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Weibull-Markov Reliability Analysis of Industrial Consumer Circuit Breakers. A Case Study of the Kawempe Industrial Area

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Abstract— *For the quality of power to be good, most Industrial Consumers should have organized maintenance frameworks and records and should ensure that maintenance and overhaul are carried out promptly as opposed to the last stage of life of an asset when serious degradation has occurred. This is however never the case since most asset operators don't pay attention to unobserved (hidden) factors that influence a rapidly rising failure rate and deterioration of the asset in its course of life. Additionally, hidden failures in protection systems cause about 75% of electrical power protection system blackouts. They therefore result into heavy technical and economic losses in case of a last stage failure on the protection system and should be given high consideration. In a preliminary study carried out in Kawempe Industrial Area, high voltage Circuit Breakers of 50% Industrial consumers had a history of cascaded failures for the last 30 years. There is therefore need to carry out a Root Cause Analysis (RCA) on Circuit breaker performance and reliability impact assessment on the aging process on CBs so as to guide investment into proper asset management frameworks that will minimize high impact of poor quality of supply margins.*

Keywords—*Asset Management, Industrial Consumers, Power Quality, Reliability*

I. INTRODUCTION

Due to the 1999 Electricity Liberalization act, Umeme Limited was given a 20 year concession effective March 2005 to maintain and operate the electricity distribution network upto 33Kv[1]. One of the reasons was to improve the quality of service, rehabilitate, upgrade and expand the distribution network [2]. In order to achieve its targets, Umeme Limited has to provide reliable and quality power supply to its customers. Umeme is therefore carrying out maintenance works at various levels for its network assets, upgrading and commissioning of network assets. Umeme Limited has taken major rehabilitation works and these include refurbishment of feeders, interconnectors, substations and transformers. Despite the fact that Umeme Limited has diligently carried out maintenance works to ensure quality supply, fault incidences on grid connected assets have still been drastically on the rise for the past 10 years. This is in accordance to the Knoema Report hub reliability statistics.

According to a current Electricity Regulatory Report published in 2020, the number of Repair and Maintenance (R&M) works stands to 16,528.43 as of 2020 compared to 6045 in 2010 [3]. This is also accompanied by a large number of industries which are currently 216,075.286 as of 2020, compared to 192,596.224 in 2010. A steady rise in the industrial consumer base poses a greater need for distribution utilities to pay more attention to management of assets not only within their jurisdiction, but also of industrial consumers they connect to the grid. Since management of utility assets has greatly improved, the only challenge that remains lies in management of consumer assets. Therefore the current R&M incidences are undoubtedly accounted for by industrial consumers [4]

According to the Global Competitiveness Report by the World Economic Forum published in 2019 among 141 countries revealed that Uganda was ranked 115 with an index of 2.1 regarding the quality of electricity. The average was set at 4.5 with 1 being the worst case scenario and 7 being the desired state. Out of 100% Uganda earned a score of 48.9% [5]. This therefore implies that the quality of supply in Uganda is below average. When potential investors look at this report, they may be discouraged from investing in the country hence negative image on the global scene. The major concepts to explore in this study include reliability and power quality assessment of industrial consumer protection assets, reliability analysis and assessment of circuit breakers based on 13 deterioration factors network due to consumer driven factors and their impact on power quality.

II. THEORETICAL APROACH AND MODEL

Probability Density functions

The use of statistical approaches in lifetime data analysis was applied in fields such as military, medicine, as well as to the power equipment. With the aid of modern computing devices, the statistical approaches have become more sophisticated and ready to use in many cases.

Failure data in general such as time-to-failure can be evaluated statistically using parametric methods or non-parametric methods. Parametric methods make assumptions about the underlying population from which the data are obtained. On the other hand, the non-parametric methods do not assume any particular family for the distribution of the data [6]

In both parametric and non-parametric methods, the failure processes are described as random events which can be considered as random variables. Random variables can have continuous or discrete characteristic. In this study, only continuous variables will be considered.

The Probability Density Function (PDF) and Cumulative Distribution Function (CDF) are the key statistical functions from which other functions of interest such as survival or reliability function, hazard function, mean time function and median life function etc. can be derived or obtained. The PDF fully describes a statistical distribution and indicates the relative probability of failure at different times [7]

If T is a non-negative continuous random variable representing a lifetime of an element or equipment, then the probability that any random chosen item fails during the time t to $t + \Delta t$ is its PDF and represented by the function f(t):

$$f(t) = \lim \Delta\rightarrow t \frac{Pr(t < T < t+\Delta t)}{\Delta t} for\ small\ \Delta t \tag{1}$$

For the whole area under the density function:

$$\int_0^\infty f(t)dt = 1 \tag{2}$$

Further any values of $t_1\ and\ t_2$ where $t_1 \leq t_2$ then the probability is the area under the density function from $t_1\ and\ t_2$ expressed as:

$$P(t_1 < t < t_2) = \int_{t_1}^{t_2} f(t)dt\ where\ f(t) \geq 0 \tag{3}$$

The Cumulative Distribution Function F (t)

The CDF defined as F(t) of a random variable T is the probability that an item under consideration will fail before time t within the interval (0,t) which is the integral of the f(t) from 0 to t and can be expressed mathematically as

$$F(t) = \Pr(T \leq t) = \int_0^t f(x)dx\ for\ t > 0 \tag{4}$$

Further, the F (t) in terms of a population is the proportion of units in the population that will fail before time "t" [8]

The term F (t) has some two useful interpretations:

- Within the product population, any product has the probability of F(t) to fail prior to time "t"
- For a group of products that have failed, F(t) is the portion of products that fails by the time "t"

Conversely:

$$f(t) = \frac{d(F(t))}{dt} = -\frac{dR(t)}{dt} \tag{5}$$

Reliability Function R (t)

The reliability function R (t) also known as survival function, is the probability that equipment will operate properly for a specified period under the design operating conditions without failure i.e. failures occur after time "t" This is expressed as:

$$R(t) = \Pr(T \leq t) \tag{6}$$

The survival function may also be defined as the probability that the equipment will not up to time "t" which in general is the integral of function f(t) from t to infinity and given by:

$$R(t) = \int_t^\infty f(t)dt \tag{7}$$

R(t) has two common interpretations

- Within the product population, R(t) is the probability of having a randomly drawn unit at time "t" that is alive (i.e. has not failed)
- R(t) within the product population, is the portion of products that will survive for atleast time "t"

In practice, as a complementary function of F(t), R(t) is often expressed as:

$$R(t) = 1 - F(t) = 1 - \int_t^\infty f(x)dx\ for\ t > 0 \tag{8}$$

The hazard function h(t)

The condition probability of failure in the time interval from t to (t+Δt) given that the system has survived to time t is given by [9]. Additionally according to [10], the hazard function describes the *'intensity of death'* at the time *t* given that the individual has already survived past time t. Like the reliability, Probability density and Cumulative density functions, the hazard rate function assumes a bathtub pattern which emphasized on three stages of the asset life: the infant mortality stage, the stage of constant failure and the deterioration stage. Hazard rate analysis is carried out basing on the stages of random failures and wear-out failures. This is because failures indicate the propensity of the asset to death. The figure 1 below shows the three stages of development of an asset in its lifetime:

Figure 1 the three stages of asset aging from the time of commissioning to death

$$\Pr(t \leq T \leq t + \Delta t | T \geq t) = \frac{R(t) - R(t+\Delta t)}{R(t)} \tag{9}$$

The hazard function h (t) is expressed as:

$$h(t) = \lim \Delta \mathrm{t} \rightarrow 0 \frac{R(t) - R(t+\Delta t)}{R(t)\Delta t} = \lim \Delta t \rightarrow 0 \frac{-[R(t+\Delta t) - R(t)]}{\Delta t}\frac{1}{R(t)}$$

(10)

As Δt approaches zero, h(t) effectively becomes the instantaneous failure rate at time t and in general can be thought of as a measure of the probability of failure

Thus the failure modeling reduces to:

$$h(t) = -\frac{-dR(t)}{d(t)}\frac{1}{R(t)} = \frac{f(t)}{R(t)} \qquad h(t) \geq 0\ for\ all\ t \tag{11}$$

Maximum Likelihood Estimation and Weibull parametization

The maximum likelihood method is an effective and important approach for parameter estimation. The estimation procedure is converted to maximize the so-called likelihood function with respect to three undetermined parameters. The three parameters are defined by the Weibull distribution [11]

The cumulative distribution function (CDF) and probability density function (PDF) of the three-parameter Weibull distribution are given by

$$F(t,\propto,\beta,\eta) = \begin{cases} 1 - e^{-\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta}}, & t > \propto \\ 0, & t \leq \propto \end{cases} \tag{12}$$

$$F(t,\propto,\beta,\eta) = \begin{cases} \frac{\beta}{\eta}\left(\frac{t-\propto}{\eta}\right)^{\beta-1} e^{-\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta}} & t > \propto \\ 0, & t \leq \propto \end{cases} \tag{13}$$

Here, $\alpha \geq 0$, $\beta \geq 0$, and $\eta \geq 0$ are location, shape, and scale parameters, respectively. Figure 2 illustrates shapes of PDF for different parameters based on probability of failure for increasing shape parameters. As can be seen, the shape of Weibull PDF is very flexible so that it can fit into a wide range of experiment data.

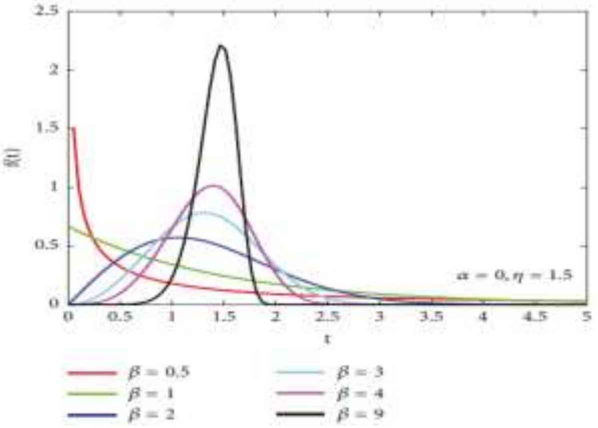


Figure 2 Weibull PDF with various values of β when assumingα =0 and η = 1.5.

In general, there are many methods to estimate the parameters of a distribution, such as probability-weighted moment, maximum likelihood method, and least square method. Among them, the ML estimators are asymptotically unbiased with the minimum variance under regularity conditions. Then, the MLE for three-parameter Weibull distribution is described briefly. Let $t1$, $t2$, $\cdot\cdot\cdot$, tn be a random sample of size n; $\vec{\theta} = (\alpha,\beta,\eta)$ is noted as the Weibull model parameters which are to be estimated; namely, $\vec{\theta} = (\alpha,\beta,\eta)$. the likelihood function is written as

$$L = \prod_{i=1}^{n} f_i(t_i;\overrightarrow{\theta}) = \prod_{i=1}^{n} \frac{\beta}{\eta}\left(\frac{t_i-\propto}{\eta}\right)^{\beta-1} e^{-\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta}} \tag{14}$$

The aim of estimation is to determine the unknown vector $\vec{\theta}$ and the three unknown parameters α, β, and η by maximizing the likelihood function. Since it contains exponential term, it is easier to obtain the maximum by its logarithm. By this way, the complexity of calculations is reduced. The logarithm of the likelihood function is shown as

$$In\left[L\left(t_i;\vec{\theta}\right)\right] = \sum_{i=1}^{n}[In(\beta) + (\beta-1)In(t_i-\alpha) - \beta In(\eta) - (\frac{(t_i-\alpha)}{\eta})^{\beta}] \tag{15}$$

Then, the vector $\vec{\theta}$ can be obtained by maximizing of the likelihood function. To achieve this, the conventional approach is to take the partial derivation of the likelihood function in terms of vector $\overrightarrow{\theta}$ and set the partial equations to zero, as

$$\frac{\partial In\left[L\left(t_i;\vec{\theta}\right)\right]}{\partial\alpha} = 0 \tag{16}$$

$$\frac{\partial In\left[L\left(t_i;\vec{\theta}\right)\right]}{\partial\beta} = 0 \tag{17}$$

$$\frac{\partial In\left[L\left(t_i;\vec{\theta}\right)\right]}{\partial\eta} = 0 \tag{18}$$

We substitute the log-likelihood function into the above equations. The following equations are obtained:

$$L_1 = \sum_{i=1}^{n}\left[\frac{1}{\beta} + In(t_i-\alpha) - In(\eta) - \left(\frac{(t_i-\propto)}{\eta}\right)^{\beta} In\left(\frac{(t_i-\alpha)}{\eta}\right)\right] = 0$$

$$L_2 = \sum_{i=1}^{n}\left[-\frac{\beta}{\eta} + \left(\frac{\beta}{\eta}\right)\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta}\right] = 0 \quad (19)$$

$$L_3 = \sum_{i=1}^{n}[-\frac{(\beta-1)}{(t_i-\alpha)} + \left(\frac{\beta}{\eta}\right)\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta-1}] = 0 \quad (19)$$

The values of β and η in Maximum likelihood estimation are determined by a relationship such that:

$$\frac{1}{\beta} + \frac{1}{\eta}\sum_{i=0}^{n} x_i + \frac{\sum_{i=1}^{n} x_i{}^{\beta} Inx_t + \sum_{j=n+1}^{N} y_j{}^{\beta} Iny_j}{\sum_{i=1}^{n} x_i{}^{\beta} + \sum_{j=n+1}^{N} y_j{}^{\beta}} = 0 \quad (20)$$

$$\eta = \left[\frac{1}{n}\left(\sum_{i=1}^{n} x_i{}^{\beta} + \sum_{j=n+1}^{N} y_j{}^{\beta}\right)\right]^{\frac{1}{\beta}} \quad (21)$$

Considering the transition rate of degradation of the circuit breakers, According to [12] in his documentation on *"SF6 Circuit Breaker Failure data and reliability Modeling"* emphasizes that reliability studies on circuit breaker failure and prediction analysis are stochastic and not deterministic in nature. This is because in the stochastic scenario, the outcome of an event does not directly depend on its inputs and is likely to take different transformations (metamorphosis); however room for prediction of outcome is available, although the outcome is not directly predicted as opposed to a deterministic approach/algorithm. [13]

Markov modeling involves representing each component in a system by states namely when it's operational (normal) and when it's non-operational (faulty). It can be considered for repairable and non-repairable systems. *"Transition rates to and from each state are the failure rates that occur in a component in order to reach or transition back to a particular state*" [14]

Esra Bas, the author of *"Introduction to Markov Models"* acknowledges that every physical asset undergoes several transitions from the time of manufacture to the moment of complete deterioration when the asset has reached the end of its life expectancy. Every stage of metamorphosis of the physical asset is non-deterministic and is both hidden and visible. This is analogous to the evolution of a human being from the time of birth all through the time of death. [15]

In this research, the Hidden Markov Model (HMM) was used for Reliability Impact Assessment of the circuit breakers based on data on years of deterioration and failure rate obtained according to the Weibull Analysis on circuit breaker performance for the sample of 14 Industrial consumers. The Markov Model is the most appropriate to study the different stochastic patterns or stages of transition to failure due to a need establish the exact stage of life that propriates a given level of observed and unobserved deterioration of the protection asset.

According to [16], in his journal article on *"Utilizing Hidden Markov Models for Formal Reliability Analysis of Real-Time Communication Systems with Errors"*, the failure level of an asset is mainly determined by unobserved factors within the system. Furthermore, [17], in his failure analysis on circuit breakers also reports that the performance and reliability of a power circuit breaker in regard to normal opening and closing motion depends on its components working capability, control, and operating mechanisms.

Unobserved factors were classified as ambient temperature, reliability of tripping and closing units, operating mechanism of internal components, damping level of devices, abnormality of monitoring and protection system and level of contamination by dust. Observable factors include: damage of auxiliary parts, low insulation integrity, and fluctuation of moisture content levels indicated by rusty internal components such as contacts, etc. [18]

According to [19], The Markov Model of transition is defined by the state equation below:

$$\Pr\left(X_{c,nc+m} = j \,\middle|\, X_{c,o} = k, X_{c,1} = l, \ldots., X_{c,nc} = i\right) = \Pr\left(X_{c,nc+m} = j \,\middle|\, X_{c,nc} = i\right) = p^{(m)}{}_{(i,j)} \quad (22)$$

Where $\Pr\left(X_{c,nc+m} = j \,\right|$ represents the state of transition of the future state

$X_{c,nc} = i$ Represents all states of transition in the current state

$p^{(m)}{}_{(i,j)}$ Represents the probability of transition from state *i* to state *j*

m represents the time of transition

$$Pc^{(m)}{}_{(i,j)} \ \forall_i \sum_{j=1}^{N_c} P^{(m)}{}_{(i,j)} = 1.0. \quad (23)$$

Assumptions to be considered in this study

1. Transitions are irreversible. This study explores a transitional algorithm which is analogous to the metamorphosis of animals where it's not likely that they can transition back to their previous stages of growth. Considering forward probability of transition to be *p* while probability of reverse transition to be *q*, the following hypothesis was generated:

$$\sum_{i=1}^{k} Pc = p \geq 0 \ \forall_i \ Pc_{max} = 1.0 \quad (30)$$

$$\sum_{i,j}^{i+1,j+1} q = 0 \text{ But}$$

$$\sum_{i,i}^{i+1,i+1} q \geq 0 \text{ And } \sum_{j,j}^{j+1,j+1} q \geq 0 \quad (24)$$

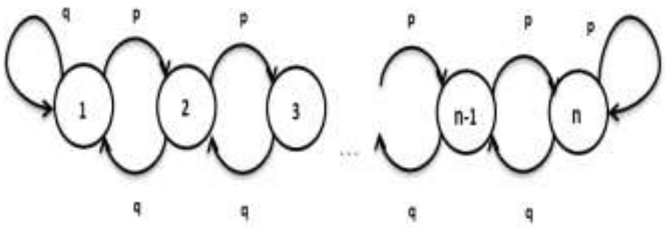


Figure 3 Metamorphosis of an asset in its life time according to the Hidden Markov Model

2. The total transition stages to failure of the circuit breakers will be four (n=4) from the time of purchase/installation to the time of complete deterioration. Hence the state equation for the empirical analysis will be:

$$k = \{1,2,3,4\} \forall \mathbb{R} \tag{25}$$

According to [21], the technical condition of a system is characterized on a scale from 1 to 4 according to the Norwegian Electricity Industry Association (EBL) Thus, the continuous degradation of a component is simplified by dividing it into four states. The state description is given in figure 2.4 and in the following; these four states will be denoted *main states k*. A component as-good-as-new is in state $k = 1$. When the condition is characterized as critical, the state is $k = 4$ and normally maintenance actions must be taken immediately.

III. PRESENTATION OF RESULTS

As mentioned earlier in Section II, there is a need to evaluate the performance of an asset throughout its life so as to determine its endurance, probability of deterioration, hazard rate, etc. This will enable the operator make accurate perspective planning and cost effective decisions hence saving future corrective maintenance costs and maintaining of productivity of the operational assets in the long run. The input data included the life of the Miniature Circuit Breakers, Molded Circuit breakers and Air circuit breakers and the elapsed time of overhaul. The Circuit Breakers under study included those which require overhaul i.e. those in critical condition and those which have failed.

Circuit breaker life

Analysis of circuit breaker health prediction over its entire life was done in MATLAB 2021a environment where life predictions for Industrial consumer circuit breakers were done. According to [20] the maximum life of all circuit breakers was selected to averagely 40 years.

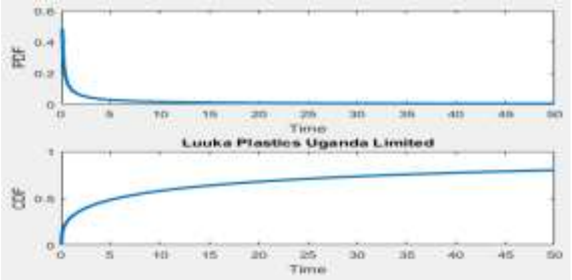


Figure 4 PDF and CDF plots for Luuka Plastics Uganda Limited Circuit breakers

The PDF shown in figure 4 represents the predictability of Luuka Plastics Uganda Circuit breakers for a life of 40 years from the time of installation. The life of an asset is analyzed in a bathtub pattern considering three stages namely: the premature/birth stage, the stage of random failure/constant aging, and the wearout stage.

According to the PDF in figure 4, the circuit breakers under study will undergo a stage of infant mortality where the failure rate decreases over the life time of the circuit breaker. This is because the asset is considered to be As Good As New (AGAN) where there are no signs of depreciation since shape parameter $\beta < 1$ in this stage.

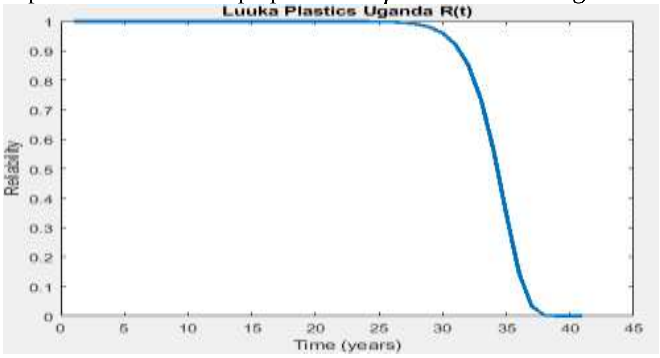


Figure 5 Reliability plot for Luuka Plastics Uganda

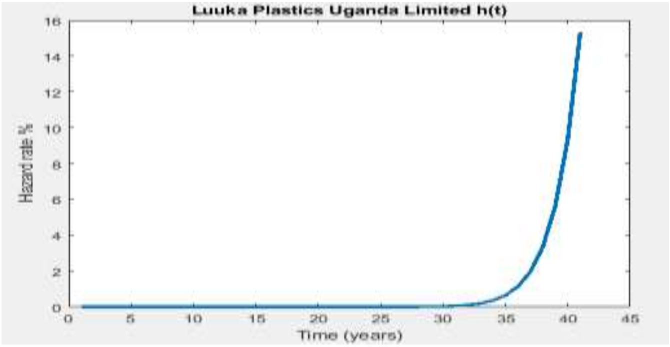


Figure 6 Hazard plot for Luuka Plastics Uganda Limited

According to Figure 5, the reliability plot shows that the reliability of circuit breakers is 0.9907 upto a life time of 28 years. Beyond 28 years of the circuit breaker life, the stage of serious degradation/wearout starts. At 95% of the circuit breaker life, the probability of survival will be 0.002392. The hazard plot in figure 4.3 shows that beyond 31 years, the propensity to death of the circuit breaker is 5.6%. This means that beyond 31 years, the circuit breaker will have 94.4% chances of death.

According to CIGRE Surveys on hazard rate of an asset, it is recommended that an asset with maximum chances of serious degradation or complete wearout will have a propensity of death of 2%. According to figure 6, a 2% propensity is achieved at 37 years.

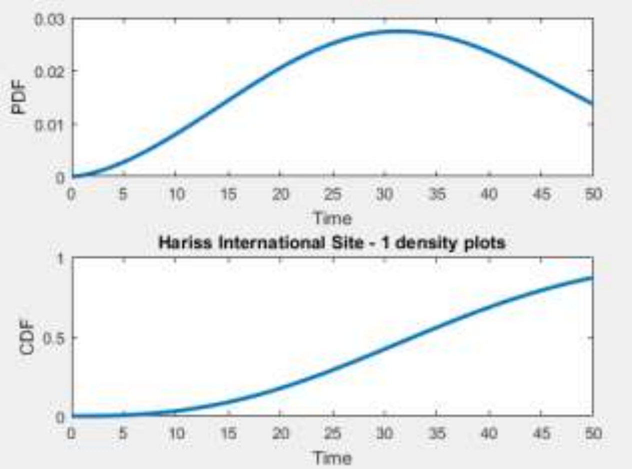


Figure 7 Hariss International Uganda PDF and CDF plots

According to the PDF in figure 7, the circuit breakers under study will undergo increasing deterioration upto about 31 years of operation which is the maximum deterioration stage with probability of 2.8%. This signifies that at about 75% of the circuit breaker life, the probability of failure is 0.028. The CDF in figure 4.1 shows that 75% of the circuit breaker life, 40% circuit breakers will have undergone complete deterioration.

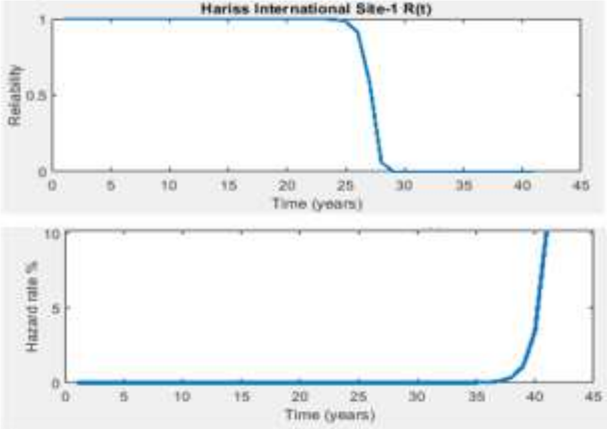


Figure 8 Hariss International site-1 Reliability and Hazard rate plots

According to Figure 8, the reliability plot shows that the probability of survival of circuit breakers is 0.9976 upto a life time of 25 years. Beyond 25 years of the circuit breaker life, the stage of serious degradation/wearout starts. At 73% of the circuit breaker life, the probability of survival will be 0.00009. The hazard plot in figure 4.5 shows that beyond 37 years, the propensity to death of the circuit breaker is 10%. This means that beyond 37 years, the circuit breaker will have 90% chances of death. According to figure 6, a 2% CIGRE survey limit propensity is achieved at 35 years

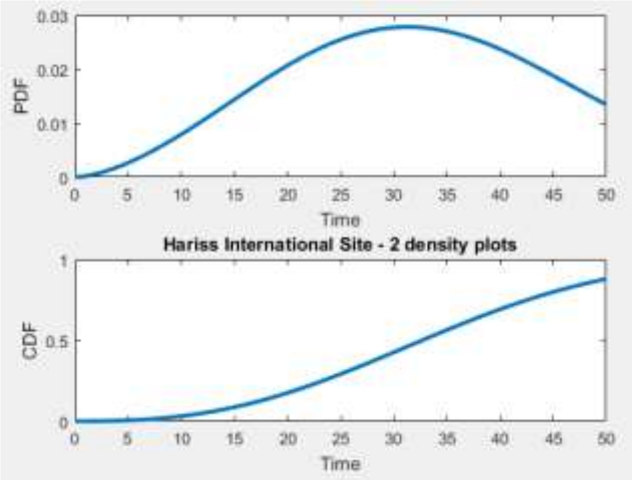


Figure 9 PDF and CDF plots for Hariss International Site – 2

According to the PDF in figure 9, the circuit breakers under study will undergo a stage of random failures upto 33 years of operation. Beyond 33 years, the circuit breakers start wearing out with a probability of 2.8% achieved. This signifies that at about 76% of the circuit breaker life, the probability of failure is 2.8%. The CDF in figure 9 shows that 76% of the circuit breaker life, 48% circuit breakers will have undergone complete deterioration.

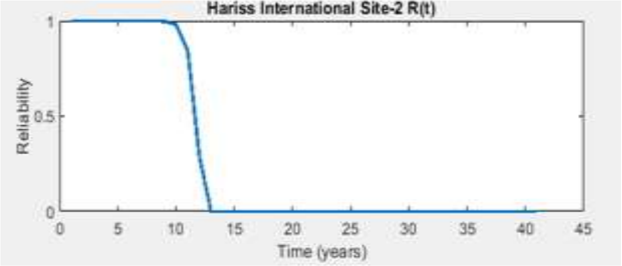


Figure 10 the reliability plot for Hariss International site 2

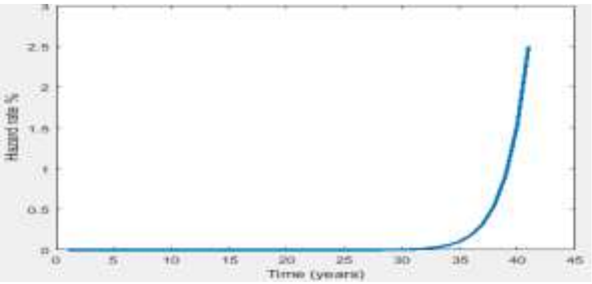
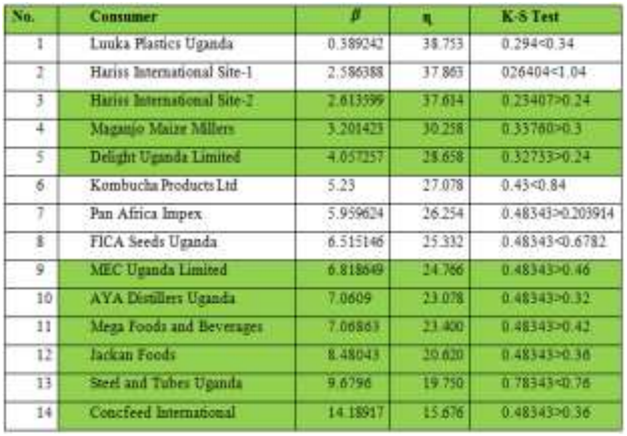


Figure 11 Hazard rate plot for Hariss International Site – 2

A comprehensive reliability analysis was carried out on 14 Industrial Consumers in the Kawempe Industrial Area considering the behaviour of the shape and scale parameters for a 30-40 year CB cycle. It was observed that the shape parameter varies for different consumer circuit breakers.

the circuit breakers under study included Miniature Circuit Breakers (MCBs), Molded Case Circuit Breakers (MCCBs) and Air Circuit Breakers (ACBs). Table 1 below shows the MLE parameters comparing the CB aging for the 14 Industrial Consumers

Table 1: Weibull parameters comparing the CB aging for the 14 Industrial Consumers achieved by Maximum Likelihood Estimation



No.	Consumer	β	η	K-S Test
1	Luuka Plastics Uganda	0.389242	38.753	0.294<0.34
2	Hariss International Site-1	2.586388	37.863	026404<1.04
3	Hariss International Site-2	2.613599	37.614	0.23407>0.24
4	Maganjo Maize Millers	3.201423	30.258	0.33760>0.3
5	Delight Uganda Limited	4.057257	28.658	0.32733>0.24
6	Kombucha Products Ltd	5.23	27.078	0.43<0.84
7	Pan Africa Impex	5.959624	26.254	0.48343>0.203914
8	FICA Seeds Uganda	6.515146	25.332	0.48343<0.6782
9	MEC Uganda Limited	6.818649	24.766	0.48343>0.46
10	AYA Distillers Uganda	7.0609	23.078	0.48343>0.32
11	Mega Foods and Beverages	7.06863	23.400	0.48343>0.42
12	Jackan Foods	8.48043	20.620	0.48343>0.36
13	Steel and Tubes Uganda	9.6796	19.750	0.78343<0.76
14	Concfeed International	14.18917	15.676	0.48343>0.36

Most of the Circuit breakers under study of Industrial consumers such as Delight Uganda Limited, Arise and Shine Millers Ltd, Pan Africa Impex Uganda Limited, FICA Seeds, MEC Uganda, Jackan Foods and Concfeed International Limited have a minimum lifespan of 29 years of operation from the time of installation. The predictability of their operation considering the fact that no replacement of old circuit breakers has been done, yields limited chances of survival for the next five years. This is because the circuit breakers are operating in the last stage of asset life known as wearout (30 to 40 years). This renders very limited capability of efficient operations such as quenching of arc, tripping promptly in event of a fault, etc.

Circuit breakers of Industrial consumers for instance Kombucha Products limited also have high chances of serious deterioration/complete death in the next years with 88.62% circuit breakers expected to have failed by 30 years. Kombucha circuit breakers under study have an average life of 25 years from the time of installation. This arouses a contradiction since the circuit breakers have not operated for even 75% of their prescribed life by the manufacturers i.e. ABB, TRONIC and Telemechanic.

This then could be attributed to need to pay keen attention to factors like the poor quality of the circuit breakers, inaccurate sizing, low insulation capabilities, etc. This also creates a need to review the criterion followed in carrying out Factory Acceptance and endurance tests prior to asset commissioning. For an asset to operate in the life time prescribed for it, it is important that the asset passes all preliminary tests carried out to verify its viability. If preliminary tests are not effectively carried out, the possibility of commissioning substandard assets is likely to be high, hence limiting effective performance of the protection system. The figures 12, 13 and 14 below show the general predictability of Industrial consumer circuit breaker performance considering the probability of failure. (P.O.F)

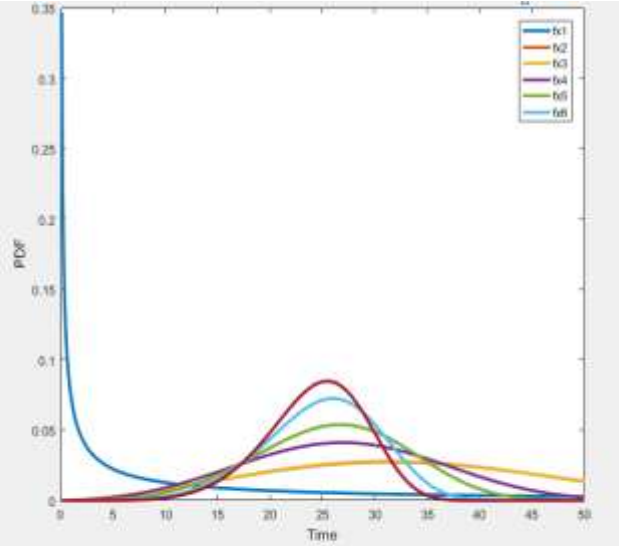


Figure 12: probability of failure for Industrial Consumer 1-6

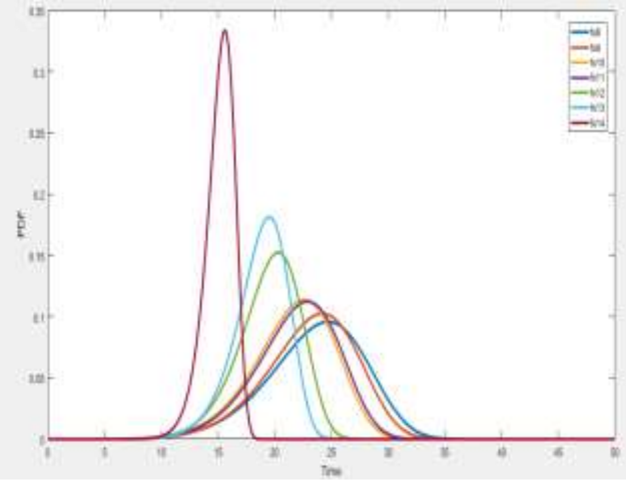


Figure 13: probability of failure for Industrial Consumer 8-14

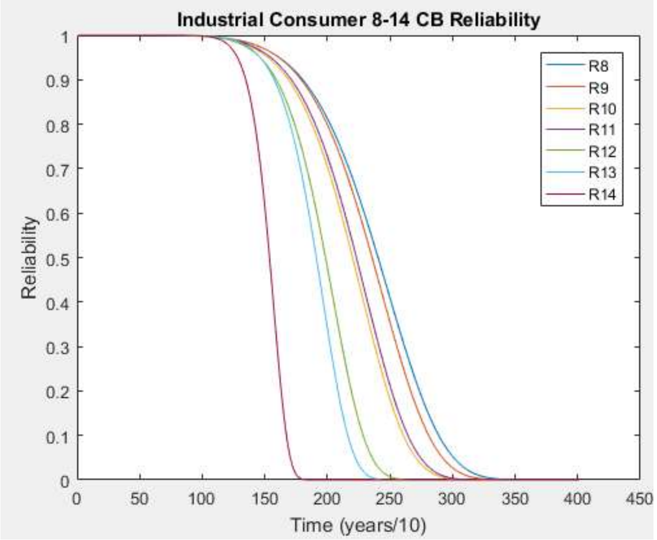


Figure 14: Reliability of failed circuit breakers:

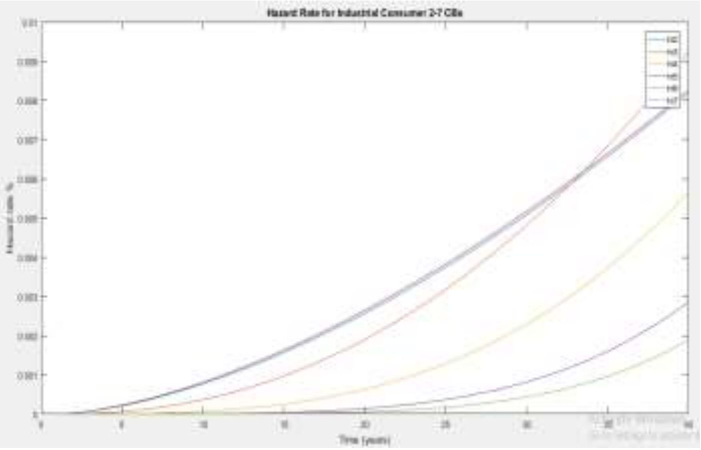


Figure 15: Hazard rate of circuit breakers

Markov Transition modelling was also carried out comparing 13 factors affecting from reliability of circuit breakers in their lifetime. The purpose of this model was also to ascertain the eact time of transition when replacement should be done. The tables 2, 3 and 4 below show this analogy

Table 2: Predicted failure rate of FICA Seeds Uganda considering 4 stages of failure transition in CB life

S/n	Ageing Factors	NOS	$\lambda(t1)_{max}$	$\lambda(t2)_{max}$	$\lambda(t3)_{max}$	$\lambda(t4)_{max}$
1	Poor workmanship	$\theta\|\omega \to \theta$	0	$0.11414835s_2$	$0.23529s_3$	$1s_4$
2	Mechanical failure due to switching (MCB)	$\theta\|\omega \to \theta$	$0.4166667s_1$	$0.60402685s_2$	$0.82443s_3$	$1s_4$
3	Mechanical failure due to switching (ACB)	$\theta\|\omega \to \theta$	$0.6637168s_1$	$0.78994614s_2$	$0.82443s_3$	$1s_4$
4	Poor Quality	$\omega\|\omega \to \theta$	0	$0.16s_2$	$0.60302s_3$	$1s_4$
5	Loose Contacts	$\theta\|\omega \to \theta$	0	$0.17777778s_2$	$0.75016s_3$	$1s_4$
6	Improper sizing	$\omega\|\omega \to \theta$	0	0	$0.39894s_3$	$0.99962s_4$
7	Unmatched tolerance	$\omega\|\omega \to \theta$	0	0	$0.75s_3$	$1s_4$
8	Contamination by dust	$\omega\|\omega \to \theta$	0	$0.50505051s_2$	$0.78764s_3$	$1s_4$
9	Corrosion by moisture	$\omega\|\omega \to \theta$	0	$0.1s_2$	$0.66635s_3$	$1s_4$
10	Ambient Temperature	$\omega\|\omega \to \theta$	0	$0.5s_2$	$0.75048s_3$	$1s_4$
11	Age of breaker	$\omega\|\omega \to \theta$	0	$0.5s_2$	$0.71385s_3$	$1s_4$
12	Insulation of breaker	$\omega\|\omega \to \theta$	0	$0.70607553s_2$	$0.49039s_3$	$1s_4$
13	Premature failure of thermal magnetic trip mechanism	$\omega\|\omega \to \theta$	$0.4285714s_1$	$0.75707702s_2$	$0.74184s_3$	$1s_4$

Table 3: Predicted failure rate of Luuka Plastics Uganda Limited considering 4 stages of failure transition in CB life

S/n	Ageing Factors	NOS	$\lambda(t1)_{max}$	$\lambda(t2)_{max}$	$\lambda(t3)_{max}$	$\lambda(t4)_{max}$
1	Poor workmanship	$\theta\|\omega \to \theta$	0	$0.25s_1$	$0.60200086s_2$	$1s_4$
2	Mechanical failure due to switching (MCB)	$\theta\|\omega \to \theta$	$0.1697795s_1$	$0.3345181s_1$	$0.5717555s_3$	$1s_4$
3	Mechanical failure due to switching (ACB)	$\theta\|\omega \to \theta$	$0.2374846s_1$	$0.4258471s_1$	$0.5593653s_3$	$1s_4$
4	Poor Quality	$\omega\|\omega \to \theta$	$0.227567s_1$	$0.1193949s_1$	$0.345566s_2$	$1s_4$
5	Loose Contacts	$\theta\|\omega \to \theta$	$0.359874s_1$	$0.4366812s_1$	$0.5808794s_3$	$0.9998667s_4$
6	Improper sizing	$\omega\|\omega \to \theta$	$0.2314815s_1$	$0.3989362s_1$	$0.4989605s_3$	$1s_4$
7	Unmatched tolerance	$\omega\|\omega \to \theta$	$0.4362536s_1$	$0.4376536s_1$	$0.5544006s_3$	$1s_4$
8	Contamination by dust	$\omega\|\omega \to \theta$	$0.304878s_2$	$0.4302594s_2$	$0.5544006s_3$	$1s_4$
9	Corrosion by moisture	$\omega\|\omega \to \theta$	$0.2923977s_1$	$0.4011015s_1$	$0.5211585s_3$	$0.9959255s_4$
10	Ambient Temperature	$\omega\|\omega \to \theta$	$0.2467105s_1$	$0.4072473s_1$	$0.5016447s_2$	$0.9902722s_4$
11	Age of breaker	$\omega\|\omega \to \theta$	$0.255848s_1$	$0.4238697s_1$	$0.4956341s_1$	$0.9987196s_4$
12	Insulation of breaker	$\omega\|\omega \to \theta$	$0.2741228s_2$	$0.4321809s_1$	$0.5121951s_1$	$0.9995457s_4$
13	Premature failure of thermal magnetic trip	$\omega\|\omega \to \theta$	$0.4231653s_1$	$0.6088668s_1$	$0.7096327s_3$	$0.9990796s_4$

Determining the optimal time of replacement was based on the assumption that replacement should be carried out at t-1 before maximum failure as shown in the equations and tables below:

Let the time of maximum failure rate be T and the optimal time of replacement be t. The inequality constraint will therefore be:

$$t \leq T \ \exists; \ t \in T \qquad (26)$$

This will take place in satisfying the condition that:

$$\sum_0^1 \lambda_t \exists; \ \lambda_t < \lambda_{max} \qquad (27)$$

Given that the appropriate time will be determined for each ageing factor i in a given stage of transition hence:

$$\sum_{i=1}^{n} \lambda_i \ \exists; \ \forall \ i = [1,13] \qquad (28)$$

Hence the objective function is written as:

$$\lambda\{[t],[T]\} = \sum_{t=0}^{1}\sum_{i=1}^{13}\lambda_t < \lambda_T \qquad (29)$$

Table 4: Optimal replacement time of circuit breakers

S/n	Ageing factor	Transition state of maximum failure rate	Expected time of overhaul preventive maintenance before deterioration (years)
1	Poor workmanship	3	≤ 8 years
2	Mechanical failure in switching operations (MCB)	2	≤ 5 years
3	Mechanical failure during switching operations (MCCB)	3	≤ 5 years
4	Poor quality	1	≤ 2 years
5	Loose contacts	3	≤ 8 years
6	Improper sizing	3	≤ 8 years
7	Unmatched tolerance	1	≤ 2 years
8	Contamination by dust	2	≤ 5 years
9	Corrosion by moisture	1	≤ 2 years
10	Ambient temperature	3	≤ 8 years
11	Age of circuit breaker	2	≤ 5 years
12	Insulation of breaker	2	≤ 5 years
13	Premature failure of thermal magnetic trip mechanism	2	≤ 2 years

The generation of results was based on an assumption that replacement of circuit breakers considering the 13 factors affecting their efficiency should be carried out at a time transition *t-1* before maximum failure occurs. This is the inequality time constraint of the study.

IV. DISCUSSION OF RESULTS

Collection of data of Industrial consumers' circuit breakers reliability status was combinatorial in nature. However analysis was permutational considering an ordered set of factors affecting circuit breaker performance and evaluating their health status. Stratified sampling was used for data analysis. This is similar to studies of [21], [22] and [23] since their methodology acknowledges that the quality of circuit breaker life is determined by the three major operation mechanisms i.e. pneumatic, spring and hydraulic operation mechanisms and their studies point out that the major factors that influence premature breakdown arise from the operation mechanism of the circuit breaker.

This is analogous to our study which also pointed out premature failure of thermal magnetic trip mechanism as the leading factor with the highest risk probability index according to the Weibull - HMM model. that influence premature breakdown arise from the operation mechanism of the circuit breaker.

According to ANSI MTS – 2015 standards, the operating mechanism of the circuit breaker is the key factor that determines the functionality of the breaker since it controls the motion of the breaker. Maintenance is thus carried out to ensure that the timing and speed of the contacts meet the manufacturers' specifications. If timing and speed of the contacts does not meet the manufacturer specifications, the breaker may not clear the fault as designed or even may produce a catastrophic failure. Furthermore, if a breaker closes or opens too fast, it could damage the contacts, linkages, or other parts of the breaker

According to the Weibull – Markov Analysis in section IV, deterioration of a circuit breaker is influenced by many technical factors that alter its original functionality. For instance when a breaker remains idle for years without time based maintenance rendered to it, dust, corrosion and moisture accumulate on its latching mechanism. This results into failure of the breaker to interrupt fault currents. Too many failed interruptions prospectively result into burning of contacts and contact springs become weaker. Resistance across the contacts will rise which will generate more heat deteriorating the contacts further.

Poor workmanship leads to loose breaker contacts due to failure to tighten connections during installation. Accumulated penetration of dust/dirt, moisture, etc results into thermal or physical stresses hence leading to cracking of breaker casings. According to NEMA AB 4 – 2017 Standards, cracks on the surface of a breaker may affect the structural integrity of a MCCB which is important in withstanding the stresses imposed during fault-current interruptions.

Loose connections generate heat, which further deteriorates connections. Generating more heat causes further deterioration. Heated bottom connections can affect tripping due to close proximity to the thermal tripping mechanism. Taking track of internal temperature of the circuit breaker is of great significance. For the case of MCCBs, fault interruptions cause arcing and intense heat inside the breaker case. For a high current short circuit fault which trips the breaker on the instantaneous setting, internal arcing may burn the internal components of the breaker.

V. CONCLUSION

The objective of this study was to assess and model the reliability of circuit breakers as the major factor influencing the quality of power supplied among Industrial consumers in Kawempe Industrial Area. This was achieved through developing a statistical failure predictive model for CB life and analysis of the techno-economic impact of different aging factors on the life of the circuit breaker based on a sample of Industrial consumers in Kawempe Industrial area. The life assessment of circuit breakers (CBs) revealed that the acceptable average time to failure was 19.750 years applicable to all CBs. The minimum hazard rate for all Industrial consumers was 8.5% at 40 years of the CB life. The maximum hazard rate was 1% at 88% of the CB life. RBM analysis using HMM revealed that FICA Seeds Uganda had a maximum risk of failure of $0.7096327S_1$ whereas Luuka Plastics Uganda Limited had a maximum risk of failure of $0.948213S_3$ all attributed to a factor of premature failure of thermal magnetic trip mechanism of the breaker.

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