Modeling Maintenance Process for Aging Electric Power Stations in Nigeria

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Abstract: Nigeria is known to be a nation with a very erratic and epileptic power supply. It is a fact that the estimated power consumption in megawatts required by the nation is yet to be met by the generating units of the Utility Company (PHCN). However the available megawatts being generated is not well managed due to poor maintenance culture and planning of the aging substations that are meant to distribute the available power to the consumers. This paper uses Bath-up curve approach for studying and optimizing equipment maintenance for substations. The economic cost models based on semi-Markov decision process was developed to provide a probabilistic approach, for computing the expected cost of substation equipment maintenance. The model can be used for determining optimal maintenance policies at each deterioration stage. A well-planned and efficient power sub-station maintenance program is expensive; it requires shop facilities, skilled labour, keeping records, and stocking of replacement parts. However, the cost of downtime may amount to ten or more times the actual cost of repair, and possibly compromise security and the problem cascading into related systems. Therefore, to sustain power in Nigeria it is necessary to consider effective maintenance program of aging Nigeria power substations.

Index Terms: Modeling, Electric Load, Sub-station, Aging, Maintenance, Availability.

1. INTRODUCTION

Substation Maintenance is defined as an activity to arrest, reduce or eliminate Power substation device deteriorations. The purpose of substation maintenance is to ensure optimum use of generated power, extend substation equipment lifetime, increase asset values (equipment conditions), and avoid costly consequences of power failures.

An efficient maintenance program and well-established department is necessary that will schedule in advance jobs that cannot be performed while a power plant is in operation. Maintenance operations not performed when scheduled have grave negative influence on the equipment [1]. Operators of Power Stations are generally advised to consult manufacturers of their plants before selecting test equipment [2]. Aging infrastructure of Electricity generally has profound effect on electricity generation and distribution [3]. The effect of Aging, Maintenance and Reliability of power system has been reported by Endrenyi et al [4]. They also investigated the effect of maintenance on reliability of power system equipment [5].

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Most of the current electric utility transmission and distribution equipments in Nigeria are over 30 years old [1].

As more and more equipment and systems age, electric utilities will be required to develop and implement asset management strategies and practices to balance their investment and operation and maintenance (O&M) costs to increase earnings while meeting reliability requirements and operation under budget constraints [7].

If components appear to be wearing out faster or repairs are required more frequently than in the past, it could be that the equipment is now required to carry additional loads for prolonged periods of time. This will accelerate maintenance requirements and alter the maintenance schedule. A reduction in the life expectancy of expendable items such as contacts can only come about due to a greater number of operations or under additional load requirements.

The aging problem in power substation equipment in Nigeria with emphasis to power substation equipment like power transformers, cables, wires and circuit breakers is associated with maintenance problem and required that different maintenance policies that are utilized to mitigate the aging process are put in place. In electric power industry, most electrical equipment or other assets are kept under service. During operation, the physical and electrical strengths of equipment gradually deteriorated, until some point of insulation failure, or other types of failures. This process can be called as *aging process* as described by Endrenyi et al. [4]. The word "*aging*" means that the strength of components deteriorates, as a function of chronological time in service.

However serious consideration has not been given to the maintenance of components of power substation when affected by aging and some other factors that can lead to deterioration

of the components. Electric power distribution and development in Nigeria has been analyzed in the past [18]. Factors determining the level of maintenance based on the physical causes failure and other determinants shall be discussed in this work to improve reliability of power substation equipment in other to sustain power effectively at a reduced cost for utility companies and consumers in Nigeria.

A standard scheme for maintenance activities in a power plant was presented by Eti [8]. The deterioration failures of Power Transformers are usually due to degrading and aging of cellulose and oil used for transformer insulation [9]. Maintenance is defined as an activity to arrest, reduce or eliminate device deterioration [1,15,19].

Major factors affecting power substation equipment are: Equipment/Installation, Aging, Dielectric loss, Shrinkage/Hardening, Tear, wear and Moisture retention. Substation reliability evaluation has been extensively discussed in the past [13, 14]. Different categories of equipment aging and their impact on substation equipment are:

Chronological Age (CA) --- Aging since construction. Certain materials deteriorate over time due to natural causes, most directly associated with chronological age

Cumulative Service Stress (CSS) ---- The cumulative effect of the time that the unit has been energized and the load (mechanical, electrical) it has served in that time

Abnormal Event Stress (AES) --- The cumulative impact of severe events generally not considered as "normal service".

This includes through faults for transformers, Relays, circuit breakers, storm and auto accident stress for poles, etc.

Technical Obsolescence (TO) ---- The cumulative effect of the time that the unit has been energized and the load (mechanical, electrical) it has served in that time.

1. 2. METHODOLOGY

In electric power industry, most electrical equipment or other assets are kept under service. During operation, the physical and electrical strengths of equipment are gradually deteriorated, until some point of deterioration failure, or other types of failures. This process can be called as *aging process.* The word "*aging*" means that the strength of components deteriorates, as a function of chronological time in service [3, 9].

Based on the physical causes, power system aging process can be categorized into four types. Table 1 presents the meaning and impact of four types of aging processes as stated by Endrenyi et al [5]. The term Aging is generally referred to as combination of all four effects.

Table 1: Category of Equipment Aging and their Impact

Category	Meaning and impact
Chronological Age (CA)	Aging since construction. Certain materials deteriorate over time due to natural causes, most directly associated with chronological age.
Cumulative Service Stress (CSS)	The cumulative effect of the time that the unit has been energized and the load (mechanical, electrical) it has served in that time
Abnormal Event Stress (AES)	The cumulative impact of severe events generally not considered as "normal service". This includes through faults for transformers, storm and auto accident stress for poles, etc.
Technical Obsolescence (TO)	Power substation equipment can become old by virtue, or not being compatible with new systems and equipment.

Aging can be the result of the obvious process of the passing of time. As the age of equipment increases, the equipment slowly deteriorates correspondingly. Table 2 shows several types of deterioration that affect old equipment in power system.

Table 2: Types of deterioration caused by Aging

Type of deterioration	Caused by			Comments
	CA	CSS	AES	
Corrosion	X	X	X	Chemical decomposition or combination with oxygen or other ambient elements, until the material loses its required mechanical or electrical strengths, or qualities
Dielectric loss	X	X	X	Various mechanisms (treeing, contamination) that lead to the loss of electrical withstand strength
Shrinkage/Hardening	X	X	X	Paper rubber, synthetic gaskets and seals harden or shrink with age, losing their ability to keep out moisture or contain pressure.
Wear		X	X	Mechanical components lose tolerance and bind, or do not hold with the same bond as they once did.
Moisture retention	X			Water is gradually absorbed into a material, degrading its mechanical or electric strength.

In addition to the classification according to physical causes, aging agents can also be classified as either environmental aging or operational aging.

Environmental aging agents exist continuously in the environment surrounding the equipment, whether it is in an operational state or not. Examples include vibration, temperature, radiation, humidity, or simply the passing of time. D*eterioration of power transformers* is primarily due to environmental aging agents. The deterioration failures of power transformers are usually due to degradation and aging of cellulose and oil used for transformer insulation.

Operational aging agents exist primarily when the equipment is under operation. Examples of operational agents include internal heating from electrical or mechanical loading, physical stresses from mechanical or electrical surges, and abrasive wearing of parts such as seen in Circuit Breakers. Previous research on aging process [5] has validated the relationship between the equipment likelihood of failure over a period of time. This relationship is represented by the well-known "Bathtub curve", and can be used for all types of devices.

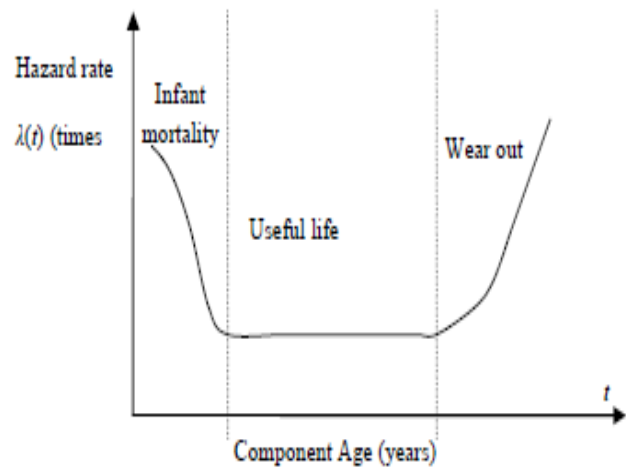Figure 1 illustrates the Bathtub curve for aging equipment hazard rate or failure rate modeling.

Fig. 1 Traditional Bathtub Failure Rate Curve

Systems having this hazard rate function experience decreasing failure rate in their early life cycle (infant mortality), followed by a nearly constant failure rate (useful life), then by an increasing failure rate (wear out). This curve may be obtained as a composite of several failure distributions. During useful life period, exponential distribution is usually used to model the probability of time to failure, or constant failure rates. Most equipment reliability models will use this useful life period, as the failure rate within this period is constant.

Assuming the useful life period, the hazard rate or failure rate is λ, the time to failure follows an exponential distribution, modeled in (1) as established by Leonard and Grigsby (2004):

$$f(T) = \lambda e^{-\lambda T}, \ T > 0 \tag{1}$$

For the infant mortality or wear out periods, log-normal or Weibull distribution are frequently deployed to model this nonlinear failure rates. For example, at wear out period, the time to failure T may follow Weibull distribution, with scale parameter α and shape parameter β in equation 2:

$$f(T) = \alpha\beta T^{\beta-1}e^{-\alpha T^{\beta}}, \; T > 0 \tag{2}$$

In some cases, a function of piecewise linear failure rates is also utilized to represent the non-linear failure rates, such as using following piecewise linear equations in (3), to minimize the bathtub function.

$$\lambda(t) = \begin{cases} C_0 - C_1 t + \lambda, & 0 \le t \le C_0/C_1 \\ \lambda, & C_0/C_1 < t < t_0 \\ C_2(t - t_0) + \lambda, & t_0 < t \end{cases} \tag{3}$$

Then the time to failure follows the following distribution:

$$f(t) = \begin{cases} \exp-\{(C_0+\lambda)t - C_1(t^2/2)\} & 0 \le t \le C_0/C_1 \\ \exp-[\lambda t + C_0^2/(2C_1)] & C_0/C_1 < t < t_0 \\ \exp-\{(C_2/2)(t-t_0)^2 + \lambda t + C_0^2/(2C_1)\} & t_0 < t \end{cases} \tag{4}$$

The aging mitigating actions are typically attempt to eliminate the stresses that cause the aging in the first place, since aging is unavoidable. This includes reducing the environmental or operational agents that cause deterioration. Environmental stress such as heat and radiation are known to induce aging degradation, particularly in organic materials. Examples of adjustments in the operating environment include adding thermal insulation, venting electrical enclosures, or adding radiation shielding. However, these adjustments only slightly prolong the deterioration process. Deterioration failure is still the inevitable fate of the equipment.

Another way to mitigate the aging effect is through maintenance. Effects of different maintenance policies can be studied by comparing their impacts on the equipment life curve. As equipment deteriorate further, its asset value (or condition) decreases. The relationships among asset values and maintenance are shown in Figure 2, which is called *equipment life curve*.
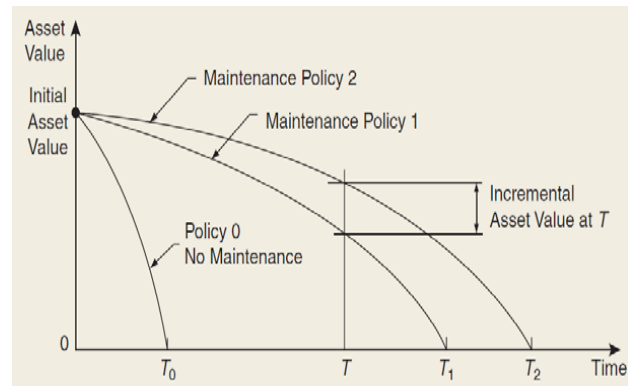

Fig. 2 Life Curve and the Impact of Maintenance Policies

Figure 2 illustrates the effect of three different maintenance policies. Clearly, policies 1 and 2 are far superior relative to policy 0 (no maintenance) as they extend the equipment life. Compared with Policy 1, Policy 2 is better as it increases the asset value at time T.

3. RESULTS AND DISCUSSION

Before using Markov processes for modeling aging and maintenance of equipment, it is necessary to provide a brief introduction of the definitions and calculations of various Markov processes.

A *stochastic process* is a family of random variables based on time. Stochastic processes are called *Markov processes* if the process possesses the Markovian property.

The *Markovian property* states that the probability that a system will undergo a transition from one state to another state depends only on the current state of the system, and not on any previous states the system may have experienced. In other words, the transition probability is not dependent on the past (state) history of the system. This is called a '*memory-less*' property by Ross (1996).

Table 3: Summaries of Markov Processes and Corresponding Solutions

Name	Characteristics	Mathematic model	Solution	Application filed

Discrete time Markov processes	The time to transition are the same and the chance is defined by the probability simple but not very practical	$\begin{cases} \prod P = \Pi \\ \sum_{k \in s} \pi_k = 1 \end{cases}$	$\Pi = e'(I + E - P)^{-1}$	Calculate the system probability at discrete time point not very applicable
Continuous time Markov process	The time to transition belongs exponential distribution Advantages: easy for calculating, especially in large complex systems Broadly applied in power system	$\begin{cases} \prod Q = 0 \\ \sum_{k \in s} \pi_k = 1 \end{cases}$	$\Pi = e'(Q + E)^{-1}$ $\pi_i = E(h_i) \bullet$ $\pi^e_i / \sum \pi^e_k E(h_i)$	Widely used in power system reliability assessment. However, not applicable for modeling aging equipment, where the time to failure may be non- exponential
Semi-Markov Processes	Introducing sojourn time. Can model more complicated stochastic processes.	$\begin{cases} \prod^e P = \Pi^e \\ \sum_{k \in s} \pi^e_k = 1 \end{cases}$	$\Pi^e = e'(I + E - P)^{-1}$	More suitable to model aging processes and maintenance, where the times to transitions are sometime non-exponential

Application of the above Markov process leads to the investigation of the relationship between substation reliability also known as Availability and Maintenance rate (λ_M).

$$A = \frac{1.6 \cdot (9.2e10^3 \lambda_M + 5.8 + 5.5e10^6 \lambda_M^2 + 1.6e10^9 \lambda_M^3}{1.5e10^4 \lambda_M + 9.4 + 8.8e10^6 \lambda_M^2 + 2.5e10^9 \lambda_M^3 + 2.5e10^9 \lambda_M^4}$$

(5)

A= Availability of power station (%), λ_M =Maintenance rate (per day)

When the above equation is computed with the use of MATLAB when maintenance rate value is varied, the results show that the Substation Availability is high with high values of planned maintenance rate.

The curve in Fig 3 illustrates the cost advantage of planned preventive maintenance in Eket substation over the breakdown or corrective maintenance policy that has been in use till date. The maintenance cost for breakdown policy goes up to as high as 35million naira ($1=168 naira) in a month especially during raining season while the maximum cost of Preventive maintenance policy type is 5.8million naira in the month of February and March when maintenance can be planned for the bulk transformers.
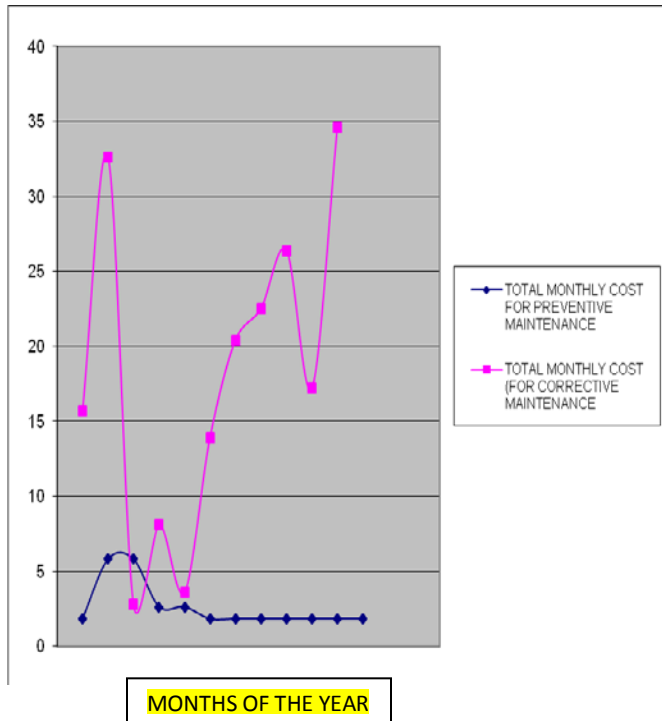
MILLIONS

MONTHS OF THE YEAR

Fig. 3 **Breakdown versus Preventive cost at Eket Power station in 2009**

4. CONCLUSION

The Preventive maintenance policy with special consideration to effect of aging if adopted will prevent so much power outages that have always resulted from equipment breakdown in our substations. The reduction of breakdowns of the components of the substations will save appreciably the cost of component procurement and replacement, money saved from such venture can be used to develop other sectors of Nigerian economy.

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