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Development of a Predictive Model for Industrial Circuit Breaker Degradation in Stochastic Environments

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Abstract*—The need to improve asset management frameworks has been a major concern among industrial consumers in Uganda. Poor asset management increases frequency of faults among industrial consumers thus resulting into poor quality of power supplied. This research was developed based on the fact that cases of cascaded failures in connected systems have rampantly increased among industrial consumers in Kawempe Industrial Area. This has been due to factors such as proliferation of substandard circuit breakers, malfunctioning of circuit breaker components, external conditions that affect circuit breaker performance such as temperature, dust, etc., and negligence in conduction of compliance tests among others. These factors have not been put into consideration for the sake of effective asset management. Prior to implementation of an effective asset management framework, there is need for diagnosis of the present factors that hamper effective asset management and develop replacement strategies. This paper focused on Circuit Breakers (CBs) since they consume a large proportion of budgets of maintenance of utilities and are critical to system reliability. The parameters influencing CB performance were determined by Weibull modeling in MATLAB 2018: findings revealed that the industrial CBs had a maximum hazard rate of 5.6% with an average mean time-to-failure of 13.47 years, which represents a high propensity to death and critical condition of all CBs.*

Keywords—Asset Management, Industrial Circuit Breakers, Reliability

I. Introduction

Globally, distribution utilities are directing significant effort towards ensuring proper asset management on distribution network [1]. However, industrial consumers have left a substantial debt in the need to improve the management of electrical systems which poses a great need to manage them according to [2]. Ultimately, every industrial consumer's goal is to ensure maximum reliability during operational activities. Operational reliability is characterized by minimum equipment deterioration for asset protection equipment, regulatory and operational assets which basis for effective asset management [3] [4]. Due to the limited existing electrical consumer protection strategies in Uganda, several industrialists have been cheated by dealers of substandard equipment, tools and accessories, uncertified electricians, utility supplier rigidities and routine power surges [5]. Circuit Breakers (CBs) in particular are critical electrical systems elements that should be given ultimate priority for smooth industrial operations [6].

The deterioration of circuit breakers depends on factors such as equipment quality, operational load stress, existing maintenance strategies, the surrounding environment with regards to temperature, moisture, pollution among others [7]. In the event of occurrence of an overload induced from connected assets such as motors, Variable Frequency Drives (VFDs) and Variable Speed drives, (VSDs), a faulty circuit breaker will fail to open [8]. Failure to prevent the fault will lead to the destruction of property and significant downtimes, reduction in; productivity, profitability and firm competitiveness according to [9]. [10] Also emphasize that circuit breaker failure threatens the functioning of other equipment, which directly affects the quantity of non-supplied electrical energy. This is one of the main reasons for the accurate prediction of a circuit breaker's remaining useful life (RUL). It is therefore important for industrial consumers to know the expected time of maximum degradation of a circuit breaker and assess the impact of the driving factors. This will act as a basis for identification of symptomatic circuit breakers and establishment of proper replacement strategies. [10] defines a replacement strategy as one which clearly predicts the risk of failure/likelihood of failure, conditions behind and advocates for the opportune time and measures for replacement. Present circuit breaker assessment strategies in industrial consumers apply only scheduled maintenance where reliability of the circuit breaker is ensured only by planned schedules and less consideration on the actual condition of the circuit breakers. This therefore results into hidden growth in magnitude of faults leading to unexpected deterioration upon occurrence and high cost of corrective maintenance as opposed to condition based maintenance strategies which accurately predicts future fault occurrence giving room for earlier remedial action [11]. A survey that was conducted in Kawempe Industrial Area noted a record of cascaded failures in CB connected systems of 73% industrial consumers of Kawempe Industrial area over the past three decades.

II. Theoretical Approach and Model

Predictive Modeling of Circuit Breaker Degradation in Stochastic Environments

Life assessment is necessary in acquiring effective replacement strategies since it ascertains or understands the failure pattern of industrial CBs throughout their life span thus predicting the expected extent of failure in a prescribed time frame and consequently the opportune replacement time. The basic concepts of performing life data analysis include attempts to make predictions about the life of all products in the population by fitting a statistical distribution (model) to life data from a representative sample of units. The parameterized distribution of the data set can be used to estimate important life characteristics of the product such as reliability or probability of failure at a specific time, the mean life and failure rate. Life data analysis requires the following:

i. Gather life for the product
ii. Select a lifetime distribution that will fit the data and model the life of the product
iii. Estimate the parameters that will fit the distribution to the data
iv. Generate plots and results that estimate the life characteristics of the product, such as reliability or mean life [12].

Probability Density Functions (PDFs) used in life assessment

PDFs are instrumental in prediction of the probability of failure of an industrial circuit breaker. 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 [13].

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 or predictors 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 [14]. 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):

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

For the whole area under the density function: (2)

$$\int_0^\infty f(t)dt = 1$$

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:

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

The Cumulative Distribution Function F (t)

[14] defines the CDF F(t) of a random variable T as 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:

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

Further, the F (t) in terms of a population is the proportion of units in the population that will fail before time "t [15]. The term F (t) has some two useful interpretations:

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

Conversely:

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

B(x) lives

B(x) lives are often used to indicate certain levels of reliability based on the age of a component. The B(x) lifetime can be defined as the estimated time when the probability of failure will reach a specified point (X %). The B(x) lives are another way to represent the CDF where the "x" is the CDF in % [16]. In the engineering field, the B(x) usually starts around B (10) suggesting that 10% of the population will fail at a certain age and that 90% survives. For example, if 10% of the products are expected to fail by 4 years of operation, B (10) lifetime is 4 years.

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 [17] i.e. failures occur after time "t" This is expressed as:

$$R(t) = \Pr(T \le t) \quad (6)$$

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:

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

i. R(t) has two common interpretations according to [18].
ii. 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)
iii. 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:

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

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 [19]. Additionally according to [20], 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:

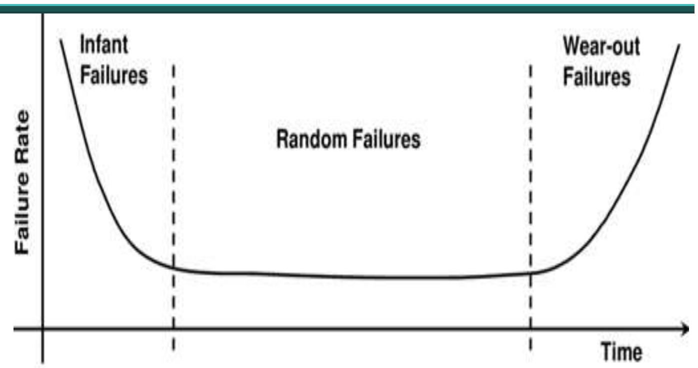

Figure 1: The three stages of asset aging from the time of commissioning to death

$$\Pr(t \le T \le t + \Delta t | T \ge t) = \frac{R(t) - R(t+\Delta t)}{R(t)} \quad (9)$$

The hazard function h (t) is expressed as:

$$h(t) = \lim \Delta t \to 0 \frac{R(t) - R(t+\Delta t)}{R(t)\Delta t} = \lim \Delta t \to 0 \frac{-[R(t+\Delta t) - R(t)]}{\Delta t} \frac{1}{R(t)} \quad (10)$$

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 [21]. Thus the failure modeling reduces to:

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

III. METHODOLOGY

Determination of Parameters that Influence Performance of Industrial Circuit Breakers

Modeling (parametization) of CB performance predictors

Let $t1, t2, \cdots, tn$ 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

$$L = \prod_{i=1}^{n} f_i(t_i; \overrightarrow{\theta}) = \prod_{i=1}^{n} \frac{\beta}{\eta} \left(\frac{t_i - \propto}{\eta}\right)^{\beta - 1} e^{-\left(\frac{(t_i - \alpha)}{\eta}\right)^{\beta}} \quad (12)$$

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 the exponential term, it is easier to obtain the maximum by its logarithm leading to reduced complexity during performance of calculations. The logarithm of the likelihood function is shown as;

$$In\left[L\left(t_i; \vec{\theta}\right)\right] = \sum_{i=1}^{n} [In(\beta) + (\beta - 1)In(t_i - \alpha) - \beta In(\eta) - (\frac{(t_i - \alpha)}{\eta})^{\beta}] \quad (13)$$

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

$\vec{\theta}$ and set the partial equations to zero, as

$$\frac{\partial In[L(t_i;\vec{\theta})]}{\partial \alpha} = 0 \qquad (14)$$

$$\frac{\partial In[L(t_i;\vec{\theta})]}{\partial \beta} = 0 \qquad (15)$$

$$\frac{\partial In[L(t_i;\vec{\theta})]}{\partial ɳ} = 0 \qquad (16)$$

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

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

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

$$L_3 = \sum_{i=1}^{n}[-\frac{(\beta-1)}{(t_i-\alpha)} + \left(\frac{\beta}{ɳ}\right)\left(\frac{(t_i-\alpha)}{ɳ}\right)^{\beta-1}] = 0 \qquad (17)$$

The shape parameter represented the rate of deterioration of the industrial circuit breakers whilst the scale parameter represented the time of failure. The developed parameters became inputs for the Weibull predictive model. Formulation of the parameters is shown in equations (18) to (19) below: The values of β (shape parameter) and ɳ (scale parameter) in Maximum likelihood estimation are determined by a relationship such that:

$$\frac{1}{\beta} + \frac{1}{ɳ}\sum_{i=0}^{n} x_i + \frac{\sum_{i=1}^{n} {x_i}^{\beta} In x_t + \sum_{j=n+1}^{N} {y_j}^{\beta} In y_j}{\sum_{i=1}^{n} {x_i}^{\beta} + \sum_{j=n+1}^{N} {y_j}^{\beta}} = 0 \qquad (18)$$

$$ɳ = \left[\frac{1}{n}\left(\sum_{i=1}^{n} {x_i}^{\beta} + \sum_{j=n+1}^{n} {y_j}^{\beta}\right)\right]^{\frac{1}{\beta}} \qquad (19)$$

$$B = \frac{\sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i}{n}}{\sum_{i=1}^{n} {x_i}^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}} \quad \text{Where } \beta = B^{-1}$$

(3–9)

$Y' = A + BX'$ Where $Y' = In(t)$ and $X' = InIn\left(\frac{1}{1-F'(t)}\right)$

(20)

Where x represents the time of operation (life) of the circuit breaker (years)

The figure 2 shows the flowchart showing the process of establishment of parameters (parametization) for circuit breaker performance:

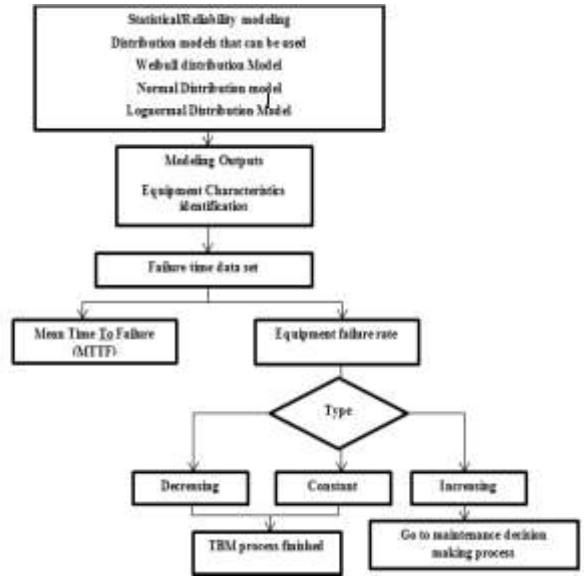

Figure 2: Systematic process of parametization of Industrial circuit breaker performance

Assumptions of determination and assessment of Industrial Circuit breaker performance parameters

i. For values of $\beta < 1$, the failure rate decreases with time.
ii. For values of $\beta > 1$, the failure rate increases with time.
iii. For values of $\beta = 1$, the failure rate is constant
iv. As ɳ tends to 40 years, which is the maximum life, the reliability of the circuit breakers keeps reducing.

Prediction Modeling and Simulation using the Weibull Model

The application of the Weibull predictive model was done in MATLAB 2018 Software where the shape parameter and scale parameter acted as inputs for the Weibull model considering cases of all the 14 industrial consumers. The purpose of Weibull predictive models was to develop Probability density functions and Cumulative density functions from which the expected times to failure of the circuit breakers of each consumer would be achieved. Findings are shown in section IV.

Assumptions made:

i. A positive skewness of the PDF with $H.I \leq 0.5x$ represents a less time-to-failure.
ii. A negative skewness with $H.I \geq 0.5x$ of the PDF represents a longer time-to-failure. Where x is the life of the circuit breaker and H.I is the Health Index.

The PDF and CDF were determined under the Weibull predictive model as distributions which predicted the expected rate of failure at a given future time and the number of circuit breakers which will fail after a given time respectively. Formulation of the PDF $f(x)$ and CDF $F(t)$ functions were determined in MATLAB 2018 and shown by the equations 21 and 22:

$$f(x) = \frac{\beta}{\eta}\left(\frac{\beta}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \quad x \geq 0;\ \beta, \eta \geq 0 \qquad (21)$$

$$F(t) = P\{x \leq t\} = 1 - exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \quad x \geq 0;\ \beta, \eta \geq 0 \qquad (22)$$

The Mean Time to Failure and Hazard rate functions were used to verify the criticality of state of the industrial circuit breakers which will aid in formulation of proper replacement strategies. The Mean Time to Failure (MTTF) was the key parameter which aided in achieving an optimal replacement strategy by achieving the opportune time of replacement as shown in section IV. The hazard rate was used to determine the probability of survival or propensity of death. Equations 23 and 24 show the formulation of the MTTF and Hazard Rate respectively:

$$MTTF(\mu) = \eta\Gamma\left(1 + \frac{1}{\beta}\right) \qquad (24)$$

$$Hazard\ Rate\big(h(x)\big) = \frac{\beta}{\eta}\left(x^{\beta-1}\right) \qquad (25)$$

IV. PRESENTATION OF RESULTS

Determination of Parameters That Influence Performance of Industrial Circuit Breakers

Circuit breaker Life Estimation and analysis using Maximum Likelihood Estimator

As mentioned earlier in Section 2, 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 to 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 that have completely failed.. Table 1 shows the Weibull Parameters determined by the Maximum Likelihood Estimator.

Table 1 Weibull parameters achieved by the Maximum Likelihood Estimator

No.	Consumer	β	η
1	Luuka Plastics Uganda Limited	1.389242	38.753
2	Hariss International Site-1	2.586388	37.863
3	Hariss International Site-2	2.613599	37.614
4	Maganjo Maize Millers Uganda Limited	3.201423	30.258
5	Delight Uganda Limited	4.057257	28.658
6	Kombucha Products Uganda Ltd	5.23	27.078
7	Pan Africa Impex Uganda Limited	5.959624	26.254
8	FICA Seeds Uganda Limited	6.515146	25.332
9	MEC Uganda Limited	6.818649	24.766
10	Arise & Shine Millers Limited	7.0609	23.078
11	Mega Foods and Beverages Uganda Limited	7.06863	23.400
12	Jackan Foods Uganda Limited	8.48043	20.620
13	Steel and Tubes Uganda Limited	9.6796	19.750
14	Concfeed International Uganda Limited	14.18917	15.676

Development of a Predictive Model for Circuit Breaker Degradation in Stochastic Environments

Circuit breaker life

Analysis of industrial circuit breaker health prediction over its entire life was done in MATLAB 2018 environment where life predictions were done. [22] Noted that the maximum life of all circuit breakers was selected to averagely 40 years.

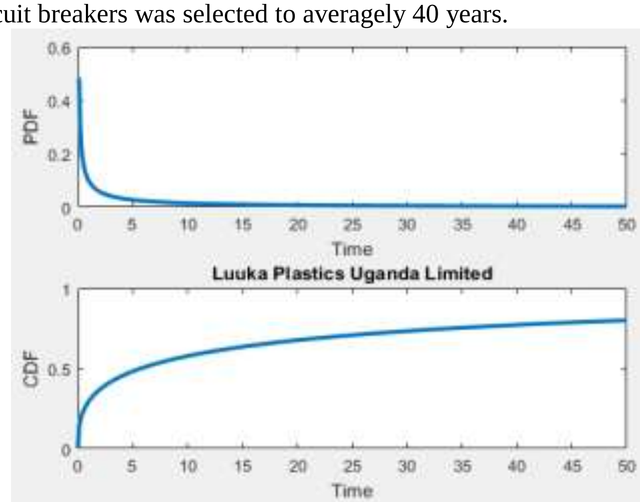

Figure 3: PDF and CDF plots for Luuka Plastics Uganda Limited Circuit breakers

The PDF shown in figure 3 represents the predictability of Luuka Plastics Uganda Circuit breakers for a life of 40 years from the time of installation. As previously mentioned in section II, the life of an asset is analyzed in a bathtub pattern considering three stages namely: the infant mortality, the stage of random failure/constant aging and the wearout stage. As shown in figure 3, 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 less signs of depreciation since shape parameter β is slightly greater than 1 in this stage. After 10 years, the circuit breakers will undergo random failures. The CB will have no wearout stage due to the fact that they are capable of being on the AGAN state for a long-time frame. At 40 years of age, only 63% of the CBs will show symptoms of failure as demonstrated in the CDF plot in figure 4.

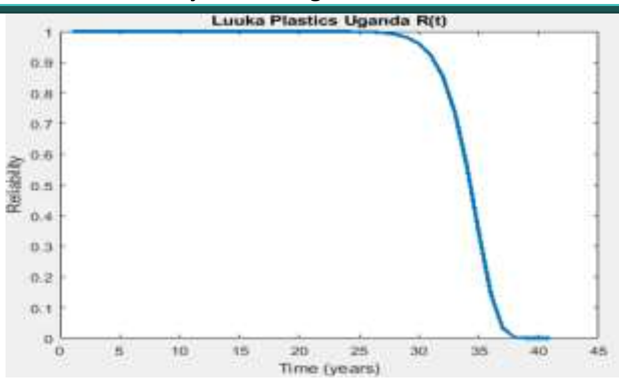

Figure 4: Reliability plot for Luuka Plastics Uganda

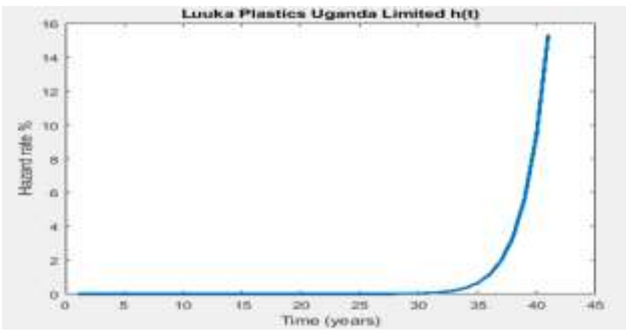

Figure 5: Hazard plot for Luuka Plastics Uganda Limited

Figure 4 reliability plot shows that the reliability of circuit breakers is 0.9907 upto a life time of 28 years. Beyond 28 years, serious degradation or wearout starts. At 95% of the circuit breaker life, the probability of survival will be 0.002392. The hazard plot in figure 5 shows that beyond 31 years, the propensity to death of the circuit breaker is 5.6%. This means that random failures exist upto 31 years. Beyond 31 years, the circuit breaker will have 94.4% chances of death.

CIGRE Surveys on hazard rate of an asset emphasize that an asset with maximum chances of serious degradation or complete wearout will have a propensity of death of 2% [23]. According to figure 4.3, a 2% propensity is achieved at 37 years.

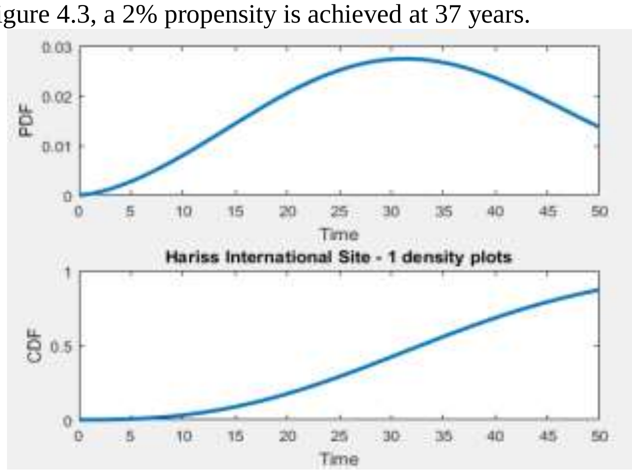

Figure 6: Hariss International Uganda PDF and CDF plots

The PDF in figure 6 shows that the circuit breakers under study will undergo increasing deterioration (wearout) 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 4.4 shows that at 40 years of the circuit breaker life, 60% circuit breakers will have undergone complete deterioration.

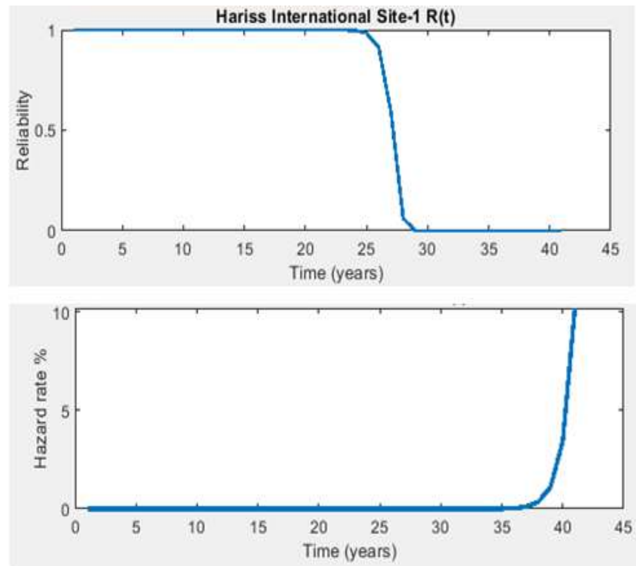

Figure 7: Hariss International Site-1 Reliability and Hazard rate plots

The reliability plot in figure 7 shows that the probability of survival of circuit breakers is 0.9976 upto a life time of 25 years. Beyond 25 years, serious degradation or wearout starts. At 73% of the circuit breaker life, the probability of survival will be 0.00009. The hazard plot in figure 7 shows that random failures will exist upto 37 years. Beyond 37 years, the propensity to death of the circuit breaker is 4.8%. This means that beyond 37 years, the circuit breaker will have 95.2% chances of death. According to figure 7, a 2% CIGRE survey limit propensity is achieved at 35 years.

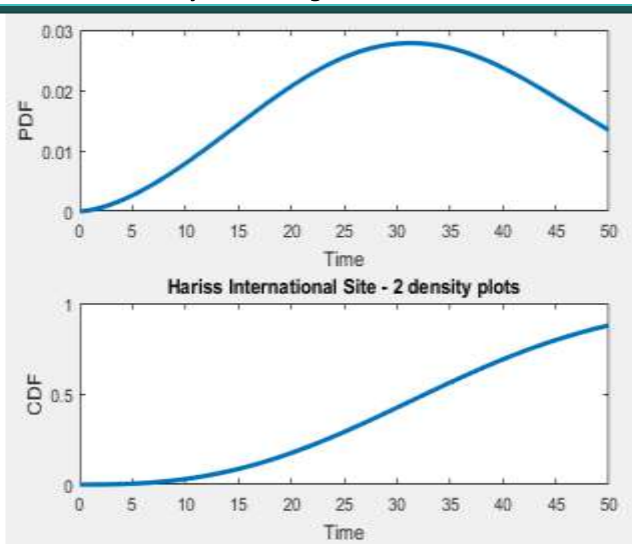

Figure 8: PDF and CDF plots for Hariss International Site – 2

The PDF in figure8 shows that the circuit breakers under study will undergo increasing degradation (wearout) upto about 33 years of operation. This signifies that at about 83% of the circuit breaker life, the probability of failure is 2.8%. The CDF in figure 8 shows that at 40 years of CB life, 91% circuit breakers will have undergone complete deterioration.

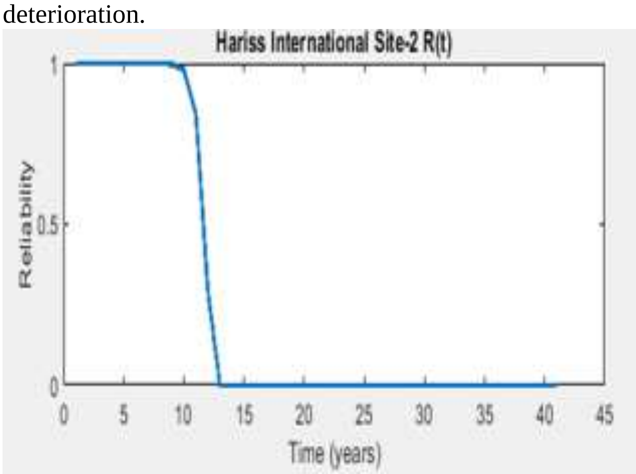

Figure 9: The Reliability Plot for Hariss International Site – 2

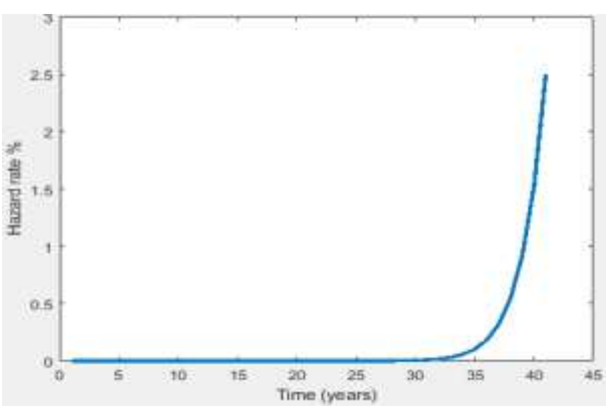

Figure 10: Hazard rate plot for Hariss International Site – 2

The reliability plot in figure 9 shows that the probability of survival of the circuit breakers is 0.9983 upto a life time of 9 years. At 33% of the circuit breaker life, the probability of survival will be 0.000595. The hazard plot in figure 10 shows that the CBs will undergo random failures upto 33 years of CB life. Beyond 33 years, circuit breaker propensity to death is 3.099%. This means that beyond 33 years, the circuit breaker will have 96.967% chances of death. Figure 10 further shows that a 2% CIGRE survey limit propensity is achieved at 30 years

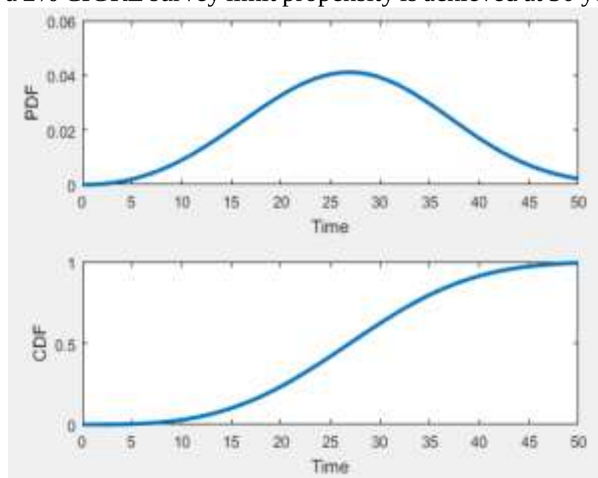

Figure 11: Maganjo Maize Millers PDF and CDF plots

The PDF in figure 11 shows that the circuit breakers will undergo a stage of increasing degradation (wearout) upto about 25 years while in operation. This signifies that at about 62% of the circuit breaker life, the probability of failure is 4%. The CDF in figure 4.1 shows that at an age of 40 years, 92% circuit breakers will have undergone complete deterioration. Circuit breakers at Maganjo Maize Millers underwent premature failure in the infant mortality stage since most of them had a minimum of 37 years from the time of installation and required replacement. As earlier mentioned, the life span of a circuit breaker is about 30 to 40 years. Operation of circuit breakers of Maganjo millers provides possibilities where they are most likely to be subjected to operational stresses and malfunctioning due to constraining of operation at a borrowed life time.

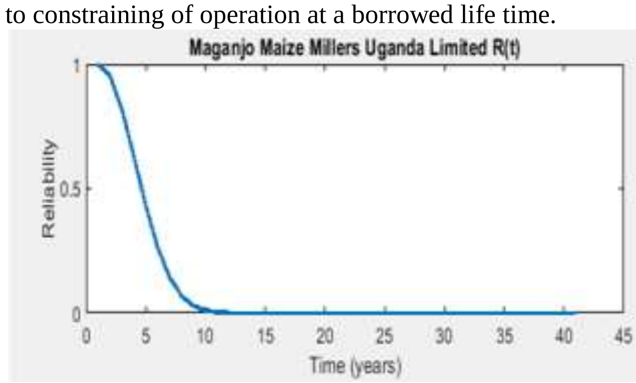

Figure 12: Reliability Plot for Maganjo Maize Millers Uganda Limited

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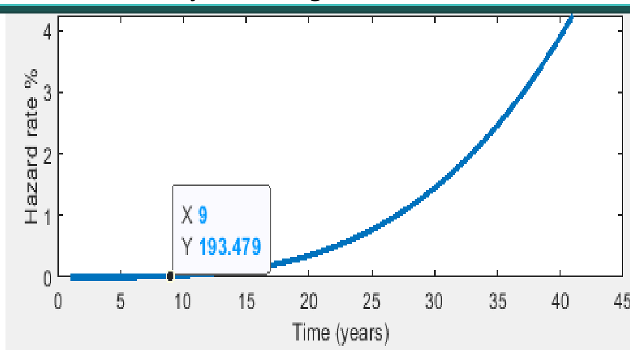

Figure 13: Hazard Plot for Maganjo Maize Millers Uganda Limited

Figure 13 reliability plot shows that the reliability of circuit breakers is 0.9983 upto a life time of 1.5 years. At 25% of the circuit breaker life, the probability of survival will be 0.01 which is the outlier point. The hazard plot in figure 4.11 shows that the CB will undergo random failures upto 13 years of operation. Beyond 13 years, the propensity to death of the circuit breaker is 0.25%. This means that beyond 13 years, the circuit breaker will have 99.75% chances of death. Figure 13 indicates that at a 2% CIGRE survey limit propensity of death is achieved at 9 years.

Circuit breakers of Kombucha Products limited also have high chances of serious deterioration/complete death in the next years with 99.76% circuit breakers expected to have failed by 40 years shown by the CDF in figure 4.12 . Kombucha circuit breakers under study have an average life of 25 years from the time of installation. At 25 years, the probability of failure is 7.6%. 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. The probability of survival (reliability) if the circuit breakers will be 0.991716 only upto 3 years of operation. The Hazard rate plot shows that the CBs will undergo random failures upto about 13 years of operation. This is exhibited by a hazard rate of 0.88%. 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 14 to 16 show the predictability of Kombucha products circuit breakers:

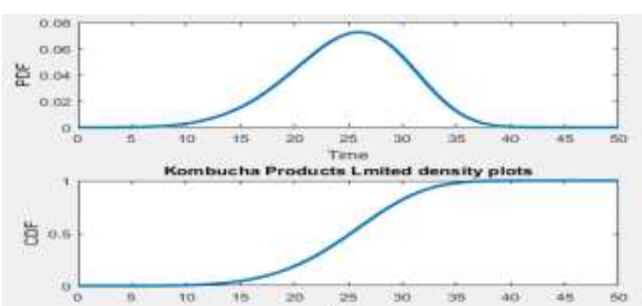

Figure 14: PDF and CDF Density Plots of Kombucha Products Uganda Limited

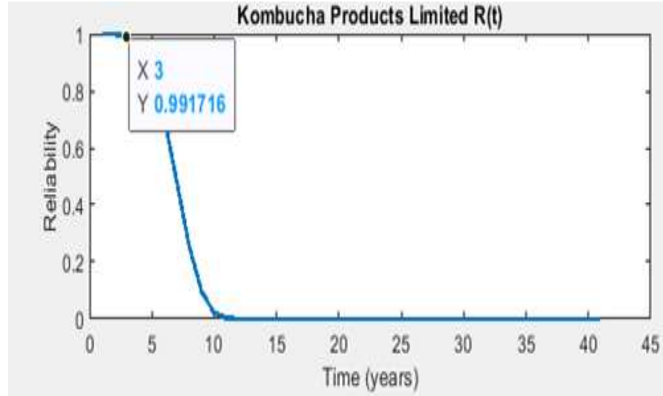

Figure 15: Reliability of Kombucha Products Uganda Limited

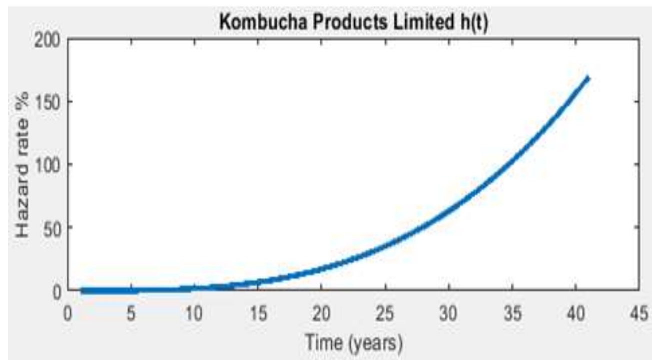

Figure 16: Hazard Plots for Kombucha Products limited

Considering the Rest of the Industrial Consumers

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 maximum 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 limited capability of efficient operations such as quenching of arc, tripping promptly in event of a fault, etc.

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. The table 2 shows the summary of description for the sample of industrial consumers under study in the Kawempe Industrial Area considering reliability parameters. Figure 17 to 18 shows the density plots for the rest of the industrial consumers.

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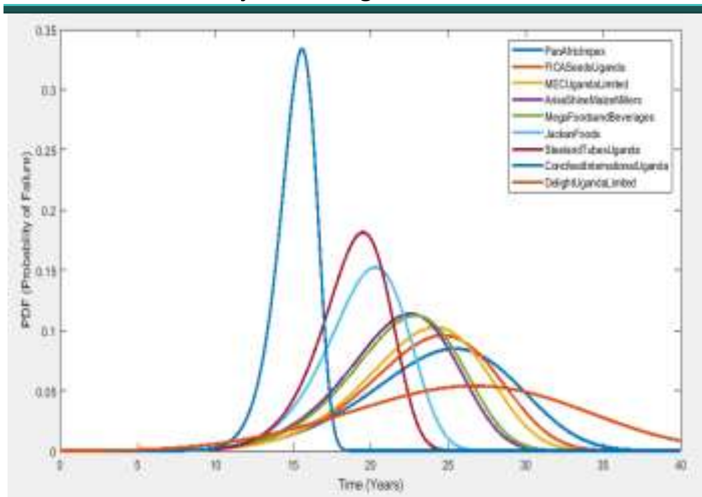

Figure 17: Probability Density Functions for the rest of the industrial consumers

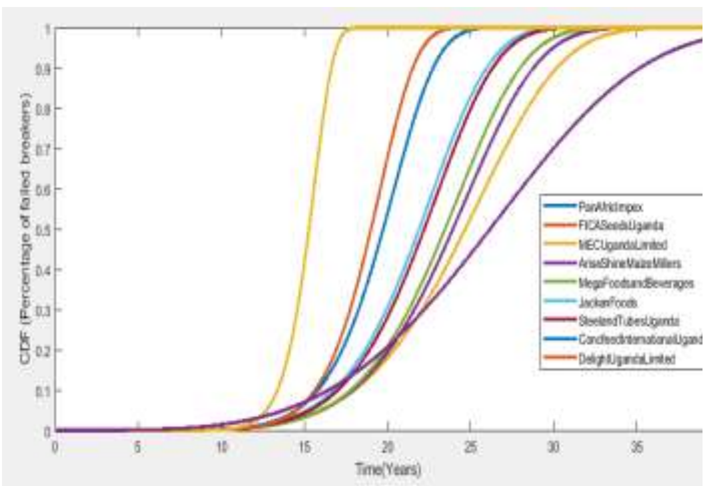

Figure 18: Number of failed circuit breakers over time

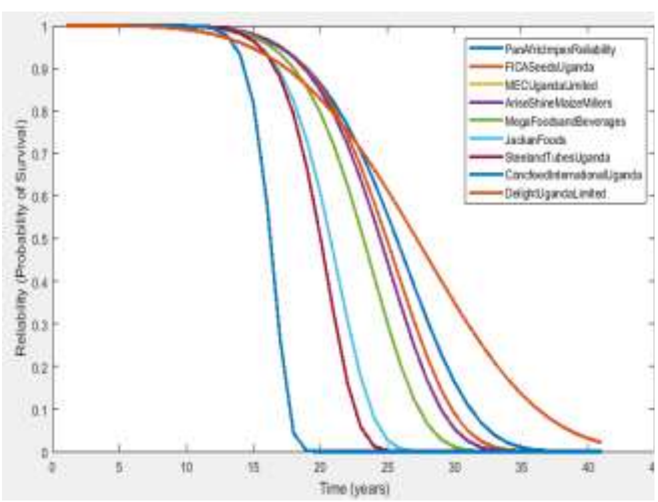

Figure 19: Reliability of the industrial circuit breakers for the remaining consumers

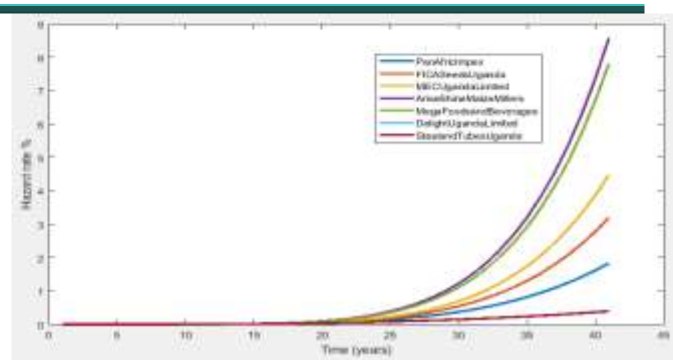

Figure 1: Hazard rate for the remaining consumers

Table 2: Summary of Reliability Parameters for the Sample of 14 Industrial Consumers

No	Industrial Consumer	PDF (Probability of failure) %	POF (years)	MTTF (years)	B(X=40) CDF (%)	Reliability R(x_{max})
1	Luuka Plastics Uganda	0.35	40	38.76	62	R(28) = 0.9907
2	Hariss International Site – 1	2.8	31	29.54	57	R(25) = 0.9976
3	Hariss International Site – 2	2.8	33	32.65	63	R(9) = 0.9983
4	Maganjo Maize Millers Ltd	4%	25	23.86	92	R(1.5) = 0.9999
5	Kombucha Products Ltd	7.6%	25	24.19	99.97	R(3) = 0.9917
6	Delight Uganda Limited	62%	10.89	9.89	98.2713%	R(6.8) = 0.9970
7	Arise Shine Millers Ltd	38%	4.1	3.6	98.62%	R(11.5) = 0.9912
8	Pan Africa Impex Ltd	58%	3.5	3	99.35%	R(2.0) = 0.9981
9	FICA Seeds Uganda	35%	9.48	9.26	99.67%	R(7) = 0.9945
10	MEC Uganda Limited	30%	2.8	2.2	98.66%	R(2) = 0.9652
11	Mega Foods and Beverages	29%	2.1	2.0667	99.54%	R(1.25) = 0.9478
12	Jackan Foods Uganda	28%	2.8	2.0256	99.73%	R(1.34) = 0.9962
13	Steel and Tubes Uganda	30%	3.3	2.8	99.08%	R(1.3) = 0.9948
14	Concfeed International	40%	1.6	1.52	99.08%	R(0.86) = 0.9956

Where x_{max} represents the maximum grace period for survival of the circuit breaker.

Table 3: Summary of Reliability and Hazard Rate Parameters

S/n	Industrial Consumer	Hazard Function (%)
1	Luuka Plastics Uganda	5.6
2	Hariss International Site – 1	4.8
3	Hariss International Site – 2	3.1
4	Arise & Shine Millers Uganda Ltd	0.25
5	Maganjo Maize Millers Ltd	0.88
6	Delight Uganda Limited	0.76
7	Kombucha Products Ltd	1.2
8	Pan Africa Impex Ltd	0.9
9	FICA Seeds Uganda	0.67
10	MEC Uganda Limited	0.1
11	Mega Foods and Beverages	1
12	Jackan Foods Uganda	1.46
13	Steel and Tubes Uganda	1.66
14	Concfeed International	1.23

V. DISCUSSION OF RESULTS

Parametization

Results presented in section IV attempted to assess the performance of the Industrial circuit breakers for a life span of 40 years using the Weibull Model which was completely time based. The Maximum Likelihood method of parameter Estimation (MLE) was used to generate the shape parameters and scale parameters which determined the reliability of the circuit breakers in their life time as described in section III. The shape parameter β predicted the possible rate of failure of the Industrial Circuit Breakers with time whilst the scale parameter ɳ represented the time of failure. These parameters enabled generation of the Probability Density Functions (PDFs) and Cumulative Density Functions (CDFs).

As shown in table 1, with exception from Luuka Plastics Uganda Limited, the failure rate of other industrial consumers increases with the life of the Industrial circuit breaker based on the assumptions in section III. This indicates that Luuka Plastics implements measures to ensure sustainability of their breakers such as proliferation of standard breakers, proper load sizing, frequent conduction of compliancy tests, and timely preventive maintenance among others which are measures characterizing effective asset management. This is why their CBs are in the As Good As New (AGAN) state irrespective of their life increment, consistent with [24] studies which noted that for a circuit breaker to be in (AGAN) state, there should be substantial preventive maintenance frameworks. This will ensure increase in reliability with CB life. This is the same case with timely replacements. The assumption that circuit breaker reliability monotonically varies with its reliability is not completely substantial as long as measures to ensure proper asset management are effective. This is in agreement with [25]

Parameter estimations using the MLE were preferred for this study with results shown in table 1. The value of $\beta > 1$ is consistent with what other researchers have used in circuit breaker life assessment such as [26] however is generally higher than most studies which are limited to $\beta < 10$. The log plots however have a low repeatability. The value of ɳ varies according to the aging time of circuit breakers. This is consistent with findings of other researchers. However findings of this research are more accurate to the extent of deterioration of the circuit breakers based on the time of operation.

Development of a Predictive Model of CB degradation in Stochastic Environments

The Probability Density Functions (PDFs) and Cumulative Density Functions (CDFs)

The shape and scale parameters that were previously discussed enabled generation of a Weibull Predictive model whose purpose was to predict the exact time of maximum degradation of the Industrial Circuit breaker. This will guide development of effective replacement strategies by identification and stratification of circuit breaker reliability based on their future performance (capability). This will consequently aid effective protection asset management frameworks. According to section IV, PDFs and CDFs where generated to predict the circuit breaker performance. As earlier discussed in section II, the PDF represents the time to failure. Luuka Plastics experiences a negative exponential trend as the life of the circuit breaker increases. This is greatly attributed to effective asset management frameworks.

Industrial Circuit breakers of Luuka Plastics remain in AGAN state even as their life passes by thus showing a decreasing failure rate with time. Results of other industrial consumers show positive exponential trend in PDF indicating the probability of failure increasing with increase in life of the breaker. This is due to a need to improve on the asset management frameworks such as procuring standard circuit breakers, frequent conduction of preliminary compliance tests, proper load sizing, etc. The consumers such as Hariss International Site – 1 and Hariss International Site – 2, with ɳ = 37.863 and 37.614 demonstrate a high value of time to failure since the circuit breakers will attain maximum degradation at about 93% of their expected life. This is opposed to findings of Concfeed International Circuit breakers which will undergo maximum degradation at 15.676 years which is about 39% of their expected life, representing premature failure.

Such consumers ought to greatly revise their asset management frameworks prior to future commissioning of breakers, so as to avoid further financial losses to be incurred in replacement of damaged equipment in event of cascaded failures. The prediction of circuit breakers to fail early represents a great need to carry out compliance tests so as to determine circuit breaker resilience under different load conditions. The findings will guide effective replacement. The CDFs represented the number of circuit breakers that would fail after a given time. This is similar to studies by [27]

Kurtosis of the PDFs and CDFs

Considering kurtosis in CB life analysis, [28] studies are only limited to a Mesorkutic pattern of distribution even during his analysis of circuit breaker failure as opposed to this study which shows varying kurtosis of the probability of failure distribution. This research considers the fact that shape parameter values obtained from MLE vary and hence the kurtosis of the different distributions will vary as well for purposes of accuracy of results. In the Weibull model, the kurtosis varies basing on the scale parameter. [28] Studies utilize the Weibull life assessment model and Maximum Likelihood estimator (MLE) but yet only consider one form of kurtosis during analysis. This means that they assume a constant value of scale parameter which therefore renders their study less accurate. Additionally, during analysis of reliability of trip coil mechanisms over time, a normal distribution with a platykurtic kurtosis is always generated for output values of trip coil reliability even for unreliable mechanisms according to Guan studies. However [29] emphasizes that, failure probability outputs are not normally distributed per se. It is therefore recommended to generate distributions such as Beta and Gamma outputs for more accurate results.

The skewness of the PDFs and CDFs (Evaluating the Health Index)

The findings of determination of exact time of circuit breaker failure where based on the fact that a positive skewness of PDF curves represents an early time-to-failure, hence a need for earlier replacement due to a low reliability of operation with time. Negative skewness represents a longer time-to-failure, hence less need for earlier replacement which is a good maintenance optimization initiative. These assumptions where elaborated in section III as well and are similar to studies by [27]

[30] And [24] establish condition based requirements for assessing circuit breaker life i.e. *"major", "minor", "healthy"* and assess circuit breaker condition based on the Health Index. This is similar to my research methodology; however [30] studies are limited to the current state of the circuit breakers and do not put into consideration the predictability factor. The article by [28] on Reliability evaluation of high voltage circuit breakers using Fuzzy Analytical Hierarchy Process (FAHP) and Genetic Algorithm is an accurate CBM technique to guide maintenance strategies, contingency plans and improvement of designs. However findings are not time bound as to when a given weighted factor is likely to cause the highest failure impact.

Hence the predictability factor is not considered as well. Studies by [28] also categorize CBM requirements of health status according to unreliability, minor, major and failure. However the health index assessment does not consider the future state of the circuit breaker. It should be noted that failure of predictability may lead to serious degradation of an asset in its final stages of life which imposes large power quality problems to the industry. Studies by [5] utilized a health index constraint of ($H \leq 0.5x$) which was an inequality constraint representing the range in the circuit breaker life at which failure/serious degradation occurs. This is similar to my research approach where using MLE; results were achieved in MATLAB 2018 environment where all location parameters below half of the circuit breaker life had a failure/beta distribution as output. Constraints of ($H \geq 0.5x$) achieved a normal distribution. These were only 27% of the Industrial consumer breakers.

The Mean Time-To-Failure (MTTF)

The standard deviations are small indicating the data spread is very minimal except for the case of the outlier circuit breakers aged 30 and above. The use of Mean Time to Failure compared to Mean Time Between Failure was due to the fact that most circuit breaker failures are not repairable. Depending on the type of failure, most times failure involves extensive damage and circuit breakers are disposed off. This fact was assumed in the study as was the case by other researchers involved in lifetime study. Other researchers such as [28] and [19] used similar approaches. The MTTF also determined the opportune time for replacement of the industrial circuit breakers as shown in section IV and varied depending on the failure rate. A higher failure rate signified that the circuit breakers were in a critical condition and needed early replacement.

B(x) Lives

The B(x) lives are used as tools to indicate the fraction of industrial circuit breakers that are expected to fail at a certain age. This was exhibited by the CDF results in section 4.3 (table 4.3) which indicated that Luuka Plastics International and Hariss International had the least expected quantity of failure (57% and 62%). This means that at 40 years of circuit breaker life, a minimum of 57% and 62% industrial circuit breakers will have failed comparing all industrial consumers. This shows that most of the industrial circuit breakers are in critical condition and need immediate attention.

The Hazard Rate

According to [20], the hazard rate is the assets's propensity to death or to die depending on the age reached and it thus plays a key role in characterizing the process of aging and in classifying lifetime distributions. [31] confirms that the analysis of hazard rate is based on non repairable components under study. This assumption was also applied in this research. Additionally, this study employs a monote hazard rate which increases as the deterioration rate of the circuit breaker increases. This is consistent with a documentation by [20] and elaborated in table 4.5 where majority of Industrial consumer circuit breakers exhibit a high hazard rate. According to table 4.5, the hazard rates for predicted failures have a maximum of 5.6% which shows that all industrial circuit breakers have a high propensity to death/limited chances of survival in the course of their life. A greater hazard rate should be noted to yield higher chances of survival of an asset.

VI. CONCLUSION

The main objective of this study was to develop a statistical predictive model for circuit breaker failure and related fault drivers in Uganda as a tool to enhance appropriate replacement strategies. The study revealed that most industrial consumers in Kawempe Industrial area have historical data of the failure status of circuit breakers, but still have increasing events of cascaded failures and complaints from utilities of increasing emerging faults. This is proven by an average MTTF value of 13.45 years. Despite availability of historical data and maintenance frameworks, only 27% of industrial consumers have records of healthy circuit breakers with a potential of lasting to the prescribed life. The remaining 73% industrial consumers are facing impacts of premature failure or deterioration of their industrial circuit breakers.

The remaining useful lifetimes of 71% of the consumers' circuit breakers are presently less than 30 years. In otherwords the life span of their circuit breakers is less than ¾ of the prescribed life. All industrial circuit breakers have a high propensity to death and exhibit minimum chances of survival given their prescribed life. This is proven by a maximum hazard rate of 5.6%. Results indicated that industrial circuit breakers with higher failure rates required earlier replacement compared to those with low failure rates. Determining opportune replacement time will aid the development of accurate inventory maintenance strategies and mitigate the financial losses arising from unexpected cascaded failures.

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