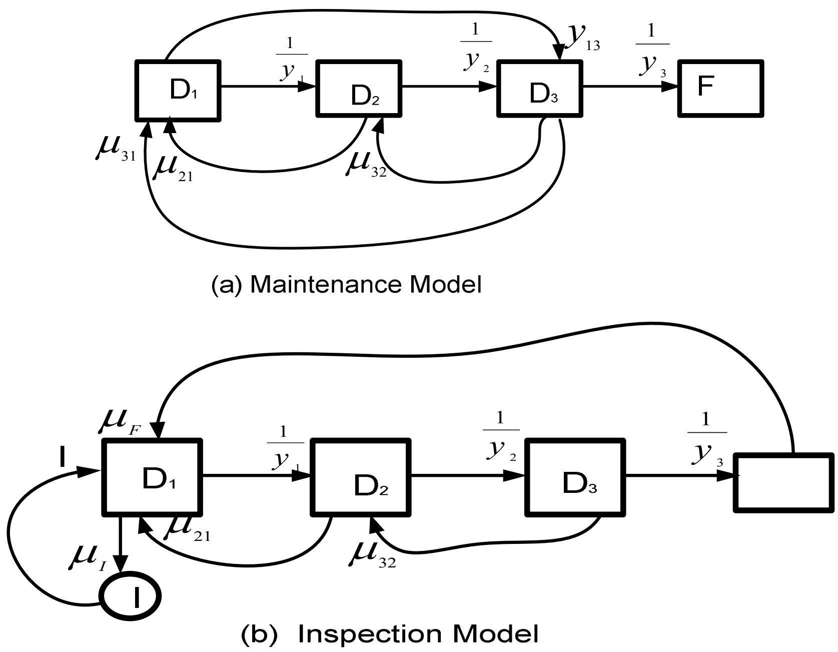


**Figure 2 Equivalent Maintenance Model**

## Results and Discussions

The simulation results of the relationship of each inspection rate for the transmission model and MTTFF are shown in Figures 3 a-c and 4a-c. The observations that could be drawn from these simulation results are as stated below:

1. In Figure 3a, the MTTFF is seen to decrease with $i_1$. This is associated with the assumption of exponential distribution of time spent in each stage. The assumption of exponential distribution implies constant failure rate. This becomes very important in stage $D_1$. This implies that the inspections, which will result in going back to $D_1$, will not improve the time to failure in $D_1$. However, those that will lead to $D_2$ and $D_3$ will result in deterioration. This means that, if we assume an exponential distribution for stage 1, maintenance at this stage will not be necessary.
2. In Figure 3b, it was observed that MTTFF increases at a decreasing rate with $i_2$ and then remains constant afterwards.
3. In Figure 3c, MTTFF and $i_3$ were observed to possess positive linear relationship.

The next stage of simulation is to modify the model in Figure 1 by representing state 1 by three sub-units in order to nullify the assumption of exponential distribution. Although each sub-unit is exponentially distributed, the overall $D_1$ is not and hence will experience deterioration. The simulation results of the relationship of each inspection rate and MTTFF based on this arrangement are shown in Figure 4a–c. In Figure 4a, MTTFF is observed to increase rapidly when $i_1$ is correspondingly increased and then decreases slightly at high $i_1$.The simulation results as shown in Figures 4b and 4c gave the same observation as that obtained in Figures 3b and 3c.

The simulation results suggest that inspection rate of $D_1$ could help in prolonging MTTFF. In addition, carrying out inspection of $D_2$ beyond a certain value will have a little or no impact on reliability. Figure 4.1c however, indicates that transformer life-time will be longer with an improved inspection rate at stage $D_3$.

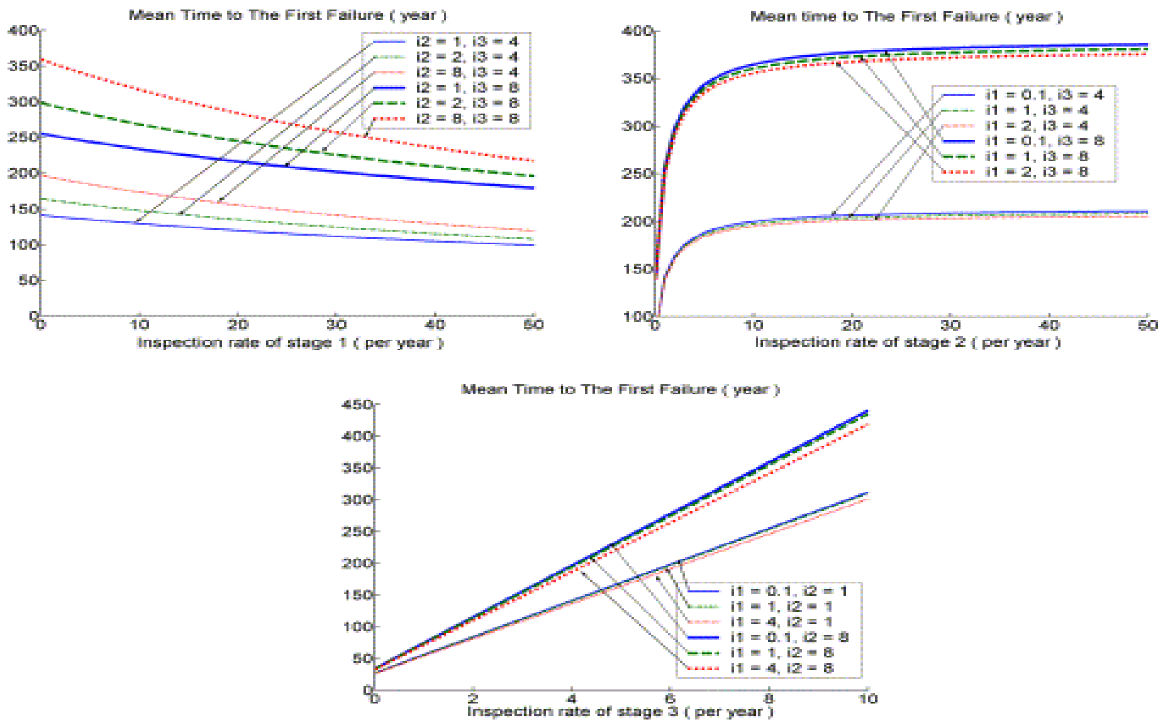


**Figure 3 a–c the relationship between inspection rate and MTTFF**

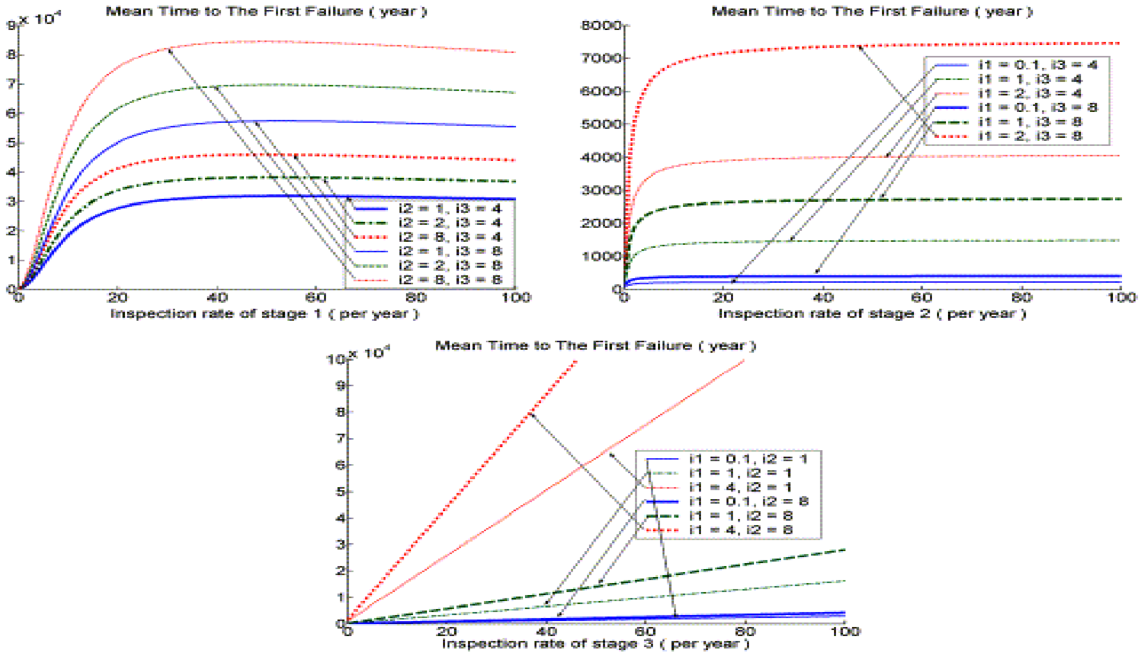


**Figure 4a-c The relationship between inspection rate and MTTFF when stage 1 is represented by three sub-units**

## vi Conclusion

Simulation results from MatLab have been shown and verified by mathematical equations of the equivalent model. The analysis of the simulation results suggests that inspection is only introduced to determine the stage of the device deterioration. This model was applied to a distribution transformer located in Abule-Egba business unit network considered in this paper. The main strength of this model is that it allows one to assess the state of insulation of several different groups of transformers relative to each other. It is a fact of life that prediction (forecast) of the condition of a distribution transformer stands on a firmer ground if they are relative rather than absolute.

## References

[1] Brown, R.E., Frimpong, G. & Willis, H.L. "Failure Rate Modeling Using Equipment Inspection Data", IEEE Transactions on power systems. Vol. 19, No. 2, May 2004.

[2] Satish N, Panida J, Mladen K, and Chanan S., "Circuit Breaker and Transformer Inspection and Maintenance: Probabilistic Models" 8th International Conference on Probabilistic Methods Applied to power systems, Iowa State University, Ames, Iowa, September 12-16, 2004.

[3] Jirutitijaroen, P, Singh, C.,"Oil-immersed transformer inspection and maintenance: probabilistic models" in proceedings of the 2003 North Americal power Symposium conference, pp 204-208.

[4] A.U. Adoghe, C.O.A. Awosope, J.C. Ekeh 'A Probabilistic modeling of distribution equipment Deterioration; An application to transformer insulation" International Journal of Engineering & Technology IJET-IJENS,Vol: 10 No: 04, 2011, 62 – 70.

[5] Ward, B. H., "A Survey of New Techniques in Insulation monitoring of power Transformers", IEEE Electrical Insulation Magazine, Vol17, No3, 2011, 16-23.

[6] Ward S.A., "Evaluating transformer condition using DGA Oil analysis", IEEE CEIDP, 2003, 463-468.

[7] NYNAS, "Transformer oil handbook, June, 2004.