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New Mixed Weibull Probability Distribution Model for Reliability Evaluation of Paper-oil Insulation

***Abstract**. This paper presents a new mixed Weibull probability distribution model for reliability evaluation of the paper-oil insulation. The breakdown voltage, furfural, and six other characteristic parameters were chosen to reflect the reliability of paper-oil insulation. The new mixed Weibull probability distribution model was established to evaluate the reliability of the paper-oil insulation. Reliability predictions of the paper-oil insulation at different times verified the feasibility of the new mixed Weibull probability distribution model.*

***Streszczenie.** W artykule przedstawiono metodę budowy modelu rozkładu prawdopodobieństwa Weibulla, w wykorzystaniu do oceny niezawodności izolacji papierowo-olejowej. Wykorzystywanych jest osiem parametrów dotyczących niezawodności. Wykonane przewidywanie niezawodności dla różnych odległości czasowych potwierdzają skuteczność metody. **(Ocena niezawodności izolacji papierowo-olejowej metodą opartą na modelu rozkładu prawdopodobieństwa Weibulla)**.*

Keywords: oil–paper, reliability, weibull, entropy weight
Słowa kluczowe: izolacja papierowo-olejowa, niezawodność, Weibull, entropia wagi.

Introduction

The reliability of power transformers and other electrical equipments is an important factor in power systems. To minimize reinvestments and costly maintenance, it is essential to evaluate the reliability of transformers [1]. Most transformers are filled with liquids that work as electrical insulation as well as heat-transfer mediums. The most commonly used liquid in transformers is mineral oil, due to its low price, good physical and dielectric properties [2]. Paper-oil insulation has been considered as a reliable insulation system serving in transformers for decades [3].

Paper-oil insulation in transformers degrades over time. It is now commonly accepted that the cellulose aging can be described by three processes: hydrolysis, oxidation, and pyrolysis. In a real transformer, all these processes do not act independently of each other and are temperature dependent [4, 5]. Some long-term aging experiments are used to obtain information to evaluate paper-oil insulation condition under different stresses [2-5]. The experimental results, as well as a large amount of field data, were used to establish aging diagnostic models and maintenance guides for transformers. The hot-spot and top-oil temperature thermal models for more accurate temperature calculations during transient states was introduced by [6]. Reference [7] presented an approach for assessing the reliability of thermal top-oil model parameters based on measured data. The life of paper-oil insulation has a direct relation to its reliability. The higher the reliability, the longer the life-time of the insulation. One of the main factors to influence the reliability of paper-oil insulation is the long term aging temperature. However, very few studies have been reported on the reliability evaluation method for paper-oil insulation based on multiple thermal aging parameters.

This paper presents aging characteristic parameters of paper-oil insulation as the reliability characteristic parameters. The mixed Weibull probability distribution model was employed to establish the new reliability evaluation model of the paper-oil insulation. A new reliability model has been established which does not include the degree of polymerization (DP) of paper. The new reliability evaluation model for the paper-oil insulation at different times in service demonstrates that is capable of predicting lifetime, without the need for knowledge of DP.

The Weibull distribution model

A. Two-parameter Weibull distribution model

Current usage of Weibull distribution model includes reliability and times in service modelling. The Weibull distribution model is more flexible than the exponential model for studying the aging in insulation [8-10].

The two-parameter Weibull distribution model is a very widely known model, and it is mainly used to describe the strength and lifetime issues of cables and machinery winding insulation as well as electronic products. The cumulative probability of failure of the two-parameter Weibull distribution model is given by equation (1) [11], and the reliability function is defined as equation (2).

$$F(x) = 1 - e^{-(x/\eta)^{\beta}} \qquad x \geq 0; \quad \eta, \beta > 0 \tag{1}$$

$$R(x) = 1 - F(x) = e^{-(x/\eta)^{\beta}} \tag{2}$$

where: x– variable, η– scale parameter, β– shape parameter.

The two-parameter Weibull distribution model is an empirical model. Parameters η and β have been assigned physical significance: η indicates an average of characteristic value or lifetime, and β indicates the dispersion. When β > 1, the rate of failure increases with time, which is intuitively a reasonable model for an aging system. When β < 1, the failure rate decreases with time. When β = 1, the rate of failure is constant over time [11, 12]. Once the two parameters η and β are determined, the two-parameter Weibull distribution model is determined.

B. Estimation of Weibull parameters

Estimation of η and β may be obtained from a plot of cumulative probability distribution data on Weibull scales. There are numerous methods used to estimate the two parameters. For instance, the Weibull probability paper method, is easy to use, but has poor precision and reproducibility. The maximum likelihood (ML) method and least-squares (LS) method are mathematical analytical methods and the results can be more precise.

The ML method is the most appropriate method to estimate the parameters (η and β) of the two-parameter Weibull distribution model [6, 11-16].The log-likelihood function for a sample of n units is given by equation (3).

$$\begin{aligned} &\ln L(\theta / X) \\ &= \ln[L(x_1, x_2, ..., x_n; \theta)] \\ &= \sum_{i \in F}[\ln(\beta) + (\beta - 1)\ln x_i - \beta \ln \eta - (x_i/\eta)^{\beta}] \\ &+ \sum_{i \in C}[-(x_i/\eta)^{\beta}] \end{aligned} \tag{3}$$

where: L – likelihood function, x_i – test data, $X = (x_1, x_2, \ldots, x_n)$ – test data column, $\theta = (\beta, \eta)$ – parameters column, F – failure data, C – censored data.

The likelihood equations of two parameter Weibull distribution can be listed as equation (4).

$$\begin{cases} \dfrac{\partial \ln L(\theta / X)}{\partial \beta} = 0 \\ \dfrac{\partial \ln L(\theta / X)}{\partial \eta} = 0 \end{cases} \tag{4}$$

Equation (5) can be inferred by solving equation (3) and (4) simultaneously. The estimation parameters of η and β can be obtained by solving equation (5).

$$\begin{cases} \dfrac{\partial \ln L(\theta / X)}{\partial \beta} \\ = \sum_{i \in F} [1/\beta + \ln x_i - \ln \eta - (x_i/\eta)^\beta \ln(x_i/\eta)] \\ + \sum_{i \in C} [-(x_i/\eta)^\beta \ln(x_i/\eta)] = 0 \\ \dfrac{\partial \ln L(\theta / X)}{\partial \eta} \\ = \sum_{i \in F} [-\beta/\eta + (\beta/\eta)(x_i/\eta)^\beta] \\ + \sum_{i \in C} [(\beta - \eta)(x_i/\eta)^\beta] = 0 \end{cases} \tag{5}$$

New reliability evaluation model

A. Characteristics parameters

There are many characteristic parameters to characterize the aging degree of paper-oil insulation in power transformers. The research results in [17-19] show that the DP of insulation paper represents the number of glucose monomer which constitutes insulation paper fibers. The DP of insulation paper is the most reliable characteristic parameter of insulating paper aging characteristic parameters. Furfural is a special product of cellulose pyrolysis. Its content in transformer oil is considered as an important indicator of the degree of paper-oil insulation aging.

Moisture content in oil is another important indicator of paper-oil insulation aging, which can reflect the cellulose pyrolysis and degradation of insulating oil. In addition, the breakdown voltage of oil, the acid value of oil and dissolved gas-in-oil can reflect the aging degree of paper-oil insulation.

Based on the analysis of relevant characteristic parameters of paper-oil insulation, the reliability evaluation index system is constructed as Fig. 1.

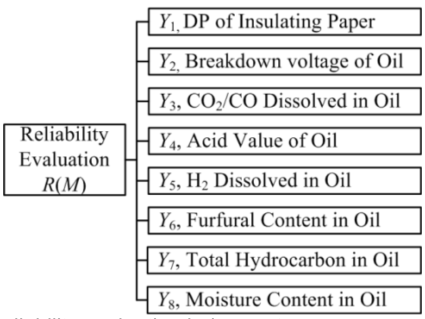

Fig. 1 The reliability evaluation index system

B. Mixture Weibull distribution model

The reliability of paper-oil insulation in power transformers is accessed by a numbers of characteristic parameters. In order to consolidate the effect of characteristic parameters on the system failure, the mixed Weibull distribution model, risk competition Weibull model, parallel Weibull model and segmentation Weibull model are utilized [8]. The mixed Weibull distribution model, which can be used to represent the product failure by a variety of factors, plays an important role in the reliability theory. In this paper, the mixed Weibull distribution model was adopted to evaluate the reliability of paper-oil insulation.

The reliability evaluation model of paper-oil insulation based on the mixed Weibull distribution model is described in the equation (6).

$$\begin{aligned} R(M_1) &= p_1 R_1(Y_1) + p_2 R_1(Y_2) + p_3 R_1(Y_3) + p_4 R_2(Y_4) + \\ &+ p_5 R_2(Y_5) + p_6 R_2(Y_6) + p_7 R_2(Y_7) + p_8 R_2(Y_8) \end{aligned} \tag{6}$$

The model represents the relationship between states of characteristic parameters and the overall reliability of paper-oil insulation, where $R(M_1)$ represents the reliability of the paper-oil insulation, and $R_1(Y_1)$, $R_1(Y_2)$, $R_1(Y_3)$, $R_2(Y_4)$, $R_2(Y_5)$, $R_2(Y_6)$, $R_2(Y_7)$, $R_2(Y_8)$ represent the reliability distribution functions corresponding to the eight characteristic parameters of paper-oil insulation, and $p_1, p_2, ..., p_8$ represent the weights of the eight characteristic parameters of paper-oil insulation respectively.

When the reliability and weights of the eight characteristic parameters are determined, the overall reliability of paper-oil insulation can be estimated.

C. Reliability distribution functions of characteristic parameters

The eight characteristic parameters influencing reliability can be divided into two categories. For the first one, the reliability decreases with the decrease of characteristic parameters, such as DP, breakdown voltage of oil, CO_2/CO ratio. For the second categories, the reliability decreases when the characteristic parameters, such as acid, H_2, furfural, total hydrocarbon content, and moisture are increasing.

Therefore, different forms of reliability distribution functions are needed for these two categories of characteristic parameters.

The reliability functions of the first categories characteristic parameters can be presented as equation (7).

$$R_1(Y_i) = 1 - e^{-(Y_i/\eta)^\beta} \tag{7}$$

where: i = 1, 2, 3.

The reliability functions of the second categories characteristic parameters could be defined by equation (8).

$$R_2(Y_i) = e^{-(Y_i/\eta)^\beta} \tag{8}$$

where: i = 4,5,6,7,8.

D. Weights of characteristic parameters

In recent years, many research works have been completed on the methods to determine the weights of different models. The most known methods are Analytical Hierarchy Process (AHP) method, Delphi method, entropy weight method, and fuzzy clustering analysis method.

The entropy weight method is considered as the most important method to determine the weights of different models [20, 21]. Thus, the entropy weight method is adopted to determine the weights of eight characteristic parameters.

For the reliability evaluation model of paper-oil insulation, the raw test data of m characteristic parameters at n times in service can be given by a matrix $\boldsymbol{X}=\{x_{ij}\}_{m \times n}$. The dimensions and orders of magnitude of each parameter are quite different. It is necessary that the raw test data be normalized.

Each row of the raw test data are normalized as equation (9) respectively.

$$z_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}, \quad 0 \le z_{ij} \le 1 \tag{9}$$

The standardization matrix of data $\boldsymbol{Z}$ can be listed as equation (10).

$$Z = \{z_{ij}\}_{m \times n} \tag{10}$$

The information entropy e_i of parameters can be obtained by equation (11).

$$e_i = -k \sum_{j=1}^{n} z_{ij} \ln z_{ij} \tag{11}$$

where: constant k is related to the number of parameters n. k can be calculated by equation (12).

$$k = (\ln n)^{-1} \tag{12}$$

The weights of parameters can be calculated by equation (13).

$$p_i = \frac{h_i}{\sum_{i=1}^{m} h_i} \tag{13}$$

where: $h_i = 1 - e_i$.

The weights of the eight characteristic parameters can be obtained and they are expressed in matrix form as equation (14).

$$p = [p_1, p_2, \cdots, p_m], \quad \sum_{i=1}^{m} p_m = 1 \tag{14}$$

Experimental results

To illustrate the concrete process of reliability evaluation for paper-oil insulation and verify the feasibility of the model, the new mixed Weibull distribution model for evaluating the reliability of paper-oil insulation was established. The experimental data of paper-oil insulation used in the new proposed mixed Weibull distribution model were according to accelerated thermal aging tests conducted in laboratory of Chongqing University.

A. Weibull probability plot

A lot of accelerated thermal aging tests on paper-oil insulation have been done, and a large amount of experimental data has been accumulated. The experimental data of eight characteristic parameters Y_1 – Y_8 were obtained by summarizing the accelerated aging tests at 130°C. The experimental data changing with aging time and are shown in Table 1.

Table 1. Experimental data of eight characteristic parameters

Parameters	Data									
Aging time(h)	0	130	260	390	520	650	780	910	975	1040
Y_1 (DP）	1200	490	320	310	300	280	270	260	250	200
Y_2 (kV)	54.0	49.2	41.4	38.5	33	33.3	30.9	24.3		
Y_3 (CO_2/CO)	44.2	37.6	25.4	23.7	25.8	19.7	20.9	15.1		
Y_4 (mg(KOH)/g)	0.01	0.03	0.07	0.11						
Y_5 ($\times 10^{-6}$)	25	150	400	300	350	400	450	450		
Y_6 ($\times 10^{-6}$)	2	6	9	10.7	12	13.5	14	15		
Y_7 ($\times 10^{-6}$)	5	7	6	8	10	11	9	13		
Y_8 ($\times 10^{-6}$)	25	8	9	10	11	12	18	11		

Before the Weibull parameters are estimated, a Weibull probability plot is adopted [22]. The purpose of the Weibull probability plot is to assess graphically whether the data may be obtained from a Weibull distribution function. The Weibull distribution function will give a linear plot; otherwise, the plot might introduce curvature. For example, the Weibull probability plot diagram of the oil breakdown voltages is shown in Fig. 2, the scale of abscissa is the test data in Table 1, and the scale of ordinate is the logarithm forms of probability. The distribution of data points linearly satisfies the Weibull distribution function. The other seven groups of data have the same characters.

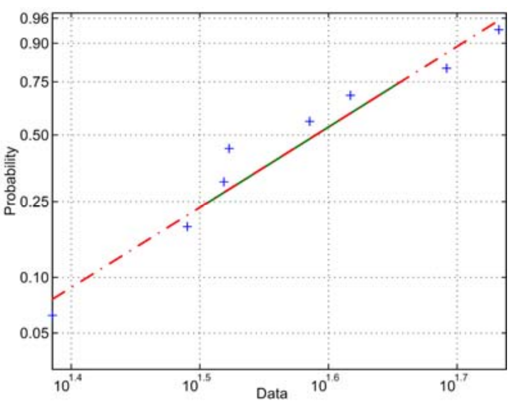

Fig. 2 Weibull probability plot of oil breakdown voltage

B. Evaluation of new mixed Weibull distribution model

The new proposed mixed Weibull distribution model for evaluation the reliability of paper-oil insulation can be obtained from (6). The evaluation process of $R_1(Y_i)$ (i = 1, 2, 3), $R_2(Y_i)$ (i = 4, 5, 6, 7, 8), and p_i (i = 1, 2, …, 8) is illustrated as follows.

The reliability distribution functions

From Table 1, the reliability of paper-oil insulation can be obtained, and it decreases with the decline of insulating paper DP. Therefore, the Weibull distribution function is built by the reliability distribution function as presented in equation (7). The scale parameter η and shape parameter β were evaluated by the maximum likelihood (ML) method, Equation (3) – (5). The value of η and β of the function were equal to 439.1555 and 1.6077, respectively.

The reliability distribution function of DP can be described as equation (15).

$$R_1(Y_1) = 1 - e^{-(Y_1/439.1555)^{1.6077}} \tag{15}$$

The relationship between reliability of paper-oil insulation and DP of insulating paper is calculated from equation (15) and shown in Fig. 3. The reliability of paper-oil insulation decreases with the decline in DP of paper.

The Weibull reliability distribution functions and the Weibull parameters of the eight characteristic parameters are shown in Table 2. The parameters β of eight reliability distribution functions are greater than 1. It could be concluded, the two-parameter Weibull distribution model is reasonable for eight parameters evaluated at thermal aging.

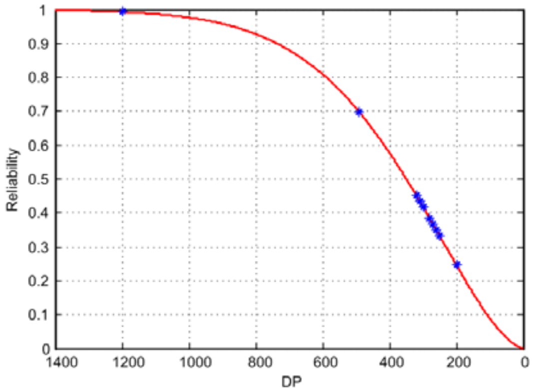

Fig. 3 The curve of reliability distribution function of DP

Table 2. The calculated Weibull parameters of reliability distribution functions

Weibull reliability distribution function	η	β
$R_1(Y_1)=1-e^{-(Y_1/439.1555)^{1.6077}}$	439.1555	1.6077
$R_1(Y_2)=1-e^{-(Y_2/41.7292)^{4.4929}}$	41.7292	4.4929
$R_1(Y_3)=1-e^{-(Y_3/29.7223)^{3.1106}}$	29.7223	3.1106
$R_2(Y_4)=e^{-(Y_4/0.0602)^{1.3818}}$	0.0602	1.3818
$R_2(Y_5)=e^{-(Y_5/348.5231)^{2.0954}}$	348.5231	2.0954
$R_2(Y_6)=e^{-(Y_6/11.4797)^{2.7318}}$	11.4797	2.7318
$R_2(Y_7)=e^{-(Y_7/9.6961)^{3.0304}}$	9.6961	3.0304
$R_2(Y_8)=e^{-(Y_8/14.6868)^{2.5556}}$	14.6868	2.5556

Weights

The weights of the eight characteristic parameters were calculated by entropy method [19, 20], Table 3.

Table 3. Weights of eight characteristic parameters

Parameters	k_i	e_i	h_i	p_i
Y_1	0.4343	0.0919	0.9081	0.1301
Y_2	0.4809	0.1236	0.8764	0.1255
Y_3	0.4809	0.1217	0.8783	0.1258
Y_4	0.7213	0.2026	0.7974	0.1142
Y_5	0.4809	0.1166	0.8834	0.1265
Y_6	0.4809	0.1189	0.8811	0.1262
Y_7	0.4809	0.1225	0.8775	0.1257
Y_8	0.4809	0.1205	0.8795	0.1260

The new mixed Weibull distribution model for evaluation the reliability of paper-oil insulation based on the result presented in Table 2 and Table 3 has been established.

C. Validation of Reliability Evaluation Model

The accelerated thermal aging tests of paper-oil insulation were carried out at 130°C. The paper and oil were sampled and tested at the times of 240, 480, 720, and 960 hours. The experimental data are shown in Table 4. The reliability of the eight characteristic parameters was calculated by substituting the experimental data into the reliability distribution functions and the results are shown in Table 5.

Table 4. The test date of paper-oil insulation at 130°C

Parameters	Data			
	240hours	480hours	720hours	960hours
Y_1	490	300	260	210
Y_2	48.2	41.5	32.7	25.8
Y_3	35.37	25.68	23.98	15.93
Y_4	0.024	0.07	-	-
Y_5	150	340	390	450
Y_6	3	8.2	13	15
Y_7	4.56	7.02	10.14	13.23
Y_8	8.03	7.55	12.51	13.80

Table 5. The reliability of eight characteristic parameters

Reliability function	Reliability			
	240hours	480hours	720hours	960hours
$R_1(Y_1)$	0.6966	0.4184	0.3498	0.2632
$R_1(Y_2)$	0.8521	0.6230	0.2842	0.1089
$R_1(Y_3)$	0.8206	0.4699	0.4012	0.1338
$R_2(Y_4)$	0.7553	0.2918	-	-
$R_2(Y_5)$	0.8429	0.3870	0.2820	0.1812
$R_2(Y_6)$	0.9747	0.6711	0.2455	0.1254
$R_2(Y_7)$	0.9033	0.6867	0.3181	0.0770
$R_2(Y_8)$	0.8076	0.8331	0.5150	0.4262

The overall reliability of paper-oil insulation at the aging time of 240, 480, 720, and 960 hours are calculated by (6) and the results are shown in Table 6. At the aging time of 240 hours, the reliability of paper-oil insulation reaches a very high value of 0.8320, which means an early life stage of paper-oil insulation as well as transformer insulation are in good condition. The reliability of paper-oil insulation decreases with aging time. The DP of insulation paper decreases to 210, at the aging of the accelerated condition and time of 960 hours. The paper-oil insulation reached its end-of-times in service. The value of reliability of paper-oil insulation calculated by the overall reliability of new proposed model dropped to 0.1669. The results show that the reliability of paper-oil insulation, calculated by the overall reliability of new proposed model based on mixed Weibull distribution model, agrees with their times in service.

Table 6. The reliability of paper-oil insulation calculated from the mixed Weibull distribution model

Aging time	240hours	480hours	720hours	960hours
Reliability	0.8320	0.5500	0.3032	0.1669
	high	moderate	low	fail

D. Evaluation of the new proposed model without DP

DP of insulating paper is not only the one of most reliable characteristic parameters of paper-oil insulation aging characteristic parameters, but also the most difficult one to obtain from power transformers in service [1]. Some of the degradation by-products dissolved in oil and their relationships with DP are used indirectly to evaluate the degree of aging. Therefore, the other seven characteristic parameters were selected to establish the reliability of the proposed model of paper-oil insulation. The model is described as equation (16).

$$R(M_2)=p_2R_1(Y_2)+p_3R_1(Y_3)+p_4R_2(Y_4)+p_5R_2(Y_5)+p_6R_2(Y_6)+p_7R_2(Y_7)+p_8R_2(Y_8) \quad (16)$$

The weights of the seven characteristic parameters were calculated by entropy method, and the results are shown in Table 7. The reliability of paper-oil insulation at the aging time of 240, 480, 720 and 960 hours are obtained, as shown in Table 8.

Table 7. Weights of reliability evaluation model for seven characteristic parameters (without DP)

Parameter	Y_2	Y_3	Y_4	Y_5
pi	0.1443	0.1446	0.1313	0.1454
Parameter	Y_6	Y_7	Y_8	
pi	0.1451	0.1445	0.1448	

Table 8. The reliability of paper-oil insulation (without DP)

Aging time	240hours	480hours	720hours	960hours
DP	490	300	260	210
Reliability	0.8552	0.5697	0.2962	0.1524

Comparing Table 8 with Table 6, the removal of parameter DP does not affect the results of overall reliability of the paper-oil insulation. Therefore, the reliability calculated by new proposed model of the seven-parameters can be applied to evaluate the reliability of paper-oil insulation.

Conclusion

This paper presents an overall reliability calculated by new proposed model of paper-oil insulation based on mixed Weibull distribution model. The results of the above work and analysis are concluded as follows.

1) The new proposed mixed Weibull distribution model is established to evaluate the reliability of paper-oil insulation.
2) The Weibull probability distribution has been shown to be a good empirical model to evaluate the reliability of paper-oil insulation from the experimental results.
3) A new reliability model has been established which does not include the DP, and it's effective and can accurately evaluate the reliability of paper-oil insulation. It can be applied in transformer monitoring system to evaluate the reliability of insulation of power transformer in service.
4) Due to the different types of transformers, with different structures and operating conditions, such as the AC power transformer and HVDC converter transformer, the different database of aging characteristic parameters needs to be built, and new proposed mixed Weibull distribution model must be amended. Subsequent studies should be done in the future.

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