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Lifetime Estimation of Electrical Equipment in Distribution system using Modified 3-Parameter Weibull Distribution

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***Abstract*—Lifetime and reliability estimation of distribution system components are very crucial for reliable operation of the distribution system. Reliability of the distribution system depends on the reliability of individual components. The distribution system equipment experiences three different types of failures i.e. infant mortality failures, random failures and aging failures. Infant mortality failures will decrease with time, random failures are induced by the external event and its occurrence is constant and random in nature throughout the life of the component. The aging failures increases with time over the useful lifetime of the equipment due to degradation of electrical and mechanical durability. The impact of aging on electrical equipment is modelled by using the failure history of the equipment. The strength of component reduces due to failures, this phenomenon is considered for lifetime estimation of equipment. This paper presents a 3-parameter Weibull distribution function with varying shape parameter for lifetime estimation. The Weibull parameters are determined by using historical failure data and particle swarm optimization. The proposed model is applied to the equipment of the practical Indian distribution system.**

***Keywords*—Weibull distribution; lifetime; aging failures; hazard rate; reliability**

I. Introduction

In a competitive decentralized market, reliable and quality power supply are the extreme concern for the profitable system operation. An optimized asset management is required for the minimization of maintenance and capital reinvestment costs. The need and benefits of asset management is mentioned in [1], [2] for transmission and distribution systems. If the distribution system equipment age increases which reduces the reliability of the equipment due to increase of aging failures. The balance between the reliability and investment/maintenance cost requires the proper estimation of equipment reliability and lifetime. The proper lifetime models of the electrical components are helpful to predict the component reliability and useful lifetime.

Authors in [3], considered that the lifetime of the electrical components is less than 40 years. If the limitation of the reinvestment, maintenance and replacement of components has to be considered, the lifetime of the components may be increased based on the system operator's reinvestment and maintenance polices. It shows that the compromise among the reliability, reinvestment cost and maintenance cost will affects the component lifetime. For reliability evaluation of distribution system, component operating and failure states were modelled by using exponential distribution [4], which is giving the constant hazard rate with time. The component was considered as good as new after restoring from failures. But in actual practice, they have an aging effect as the equipment is in continues operation. The component failure rate is not constant for the whole lifetime, but rises over the years according to the bathtub curve. The rate of failures was increasing with time over the useful life of cables, circuit breakers, and transformers [5] - [7]. The effect of insulating materials and oil on transformers aging failures was discussed [3]-[8].

The component aging effect on power system reliability was discussed in [9]. The risk management process was employed to judge the maintenance and investment priorities [10]. The electrical components perform both technical as well as economical functions in distribution systems. Three types of lifetimes are specified in [11], physical lifetime, technical lifetime, and economic lifetime. The failure probability was increases at the end-of-life of the equipment. The maintenance of component repairable failures will be slow down the effect of aging on components. General maintenance activities used in the distribution system were corrective maintenance and preventative maintenance. An electro-thermo-mechanical lifetime models were used in [12] for lifetime estimation of the electrical components. The failure probability and density of electrical components was determined using a probabilistic approach. A 2-parameter Weibull distribution function with varying scale parameter was used for estimation of lifetime [13]. The failure probability distributions of circuit breaker were determined using Weibull probability distribution function [14]. A modified additive Weibull distribution was used to estimate the useful lifetime of the systems [15]. It is giving perfect bathtub shaped hazard rate functions. The different three-parameter Weibull distribution was used for lifetime estimation of a system [16]. An addictive Weibull distribution was used in [17] to get the bathtub hazard rates. The author's contributions in this paper are as follows:

i. A three-parameter Weibull distribution function with varying shape parameter is applied to determine the failure rate/hazard rate, probabilistic failure density,

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cumulative failure density/unreliability, and survival rate/reliability of the electrical components.

ii. Random failures and aging failures are used for estimation of the lifetime and reliability of components, because infant failures are neglected due to its decreasing nature with time.

iii. Estimation of Weibull parameters using particle swarm optimization technique.

The lifetime models in [12], requires the data of laboratory testing of equipment and not in actual operation scenario. The lifetime models in this paper are developed by using Weibull distribution and Weibull parameters are determined based on failure history and failure statistics of equipment under normal working conditions.

II. FAILURES IN ELECTRICAL EQUIPMENT

Most of the failures occurred in the distribution system are due to failure of the electrical equipment present in the distribution system. The reliability models of the distribution system are normally done according to the requirement of the customer. Electrical equipment i.e., overhead lines, circuit breakers, transformers and bus bars, etc. are modelled for reliability assessment of the distribution systems. The failures in electrical components are mainly characterized as infant mortality (burn in) failures, random failures and aging (wear out) failures. The failures caused by overloading and improper connections are very less. These can be minimized by proper monitoring and frequent inspection of the equipment presents in the system. The infant mortality failures are caused by the manufacturing defects and improper installation of equipment. Generally these failures decreases with time. Proper testing, installation and regular inspection will get rid of these failures, therefore infant mortality faults are not considered for lifetime models. The random failures are due to external events like weather conditions (e.g. Heavy winds, snowfall, and vegetation etc.) and these are the main cause of failures in electrical equipment. These failures are almost independent from age of the equipment. Occurrence of random failures is almost constant during the whole life time of equipment. The frequent failures degrades the strength of the equipment and quickly reaches to wear out period i.e. increase the aging failures. The distribution system failures encounters the different types of failures and the total failures of the equipment is determined as follow.

$$f_T = f_i + f_r + f_a \quad (1)$$

Where, f_T = total failures, f_i = infant mortality failures, f_r = random failures, f_a = aging failures

Infant mortality failures are eliminated by on site testing and installation. Only random and aging failures are present on electrical equipment throughout the lifetime. The statistics of random and aging failure of different electrical components are given in Table 1.

TABLE 1. Failure statistics [10]

Electrical component	Random failures (%)	Aging failures (%)
Overhead lines	90	10
Circuit breakers	10	90
Transformers	30	70
Bus bars	10	90

A. Overhead lines

Most of the overhead line failures are due to external events such as flora, animals, human faults, vandalism and dangerous weather conditions. Different failure causes and their percentage of appearance are shown in Fig.1 [18].

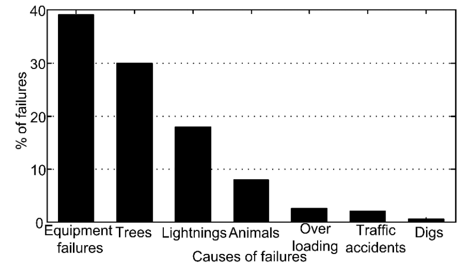

Fig. 1. Cause of failures in overhead lines

From the Fig. 1, it can be observed that equipment failures accounts the majority of failure in overhead lines. The failures due to the overloading and fault currents are less concerned with overhead lines. But the fault currents can damage the conductors, if faults are not cleared faster. From the failure statistics, it can be observed that the random failures (i.e., trees, lightning, animals, overloading etc.) are the most significant failures in overhead lines.

B. Circuit Breakers

Circuit breakers are the protecting equipment in the distribution system from the failures. The circuit breaker can be open unwantedly due to internal faults, false tripping, and operational failures. The false tripping is due to the miss coordination of protective equipment or complications with relays and its associated equipment. False tripping can be minimized by testing protective equipment coordination, relay settings, current/potential transformer ratios, and controller wiring. The operational failures of circuit breakers are failing to open or close caused by faulty controller wiring, uncharged actuators or stuck during its operation. The periodic maintenance and testing of circuit breakers will reduce the operational failure probability. Internal faults occur due to the reduction of the insulating materials dielectric strength and corrosion of the contact materials. Weather conditions are having limited impact on circuit breaker failures and they experiences less random failures during their lifetime. On the other hand, each time the circuit breaker is operated, the contacts are utilized to interrupt current, which leads to vaporization of the contact material. Due to high interruption currents the insulation strength also decreases. Because of these factors circuit breakers faces more aging failures.

C. Transformers

Transformers are the most significant equipment in distribution system for power delivery to the consumers. Two types of transformers are used in the distribution system i.e. power transformers and distribution transformers. Power transformers are located in substations and distribution transformers are located at near load points. The failures in power transformers can results in power interruption to thousands of customers, whereas failures in distribution transformers can interrupt only few customers. The failures in transformers can occur due to both external events and internal faults. External events includes storms, heavy winds and snow falls and which damages the transformer

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associated equipment like insulators, bushings, connecting cables etc. Internal faults of transformers can occur due to the overloading and short circuit currents. The overloading of transformer improves the reliability of the system for that instant, but the failure probability of overloaded transformers will increase in future. The causes of failures in transformers are divided into four major categories i.e. Assembly process, cleaning process, raw materials, and external events. The assembly process causes the faults related to insulation failures between windings and transformer core, bushings, tap changers and tank leakage Failures can be occurred due to paper insulation and sharp edge, these will damage the windings of the transformer. Different failure causes and their probability of occurrence is given in Fig. 2 [19]. It is observed that faults due to external events are less compared to transformer equipment related faults.

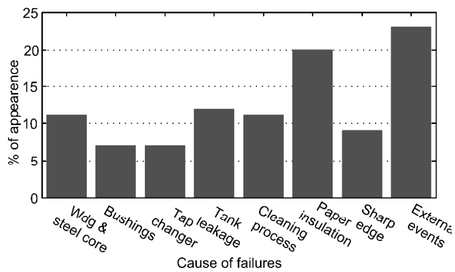

Fig. 2. Causes of transformers failure

D. Bus bars

Bus bars are common coupling points for different equipment having equal voltages level. Typically bus bars are situated in substations and combined with isolators and insulators. Failures related to bus bars lead to complete outage of the distribution substation. Because of its location and security of the substations, the effect of external events very rare and the probability of appearance of random failures is less. However, the operational failures present in bus bars, these operational failures are considered as part of random failures during the initial period of its operation. The overloading of the system degrades the dielectric strength of insulating materials used in bus bars and switching operations leads to the corrosion of contact metals. Overloading and switching operations are the major causes for aging failures in bus bars.

III. MATHEMATICAL MODELLING

The failure rate of electrical equipment shows different characteristics i.e. decrease failure rate (DFR), constant failure rate (CFR) and increased failure rate (IFR). These failure rate characteristics and different reliability measures of the components are determined using a three parameter Weibull distribution function with varying shape parameter. The failure probability density is determined by using probability density function (PDF) of the Weibull distribution function. The PDF of 3-parameter Weibull distribution [20] is as follows.

$$f(t;\beta,\alpha,\gamma)=\frac{\beta}{\alpha}.\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}.\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \quad for \quad t\geq 0 \tag{2}$$

Where, $\beta > 0$, $\alpha > 0$, $\gamma > 0$

β , α and γ are shape parameter, scale parameters and failure free parameter of Weibull distribution function respectively. t is the age of equipment in years. The Weibull parameters are calculated by using the failure history of equipment.

In (2), if β =1 the Weibull distribution becomes exponential distribution and which gives the constant failure rate. The advantage of Weibull function with the varying shape parameter gives the DFR, CFR and IFR according to the bathtub curve.

For the lifetime model analysis, DFR is not considered and CFR and IFR are taken for determination of failure rate distribution, reliability and unreliability of the components.

The total failure rate distribution of equipment as follows,

$$f(t) = f_0 + f_1(t) \tag{3}$$

Where, f_0 , $f_1(t)$ are the CFR and IFR respectively.

The probability of component failure (unreliability) is estimated by using cumulative distribution function (CDF) of Weibull distribution. CDF is determined by integrating the pdf of Weibull distribution.

$$F(t) = \int f(\mathrm{t})dt \tag{4}$$

$$F(t;\beta,\alpha,\gamma)=1-\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \tag{5}$$

The cumulative failure probability of a component due to multiple failure causes is determined by the simple combination of all failure probabilities [21], which is given by

$$F_c = \sum_{i=1}^{n} b_i.F_i \tag{6}$$

Where, $\sum_{i=1}^{n} b_i = 1$, F_c = Cumulative failure probability, F_i = Failure probability due to i^{th} failure cause, b_i = Weight factor of i^{th} failure cause, n = No of failure causes

The survival rate (Sf) is the probability of reliability of component at that instant. It is the complementary of probability of failure and denoted as *R(t)*. The survival rate is determined as follows.

$$R(\mathrm{t})=\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \tag{7}$$

The hazard rate is the instantaneous failure rate of the component will fail at time *t* and it is survived at that time. Hazard rate function (hrf) is determined by using CDF and PDF of the Weibull distribution. The hrf is

$$h(t)=\frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} \tag{8}$$

A. Characteristics of hrf

The shape parameter β having the influences on the shape of *h(t)*, so hrf is characterized based on the β value

Case 1: β<1, (8) shows that:

1. $h(\mathrm{t})$ gives decreasing hrf (DFR) with increasing *t*.
2. $h(t) \to \infty$ as $t \to 0$

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3. $h(t) \to 0$ as $t \to \infty$

Case 2: $\beta = 1$, (8) shows that

$h(t) = 1/\alpha$, it means constant hrf (CFR) with *t*.

Case 3: $\beta > 1$, (8) shows that

1. $h(\mathrm{t})$ gives increasing hrf (IFR) with increasing *t*.
2. $h(t) \to \infty$ as $t \to \infty$
3. $h(t) \to 0$ as $t \to 0$

B. Cumulative hrf (H(t))

Cumulative hrf is the simple combination of all hrf's of different failure rate functions. The cumulative hrf of a component will gives the bathtub shaped failure rate curve. The cumulative hrf is

$$H(t) = h_1(t) + h_2(t) + h_3(t) \quad (9)$$

Where, $h_1(t)$, $h_2(t)$ and $h_3(t)$ are the hazard rates of DFR, CFR and IFR functions respectively.

C. Parameter Estimation

The maximum likelihood estimator (MLE) method is used in this paper for estimating Weibull parameters. Let consider, x_1, x_2, x_3 …..x_n are the random sample taken from a probability density function $f(x,\theta)$, here θ is an unknown parameter. The likelihood function is written as follows:

$$L = \prod_{i=1}^{n} f_{x_i}(x_i, \theta) \quad (10)$$

Logarithms is applied likelihood function and is differentiated with respect to the unknown variable and equals to zero to maximize the likelihood function.

$$\frac{d \log L}{d\theta} = 0 \quad (11)$$

Now, apply the MLE method for estimation of Weibull parameters, namely location, shape and scale parameters. Let, consider the pdf given in (2), then the likelihood function is as follows:

$$L(t_1, t_2, ..t_n, \beta, \alpha, \gamma) = \prod_{i=1}^{n} \frac{\beta}{\alpha} \cdot \left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} . \exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \quad (12)$$

Applying the logarithms of (12)

$$\ln L = n \ln\left(\frac{\beta}{\alpha}\right) + \sum_{i=1}^{n}\left[(\beta-1)\ln\left(\frac{t_i-\gamma}{\alpha}\right) - \left(\frac{t_i-\gamma}{\alpha}\right)^{\beta}\right] \quad (13)$$

Partial differentiation is applied on (13) with respect to the, α, β and γ to get the maximum likelihood values. Due to the more number of parameters in (13), the solution of the parameter estimation is not unique, for given α, β and γ values, always there is a another set of solution is available. In this paper, particle swarm optimization (PSO) technique is used [22] to find the global optimal solutions of α, β and γ values. However, the explanation of PSO is out of scope for present work. The likelihood function is taken as objective function (Φ) and the value is to be maximized in order to best solutions. The objective function is as follows:

$$\phi = f(L) = \ln L \quad (14)$$

The lower and upper bounds of the shape parameter are varies with different failure rate function i.e. DFR, CFR and IFR.

IV. RESULTS AND DISCUSSIONS

To study the effectiveness of the proposed component reliability assessment method, the model is applied to the equipment of a practical Indian distribution system. The failure data of equipment with different installation age are collected. The random failure rate of overhead lines, transformer, circuit breaker and bus bars are 0.1479 failures/year/km, 0.0853 failures/year, 0.006 failures/year and 0.001 failures/year respectively. The Weibull parameters are estimated as explained in previous section and failure data is used for this purpose. The parameter values are given in Table 2.

TABLE 2. Parameters of equation (2)

Electrical component	β			α	γ
	DFR	*CFR*	*IFR*		
Overhead line	0.1	1	5	55	10
Transformer	0.1	1	6	25.9	5
Circuit breaker	0.1	1	8	27.78	7
Bus bar	0.1	1	5	30	8

The hazard rate, failure probability density, failure probability and reliability of electrical equipment are determined by using the (2)-(9) and parameters in Table 2. Fig. 3 showing the DFR, CFR and IFR hrf's of overhead lines.

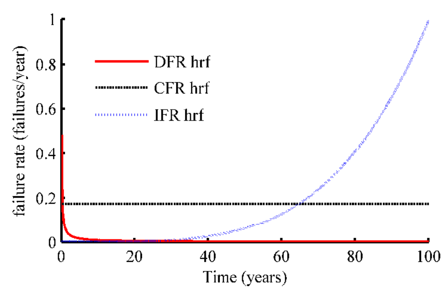

Fig. 3. Different hazard rates of overhead lines

The value of CFR is equivalent to the random failure rate of overhead line. The DFR is initially very high and it reduces to zero after few years of operation. DFR is representing the infant mortality failures. The IFR is initially zero and it is started to increase after 35 years of operation. The IFR is representing the aging failure phenomena of overhead lines. According to IFR, aging effect on overhead line is started after 35 years of operation, and this period is considered as useful life of overhead lines. The aging failures of lines were increased from 0 per year per km to 1 per year per km during the aging period. The cumulative hrf of circuit breakers, bus bars and transformers are shown in Fig. 4.

It is observed from Fig. 4 (cumulative hrf) that the useful life of circuit breakers, bus bar and transformers without aging effect is 23, 19, and 18 years respectively. From Fig. 4, the failure rate is slowly increasing after useful life of equipment according to the right wing of the bathtub curve. From Fig. 3 and Fig. 4, It is observed that overhead lines having longer aging periods. If the cumulative hrf is reaches to 1, then the time is considered as replacement time for that equipment. The failure rate of circuit breakers, bus bars and transformers are also raised after the end of useful period according to the bathtub curve. From Fig. 4, it is observed that the aging effect is started at 23, 19 and 18 for circuit breakers, bus bars and transformers respectively. The rate of

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increase of failure rate during the aging period is more in circuit breakers, bus bars and transformers as compared to overhead lines because of these equipment directly faced frequent switching operations during the entire useful life, it will decrease the strength of contacting and insulation materials.

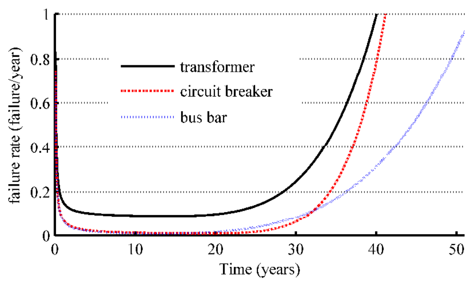

Fig. 4. Cumulative hazard rate of circuit breaker, transformer and bus bar.

Electrical equipment consists of three types of failures i.e. infant mortality failure, random failure and aging failures. Only random and aging failures are considered for evaluation of total failure probability density and infant failures are not considered, because of its falling off nature with time. The total failure probability density is determined by combining the individual failure probability densities of different failures. The total failure probability of the electrical equipment can be determined using the (5) and (6). The failure probability density of all equipment is shown in Fig. 5.

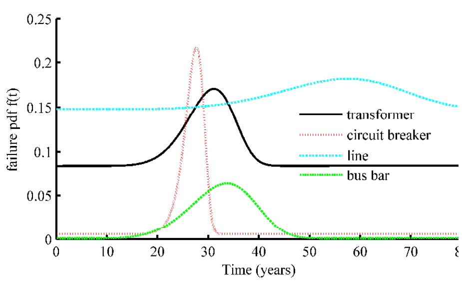

Fig. 5. Comparison of probability densities of failures of different equipment

It is observed that, failure distribution of overhead lines during the useful life is constant and high, because of overhead lines experiences more random failures during its useful life. After the useful life, the aging failures are spread evenly throughout the component lifetime. The aging failure in overhead lines is very less and these are distributed throughout the lifetime of lines. Fig. 5 also shows that, during initial period of operation the failure distribution of transformers, circuit breakers and bus bars are constantly low.

The failure probability density of circuit breaker during the aging period is very high and narrow because of total area of curve is 1. Due to the frequent operation of circuit breakers, the failures after the useful period are drastically increases. It shows that the risk of aging on circuit breaker is very high, transformers and bus bars are next in the list of aging risk. On other hand overhead lines having lesser aging risk compared to other electrical equipment. The peaks of probability densities of failure are showing that, the necessity of maintenance or replacement of electrical equipment at that time.

The cumulative probability distributions of failure/failure probability (unreliability) of electrical components are shown in Fig. 6.

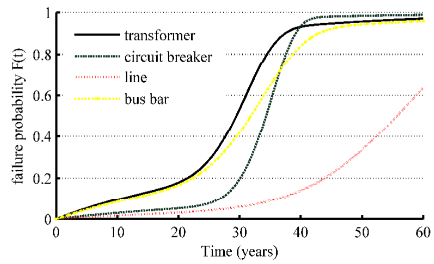

Fig. 6. Failure probability of all electrical equipment

This failure probability also indicates the lifetimes of different electrical equipment varies from 40 to 100 years (100 years for overhead lines). These failure probabilities also giving the information of failure risk over the age of equipment. Aging period of different components depends on the acceptance level of failure probability. If the failure probabilities are limited between from 10% to 90%, the aging period of circuit breaker, bus bar, transformer and overhead lines are from 27 to 38 years, from 15 to 42 years, from 16 to 36 years and from 38 to 100 years respectively. It is observed that, overhead lines are having longer aging period and transformers, bus bars and circuit breakers are next in the list respectively. The aging period of electrical equipment depends on the maintenance and replacement policy of system operators. For example, if the confidence level is from 20% to 90%, this failure probability period considered as aging time, below 20% was considered as useful lifetime and once the component failure probability reaches to 90% the component must be replaced. Scheduled maintenance activity is not required during the useful lifetime and routine maintenance was scheduled during the aging period.

The reliability/survival rate of electrical components over the age of equipment is shown Fig. 7. The reliability of components is decreasing slowly during the useful life and steep decrease during the aging time. Overhead lines are showing better reliability over the age compared to other equipment. It is also observed that the falling down of reliability from 0.9 to 0.8 is slow for overhead lines, transformers and bus bars. On the other hand, circuit breakers showing a steep fall of reliability. Once the equipment reaches to 0.8, there is a steep fall of reliability of except overhead lines.

The comparison of lifetimes of all equipment is shown in Table 3. The results of proposed lifetime models with different reliability levels are compared with manufactures and system operators experience values. The manufacture estimation of lifetime for circuit breakers and bus bars are undefined because of its lifetime depends on the number of cycles that the equipment was operated. In Table 3 all lifetime values are in years.

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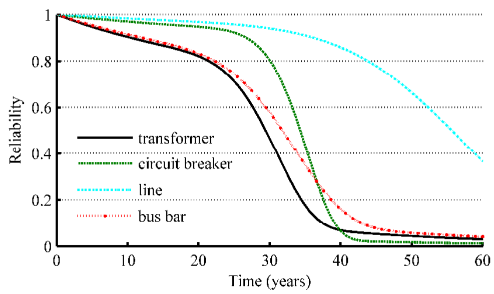

Fig. 7: Reliability/survival rate of all electrical equipment

TABLE 3. Comparison of lifetimes

Electrical Equipment	Manufacture estimation	System operators experience	Proposed lifetime models	
			Reliability >0.9	***Reliability >0.8***
Overhead lines	40-50	< 40	35	44
Transformers	20 <	< 20	12	21
Circuit breakers	Undefined	< 30	27	30
Bus bars	Undefined	< 16	13	22

V. CONCLUSIONS

A simple lifetime assessment method is developed by considering the failure data of electrical equipment under the normal operating conditions. The method uses the three parameters Weibull distribution function with varying shape parameter. By using this method, system operators can easily estimates the lifetime of electrical components without conducting any tests on components. The results are witnessed that the failures of electrical components are not constant throughout its lifetime. The proposed Weibull distribution models are applied to estimate the useful lifetime, probability density of failure, failure probability/unreliability, and survival rate/reliability of electrical components of practical Indian distribution system. The probability density of failure for circuit breaker, transformer and bus bars are constantly low during the useful life and increases during the aging time. It is observed that the aging period of overhead lines is high and in case of circuit breakers is less. It further shows that overhead lines are having lesser aging risk and circuit breakers are having higher aging risk. Regarding the behavior of overhead lines, it is concluded that most of the failures are caused by the external event whose occurrence is constant for entire lifetime of line and aging failures are distributed throughout the life after useful period. Due to the frequent operation of transformers, bus bars and circuit breakers, its electrical and mechanical strength decreases with time which leads to more aging failures than overhead lines. The degradation rate of electrical equipment is directly relates to the failure rate of equipment.

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