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Impulse Life Evaluation Method of MOV Based on Weibull Distribution

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ABSTRACT The working life evaluation of metal oxide varistor (MOV) is always expected by MOV manufacturers and users. In Oct. 2019, the International Electrotechnical Commission (IEC) SC37B established a project team PT 61643-333 led by the author of this paper to draft a technical report about MOV life assessment. As an early researching achievement of PT 61643-333, this paper provides an evaluation method for the impulse life of MOV with the median rank regression (MRR) method based on the Weibull distribution, which provides an effective means for evaluating the impulse life of MOV. Firstly, the theory of Weibull distribution and impulse life characteristics of MOV are introduced. Then the evaluation method and procedure of MOV impulse life is derived from the combination of the MRR method and the impulse characteristics of MOV. Finally, an application example of the proposed evaluation method is given with the test results from real MOV samples. By establishing three basic impulse life characteristics equations, the life evaluation of MOV under arbitrary impulse current can be achieved. In addition, the fitting validity of six groups of samples is checked to prove the effectiveness of the proposed parameter model. And further sensitivity analysis of the variables has been done to examine the effect of changes in the values of the parameters on the propose model.

INDEX TERMS MOV, impulse life, evaluation, Weibull distribution, MRR.

I. INTRODUCTION

Zinc oxide varistor invented in the 1960s is a type of sensitive component used to suppress overvoltage and divert surge current [1]. It is made of zinc oxide as the main component and sintered by adding a small amount of oxide additives, so it also called metal oxide varistor (MOV) [2]. MOV is very sensitive to the voltage across it as shown in Fig. 1. When the voltage across it is lower than its varistor voltage, MOV has very high resistance, which will not affect the normal operation of electrical or electronic circuits. Once the voltage across it is higher than its varistor voltage, the resistance of the MOV drops rapidly and becomes extremely small with increasing voltage, even to nearly short-circuit status, so it can suppress the overvoltage and divert the surge current to protect electrical or electronical circuits. Due to above-mentioned prominent nonlinear characteristics, MOV has been widely applied in arresters [3]–[6], surge protective devices (SPDs) and other related electronic products [7]–[10]. In order to evaluate the reliability of these products, it is necessary to evaluate the impulse life of MOV.

As is known to all, the working life of a component refers to the length of time that one or several performance indexes of the component are kept in line with the specified requirements under the specified stress. The specified value of performance index here is called ''end-of-life criterion''. The length of time here can be interpreted as years, hours or the number of operation cycle. No matter what kind of life length, it is an exact value for a specific component. But for a group of samples or a batch of products, the life value of each product is different and can differ by many times, so it can only be expressed by statistical values. There are three types of commonly used statistical values: the average life, the median life and the minimum life (also called the guaranteed life).

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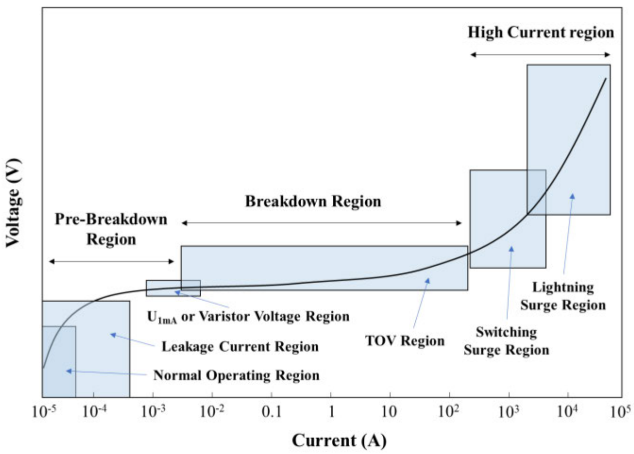

FIGURE 1. *V − I* **characteristics of MOV.**

Therefore, when talking about the life value of a sample or batch of products, it is necessary to specify what type of statistical value it is.

The impulse life of a MOV is usually considered as the number of applied specific impulses before the MOV comes to the end-of-life whose criterion is that the varistor voltage is equal to or lower than 0.9 times of the initial value [11], [12]. Regarding the impulse characteristics of MOV, researchers have conducted a lot of studies and made much achievements [13]–[17]. Among those studies, there are a few literatures about the evaluation of MOV impulse life. M. Mashaba *et al.* inferred the impulse life of MOV from the curves between the impulse current duration and its magnitudes [18]. By analyzing a large number of MOV aging tests, a method to predict MOV life using similar conditions based on the characteristics points of the $I(t)$ curve of MOV is proposed by Wen and Zhou [19]. Sheng *et al.* deduced the calculation formula of the average time before failure of MOV under lightning impact through the Markov process and established the related reliability evaluation model. This model showed that the life of MOV was proportional to the varistor voltage and the impulse current, and inversely proportional to the conversion rate [20]. However, none of the above studies has provide a systematic method to evaluate the life of MOV under any impulse current, so it is difficult to apply those studies into engineering practice.

In October 2019, IEC SC37B Subcommittee, which is responsible for formulating the international standards for components such as MOV, GDT, TVSS, etc., established a project team PT 61643-333 with experts from various countries to jointly study and formulate the standard for MOV working life evaluation. Based on the research work of IEC/SC37B/PT 61643-333, this paper firstly introduces the relevant theory of the impulse life evaluation of MOV. Secondly it introduces the process of applying this theory to the impulse life evaluation of MOV and the determination of the impulse life characteristics equations. Finally, the evaluation process is illustrated and analyzed with a case study of impulse life test on real MOV samples. The results show that the proposed method can be effectively applied to the impulse life evaluation of MOV.

II. METHODOLOGY

According to the theory of life analysis, the product life can be evaluated by establishing a parametric model with a fixed function expression [21]. It is usually assumed that the sample population obeys a certain distribution. Then the model parameters based on the failure data of the samples are estimated. Therefore, the impulse life distribution model of the MOV shall be established firstly. Then the model parameters are estimated to achieve the impulse life evaluation of MOV.

A. THE WEIBULL DISTRIBUTION

The Weibull distribution function is a statistical distribution function proposed by the Swedish physicist W. Weibull in 1951. Because it can easily infer its distribution parameters by using probability values, it is widely used in the reliability engineering, especially in the data processing of various life tests [22], [23].

In 2012, Ding *et al.* verified that the life distribution of MOV conforms to the Weibull distribution under 8/20 μs impulse current stress [24]. In 2014, Zhuhai EPCOS also verified the life distribution of MOV under 10/350 μs impulse current stress through experiments, which is also the Weibull distribution. That is to say, the life distribution of MOV under the conditions of “short waveform” and “long waveform” impulse currents conform to the Weibull distribution. The cumulative distribution function of the Weibull distribution is [25]

$$F(t) = 1 - e^{-\left(\frac{t-t_0}{\eta}\right)^{\beta}} \tag{1}$$

where $F(t)$ is the probability of component failure from 0 to t, i.e. the probability of life end. t is the test time or the number of test cycles. t_0 is the “position parameter” of the Weibull distribution which indicates the starting point of the Weibull curve, also known as the minimum life or the guaranteed life. That means failure will not occur when $t < t_0$.β is the “shape parameter” of the Weibull distribution, its geometric meaning is the slope of the Weibull straight line, its physical meaning is the changing trend of the failure risk with time: when $\beta > 1$, the failure risk (instantaneous failure rate) increases with time; when $\beta < 1$, the failure risk decreases with time; when $\beta = 1$, the failure risk is constant and does not change with time, at this time, the Weibull distribution becomes an exponential distribution. η is the “scale parameter” of the Weibull distribution. The larger is η, the longer is the life.

B. PARAMETER ESTIMATION

In order to determine the three parameters β, η and t_0 more conveniently, it is necessary to linearize (1). Assuming $t_0 = 0$, (1) becomes an equation with only two parameters β and η. The reciprocal of both sides is taken first, then the logarithm of two times is taken to obtain (2):

$$\ln\left[\ln\frac{1}{1-F(t)}\right]=\beta\ln t-\beta\ln\eta \tag{2}$$

Let the left side of (2) equal to Y, and let $\ln t = X$, then the straight-line expression can be obtained as (3) shows:

$$Y=\beta X-\beta\ln\eta=aX+b \tag{3}$$

where $a=\beta, b=-\beta\ln\eta$. Equation (3) is also called the Weibull distribution straight line.

After linearization of the Weibull cumulative distribution function, the median rank regression (MRR) method can be used to evaluate the Weibull parameters [26]. It uses the least-square method to get a best-fitting linear curve of Y and X in (3) to minimize their least square error for the data from the life test results. So MRR is considered as a standard parameter evaluation method.

If there is no median rank table and the total number of samples is less than 30, Bernard's approximation as (4) shows can be used to calculate the median rank as the value of the Weibull cumulative distribution function.

$$F_i=\frac{i-0.3}{N+0.4} \tag{4}$$

where i is the ranked position of the failed sample and N is the total number of the samples.

If $N \geq 30$, the median rank can be calculated by (5) directly.

$$F_i=\frac{i}{N} \tag{5}$$

When it is at the median lifetime t_{med}, there are $F(t)=0.5$ and $Y=-0.3665$. Let $t_{med}=e^x$, so there is

$$x=\frac{-b-0.3665}{a} \tag{6}$$

where a and b are respectively the slope and intercept of the Weibull distribution straight line. So t_{med} can be quickly calculated by using (6).

According to the Weibull distribution function established by fitting the life test data, t_0 cannot be directly calculated. Generally, the "trial algorithm" is used to determine the values of t_0. The "trial algorithm" is described as follows:

For the data which are conforming to the Weibull distribution, $F(t)$ and t will have a distribution relationship as shown in Fig. 2. The intersection point of the curve and the x-axis is the approximate value of t_0.

Assume several values around the intersection point, such as $t_{01}, t_{02}, t_{03}\ldots$ and then calculate the corresponding $X_1=\ln(t-t_{01}), X_2=\ln(t-t_{02}), X_3=\ln(t-t_{03})\ldots$ At the same time, calculate $Y_1=f(t_{01}), Y_2=f(t_{02}), Y_3=\mathrm{f}(t_{03})\ldots$ by (2) and (4).

By performing the linear fitting algorithm to the corresponding X and Y, the t_0 value corresponding to the straight line with the smallest fitting error is the minimum life to be solved.

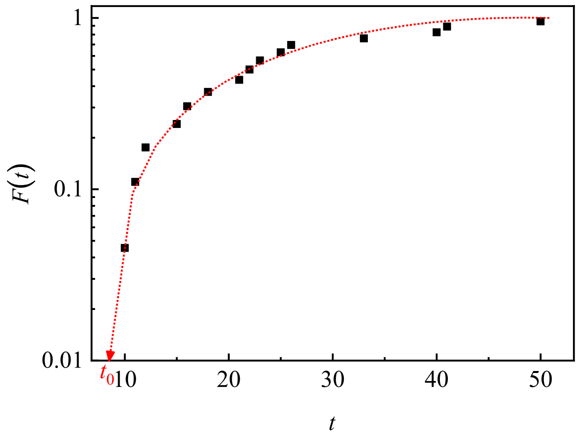

FIGURE 2. Estimation of t_0.

III. IMPULSE LIFE CHARACTERISTICS

The impulse life characteristics of MOV can be expressed by figures, equations and tables to illustrate the quantitative relationship between impulse current stress (I_p, τ) and life number (n). I_p is the peak value of the impulse current, τ is the equivalent square wave width. Assuming that the total charge of the impulse current is Q, then $I_p=Q/\tau$.

A. IMPULSE LIFE CHARACTERISTICS CURVE

The impulse life characteristics of MOV can be expressed by two different curves: one is the $\lg I_p \sim \lg\tau$ curve with the constant life number n as Fig. 3(a) shows; the other is the $\lg I_p \sim \lg n$ curve with the constant equivalent square wave width τ as Fig. 3(b) shows.

B. IMPULSE LIFE CHARACTERISTICS EQUATION

The impulse life characteristics can also be expressed in the form of equations. According to a large number of test results from Panasonic and other MOV manufacturers [17], it is shown that when the $\lg I_p \sim \lg\tau$ curve with the constant life number n, the mathematical relationship between τ and I_p is basically linear in the logarithmic coordinate system. Its equation expression is

$$\lg I_p=B_n-b_n\lg\tau\left(n=10^1\sim10^6\right) \tag{7}$$

When $n \geq 10$, the quantitative relationship between the life number n and the current impulse stress (I_p, τ) is basically linear in the logarithmic coordinate system. But the slope is different in different ranges, which may be quite different between the short impulse range and the long impulse range. Therefore, the two ranges should be expressed with different equations:

$$\begin{cases}\lg I_p=A_{\tau_1}-a_{\tau_1}\lg n & 20\mu\mathrm{s}\leq\tau_1\leq200\mu\mathrm{s}\\ \lg I_p=A_{\tau_2}-a_{\tau_2}\lg n & 200\mu\mathrm{s}\leq\tau_2\leq2\mathrm{ms}\end{cases} \tag{8}$$

From (7) and (8), it can be seen that the impulse characteristics equations are determined from the parameters (A_τ, a_τ) or (B_n, b_n) through the impulse life test of the MOV samples.

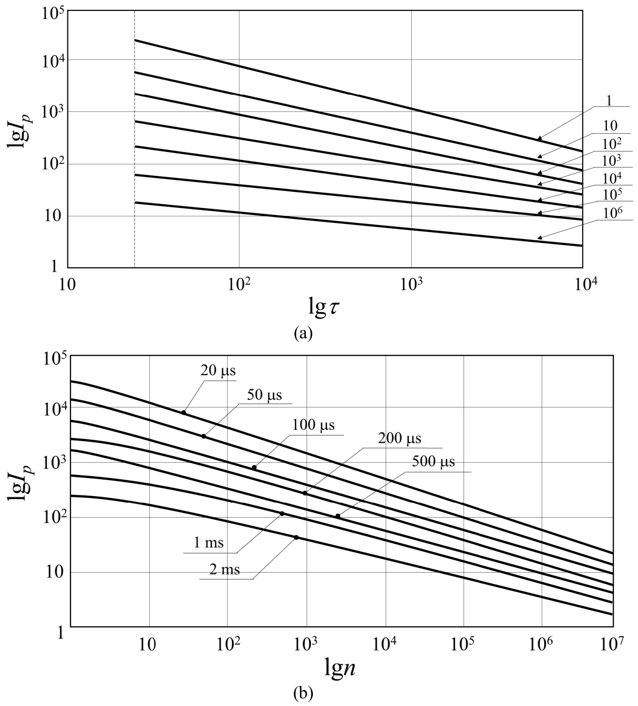

FIGURE 3. Impulse life characteristics curve of MOV. (a) Impulse life curve when n is constant. (b) Impulse life curve when τ is constant.

C. IMPULSE LIFE CHARACTERISTICS TABLE

In practice, data are often expressed in the form of tables. The unlisted data can be calculated by the interpolation algorithm based on the existing data in the tables. This expression is convenient to be used and more intuitive. Table 1 shows an example of MOV life characteristics under 8/20 μs impulse current.

TABLE 1. Impulse life characteristics table.

Waveform	I_p (A)	n
	150000	1
	4000	10
	1500	100
8/20 µs	400	1000
	150	10000
	40	100000
	15	1000000

IV. EXPERIMENTAL METHOD FOR DETERMINING IMPULSE LIFE CHARACTERISTICS EQUATION

The method for determining the life characteristics equation through impulse life test mainly includes the following steps:

1) Six groups of samples are chosen from the product population. These samples pass the specified reliability screening to eliminate the products with abnormal early failure risks. The unipolar impulse currents with three specified waveforms are respectively applied. For each waveform, the life tests are carried out with two different magnitude currents (I_{p1}, I_{p2}).

According to different equivalent square wave width τ, three waveforms are classified as the short waveform "S" ($\tau = 20\mu$s), the medium waveform "M" ($\tau = 200\mu$s) and the long waveform "L" ($\tau = 2000\mu$s).

The selection principle of the two different magnitudes current is that I_{p1} should correspond to the product life between 10∼100 times. So, for the short waveform, I_{p1} is approximately equal to the nominal discharge current I_n of MOV. Consequently, for the short waveform, I_{p2} is approximately 0.2 times of I_{p1}. For the medium and the long waveform, I_{p2} is approximately 0.6 times of I_{p1}. The selected magnitudes and waveforms of impulse currents for the six groups of samples in the test are illustrated in Fig. 4.

For the current magnitude I_{p1}, the time interval between two short waveforms "S" is 60 s. Similarly, the time intervals for the medium waveform "M" and the long waveform "L" are, respectively, 90 s and 120 s. For I_{p2}, the time intervals of three waveforms are all 30 s.

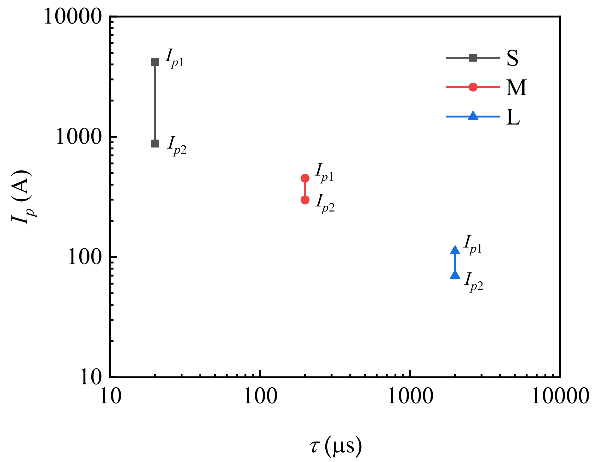

FIGURE 4. Parameters of impulse currents used in the life test of six groups.

2) The initial varistor voltage U_n of each sample were measured and recorded before the test. After each impulse current test, the varistor voltage U_n of each sample shall be measured and recorded again for comparison purpose. When the decrease of the varistor voltage relative to the initial measured value is $\geq 10\%$, the sample is judged to be invalid and the test is terminated, and the number of impulses at the end of the test is taken as the life number n of the sample; or when the varistor voltage of the sample is still higher than 0.9 times the initial value, but flashover or structural damage occurs, the sample is judged to be invalid and the test is terminated, the number of impulses before the termination of the varistor voltage, the varistor voltage in the reverse direction of the current shall be measured within 25 s to 30 s after the impulse. If the varistor voltage is close to the failure criterion, the sample continues to recover to the ambient

temperature value. Then the varistor voltage is measured to judge whether the MOV fails.

3) According to the life distribution of each group, the average life (n_{ave}), the median life (n_{med}) and the minimum life (n_{min}) can be calculated. According to the tested life data of each waveform with two different magnitudes, three basic equations of $\lg I_p \sim \lg n$ can be obtained.

4) Using the obtained basic equations, once any two parameters are given among I_p, τ, and n, the third parameter can be calculated.

Because the experimental method is just based on the MOV material characteristics instead of the size of MOV. The proposed experimental method is also applicable to other MOVs with different sizes (e.g. distribution and station class MOVs), only by properly adjusting the test parameters of impulse currents according to the above.

V. EVALUATION EXAMPLE

According to the method proposed in Section IV, six groups are built by randomly selecting samples from the same batch of Φ20 MOV products. Each group contains 15 samples. The samples of the six groups are subjected to the repeated impulse tests as required. The test results of six groups were recorded until all samples failed as shown in Table 2∼7.

TABLE 2. Test data of Group 1.

i	n	$F(t)$	Y_i	X_i
1	13	0.0455	-3.0679	–
2	14	0.1104	-2.1458	0
3	14	0.1753	-1.6463	0
4	15	0.2403	-1.2918	0.6931
5	15	0.3052	-1.0103	0.6931
6	15	0.3701	-0.7717	0.6931
7	15	0.4351	-0.5603	0.6931
8	17	0.5000	-0.3665	1.3863
9	17	0.5649	-0.1836	1.3863
10	18	0.6299	-0.0061	1.6094
11	18	0.6948	0.1713	1.9094
12	18	0.7597	0.3549	1.6094
13	22	0.8247	0.5545	2.1972
14	25	0.8896	0.7902	2.4849
15	27	0.9545	1.1285	2.6391

TABLE 3. Test data of Group 2.

i	n	$F(t)$	Y_i	X_i
1	174	0.0455	-3.0679	3.0910
2	198	0.1104	-2.1458	3.8286
3	204	0.1753	-1.6463	3.9512
4	226	0.2403	-1.2918	4.3041
5	226	0.3052	-1.0103	4.3041
6	258	0.3701	-0.7717	4.6634
7	273	0.4351	-0.5603	4.7958
8	292	0.5000	-0.3665	4.9416
9	304	0.5649	-0.1836	5.0239
10	351	0.6299	-0.0061	5.2933
11	371	0.6948	0.1713	5.3891
12	402	0.7597	0.3549	5.5215
13	411	0.8247	0.5545	5.5568
14	430	0.8896	0.7902	5.6276
15	445	0.9545	1.1285	5.6802

TABLE 4. Test data of Group 3.

i	n	$F(t)$	Y_i	X_i
1	11	0.0455	-3.0679	0.6931
2	15	0.1104	-2.1458	1.7918
3	19	0.1753	-1.6463	2.3026
4	20	0.2403	-1.2918	2.3979
5	21	0.3052	-1.0103	2.4849
6	22	0.3701	-0.7717	2.5649
7	23	0.4351	-0.5603	2.6391
8	24	0.5000	-0.3665	2.7081
9	25	0.5649	-0.1836	2.7726
10	30	0.6299	-0.0061	3.0445
11	34	0.6948	0.1713	3.2189
12	36	0.7597	0.3549	3.2958
13	44	0.8247	0.5545	3.5553
14	61	0.8896	0.7902	3.9512
15	77	0.9545	1.1285	4.2195

TABLE 5. Test data of Group 4.

i	n	$F_i(t)$	Y_i	X_i
1	149	0.0455	-3.0679	1.6094
2	188	0.1104	-2.1458	3.7842
3	190	0.1753	-1.6463	3.8286
4	317	0.2403	-1.2918	5.1533
5	414	0.3052	-1.0103	5.5984
6	456	0.3701	-0.7717	5.7430
7	503	0.4351	-0.5603	5.8833
8	835	0.5000	-0.3665	6.5381
9	920	0.5649	-0.1836	6.6542
10	1064	0.6299	-0.0061	6.8244
11	2176	0.6948	0.1713	7.6168
12	2436	0.7597	0.3549	7.7372
13	3067	0.8247	0.5545	7.9804
14	5863	0.8896	0.7902	8.6515
15	16106	0.9545	1.1285	9.6780

TABLE 6. Test data of Group 5.

i	n	$F(t)$	Y_i	X_i
1	10	0.0455	-3.0679	0
2	11	0.1104	-2.1458	0.6931
3	12	0.1753	-1.6463	1.0986
4	15	0.2403	-1.2918	1.7918
5	16	0.3052	-1.0103	1.9459
6	18	0.3701	-0.7717	2.1972
7	21	0.4351	-0.5603	2.4849
8	22	0.5000	-0.3665	2.5649
9	23	0.5649	-0.1836	2.6391
10	25	0.6299	-0.0061	2.7726
11	26	0.6948	0.1713	2.8332
12	33	0.7597	0.3549	3.1781
13	40	0.8247	0.5545	3.4340
14	41	0.8896	0.7902	3.4657
15	50	0.9545	1.1285	3.7136

In these tables, i is the rank of sample, n is the number of impulse life, and $F(t)$ is the failure probability satisfying the Weibull distribution obtained by MRR method.

In order to characterize the most likely impulse life of a batch of MOV products, this paper uses the median life

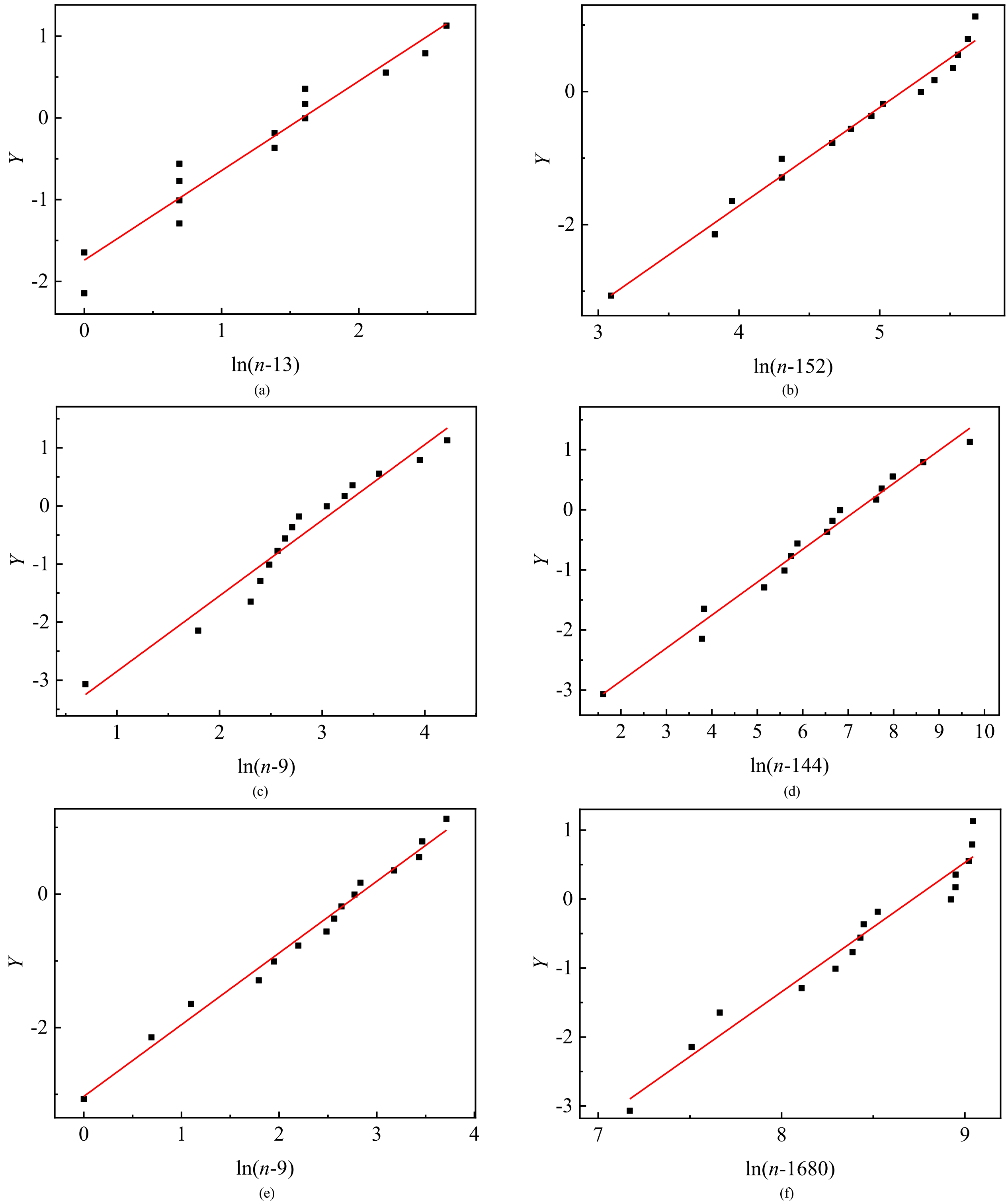

FIGURE 5. Fitting curves of six groups. (a) Group 1. (b) Group 2. (c) Group 3. (d) Group 4. (e) Group 5. (f) Group 6.

n_{med} as an evaluation indicator. Take Group 1 as an example, calculate its median life. The waveform equivalent width of the impulse current applied at Group 1 is 20 μs. The current amplitude is 4170 A. Apply the "trial algorithm" to the data in Table 2 to get the Weibull distribution straight line with the smallest fitting deviation. At this time, the minimum impulse life of the sample is 13, the slope of the line is 1.0957, and the intercept is -1.7408, as shown in Fig. 5(a). The median

TABLE 7. Test data of Group 6.

i	n	$F(t)$	Y_i	X_i
1	2983	0.0455	-3.0679	7.1724
2	3505	0.1104	-2.1458	7.5093
3	3808	0.1753	-1.6463	7.6629
4	5007	0.2403	-1.2918	8.1098
5	5681	0.3052	-1.0103	8.2943
6	6071	0.3701	-0.7717	8.3873
7	6264	0.4351	-0.5603	8.4303
8	6345	0.5000	-0.3665	8.4478
9	6718	0.5649	-0.1836	8.5248
10	9186	0.6299	-0.0061	8.9235
11	9378	0.6948	0.1713	8.9487
12	9383	0.7597	0.3549	8.9494
13	9957	0.8247	0.5545	9.0212
14	10113	0.8896	0.7902	9.0399
15	10154	0.9545	1.1285	9.0448

life of Group 1 can be calculated by using (6):

$$x = \frac{-b - 0.3665}{a} = 1.2542 \tag{9}$$

$$n_{med1} = e^{x} + n_{min1} = 16.5 \tag{10}$$

The results of the other five groups were processed with the same method. The Weibull distribution straight lines with the smallest error was obtained respectively as shown in Fig. 5(b) ~5(f).

With different impulse currents introduced in Section IV, the median life of each group is calculated according to the slope and intercept of each Weibull distribution straight line. The results are illustrated in Table 8.

TABLE 8. Median life of six groups.

Group	τ (μs)	I_p (A)	n_{min}	n_{med}
1	20	4170	13	16.5
2	20	876.8	152	288.1
3	200	451	9	27.3
4	200	298	144	829
5	2000	112	9	20.9
6	2000	70	1680	6703.3

According to the median life of the six groups, the impulse life characteristics equations at $\tau = 20$ μs, 200 μs and 2000 μs can be calculated. For the impulse current with $\tau = 20$ μs, the slope of the impulse life characteristics equation is

$$a_{20} = \frac{\lg\left(I_{p1}/I_{p2}\right)}{\lg\left(n_{med2}/n_{med1}\right)} = 0.5453 \tag{11}$$

The intercept of the impulse life characteristics equation is

$$A_{20} = \lg I_{p1} + a_{20} \lg n_{med1} = 4.2840 \tag{12}$$

So the impulse life characteristics equation at $\tau = 20$ μs is

$$\lg I_{p(20)} = 4.2840 - 0.5453 \cdot \lg n_{med} \tag{13}$$

Similarly, the impulse life characteristics equations at $\tau = 200$ μs and $\tau = 2000\mu$s are

$$\lg I_{p(200)} = 2.8285 - 0.1214 \cdot \lg n_{med} \tag{14}$$

$$\lg I_{p(2000)} = 2.1567 - 0.0814 \cdot \lg n_{med} \tag{15}$$

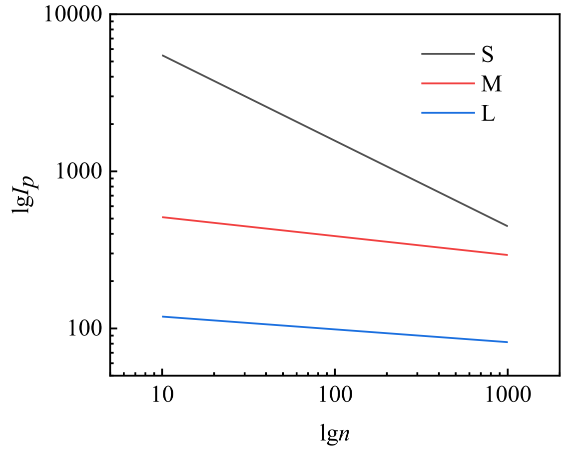

FIGURE 6. Three basic impulse life characteristics curves.

Therefore, (13), (14) and (15) are the three basic impulse life characteristics equations of the selected samples and the corresponding curves are shown in Fig. 6.

It is noted from Fig. 6 that the slope of the impulse life characteristics curves of MOV decrease with the increasing equivalent square wave width τ. The slope of the curve in the short impulse range is obviously larger than that in the long impulse range. This shows that the impulse life of MOV changes more sharply with the magnitude of impulse current in the short impulse range. At the same time, the life of MOV is positively correlated with the charge of impulse current, that is to say, when the magnitude of impulse current is the same, the larger is the equivalent square wave width of impulse current, the shorter is the life of MOV.

The life of the same MOV products under any impulse current can be evaluated from three basic equations by the interpolation algorithm. Taking the MOV products tested in this paper as an example, to know its median life under impulse current with $\tau = 100\mu$s and $I_p = 400$ A.

According to the basic equations, the relationship between the life number of the MOV at 400 A and the equivalent square wave width is derived. Because the equivalent square wave width of this impulse current is 100 μs, which lies between 20μs and 200 μs. So $I_p = 400$ A is substituted into (13) and (14), the median life at 20 μs is 1215, and the median life at 200 μs is 73. With these parameters, the linear equation (16) between the life number n and the equivalent square wave width τ is established, as shown in Fig. 7.

$$\lg n_{med} = 4.6709 - 1.2192 \cdot \lg \tau \tag{16}$$

According to (16), the median life of the MOV under impulse current with $\tau = 100\mu$s and $I_p = 400$ A is calculated to be 171.

VI. FITTING VALIDITY CHECK

The coefficient of determination (r^2) is widely used indicators that indicate how a model fits the actual values or numerical predictions [27]. r^2 presents the variable value of

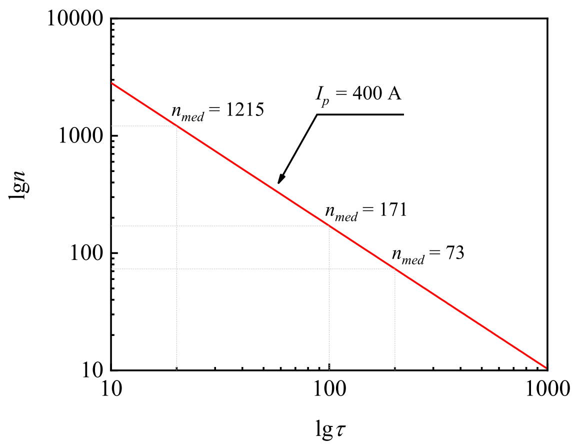

FIGURE 7. Impulse life characteristics curve (when $I_p = 400$ A).

the response variation explained by a linear model. When the value of r^2 is closer to 1, the fitting validity is better. When the value of r^2 is 1, total variations of the fitted response meet a linear relationship. Therefore, in order to check the fitting validity of the six-groups test data, each r^2 is calculated by (17).

$$r^2 = \frac{\left(\sum_{i=1}^{N} X_i Y_i - \sum_{i=1}^{N} X_i \sum_{i=1}^{N} Y_i \Big/ N\right)^2}{\left(\sum_{i=1}^{N} X_i^2 - N\left(\overline{X}\right)^2\right)\left(\sum_{i=1}^{N} Y_i^2 - N\left(\overline{Y}\right)^2\right)} \tag{17}$$

where $\bar{X}$ and $\bar{Y}$ are averages of X_i and Y_i, respectively.

Based on the calculation results in Table 9, r^2 of six groups are all greater than 0.93, which indicates that the proposed parameter model has a good fitting validity and also confirms that the life distribution of MOV under short, medium and long impulse currents conform to the Weibull distribution.

TABLE 9. Coefficient of determination of six groups.

Group	1	2	3	4	5	6
r^2	0.9353	0.9789	0.9494	0.9815	0.9862	0.9520

VII. SENSITIVITY ANALYSIS

The slope and intercept of the Weibull distribution straight lines obtained by fitting are written in the form of shape parameter and scale parameter. The expression of the median life is obtained as follow

$$n_{med} = \eta e^{-0.3665/\beta} + t_0 \tag{18}$$

The sensitivity analysis for the parameters having crisp value, the effects of changing the value of the parameters β, η and t_0 on the median life n_{med} is presented. The sensitivity analysis is performed by changing each of parameters by 10%, 5%, −5% and −10% taking one parameter at a time and keeping the remaining parameters unchanged. Table 10, 11 and 12 represent sensitivity analysis for the three parameters of the proposed model.

TABLE 10. Sensitivity analysis of shape parameter.

Parameter	Change(%)	Group	n_{med}	Change(%)
β	10	1	16.61	0.6557
	5		16.56	0.3410
	-5		16.44	−0.3706
	-10		16.38	−0.7748
	10	2	291.18	1.0764
	5		289.70	0.5608
	-5		286.32	−0.6122
	-10		284.39	−1.2831
	10	3	27.77	1.7391
	5		27.55	0.9054
	-5		27.03	−0.9867
	-10		26.74	−2.0660
	10	4	871.91	5.1815
	5		851.14	2.6758
	-5		805.28	−2.8559
	-10		779.92	−5.9156
	10	5	21.31	1.7952
	5		21.13	0.9334
	-5		20.72	−1.0142
	-10		20.49	−2.1199
	10	6	6793.36	1.3429
	5		6750.30	0.7004
	-5		6651.96	−0.7666
	-10		6595.47	−1.6092

TABLE 11. Sensitivity analysis of scale parameter.

Parameter	Change(%)	Group	n_{med}	Change(%)
η	10	1	16.86	2.1237
	5		16.68	1.0618
	-5		16.33	−1.0618
	-10		16.15	−2.1237
	10	2	301.69	4.7237
	5		294.89	2.619
	-5		281.28	−2.3619
	-10		274.47	−4.7237
	10	3	29.13	6.7032
	5		28.21	3.3516
	-5		26.38	−3.3516
	-10		25.47	−6.7032
	10	4	897.45	8.2629
	5		863.20	4.1314
	-5		794.71	−4.1314
	-10		760.46	−8.2629
	10	5	22.13	5.7004
	5		21.53	2.8502
	-5		20.34	−2.8502
	-10		19.74	−5.7004
	10	6	7205.68	7.4938
	5		6954.51	3.7469
	-5		6452.18	−3.7469
	-10		6201.01	−7.4938

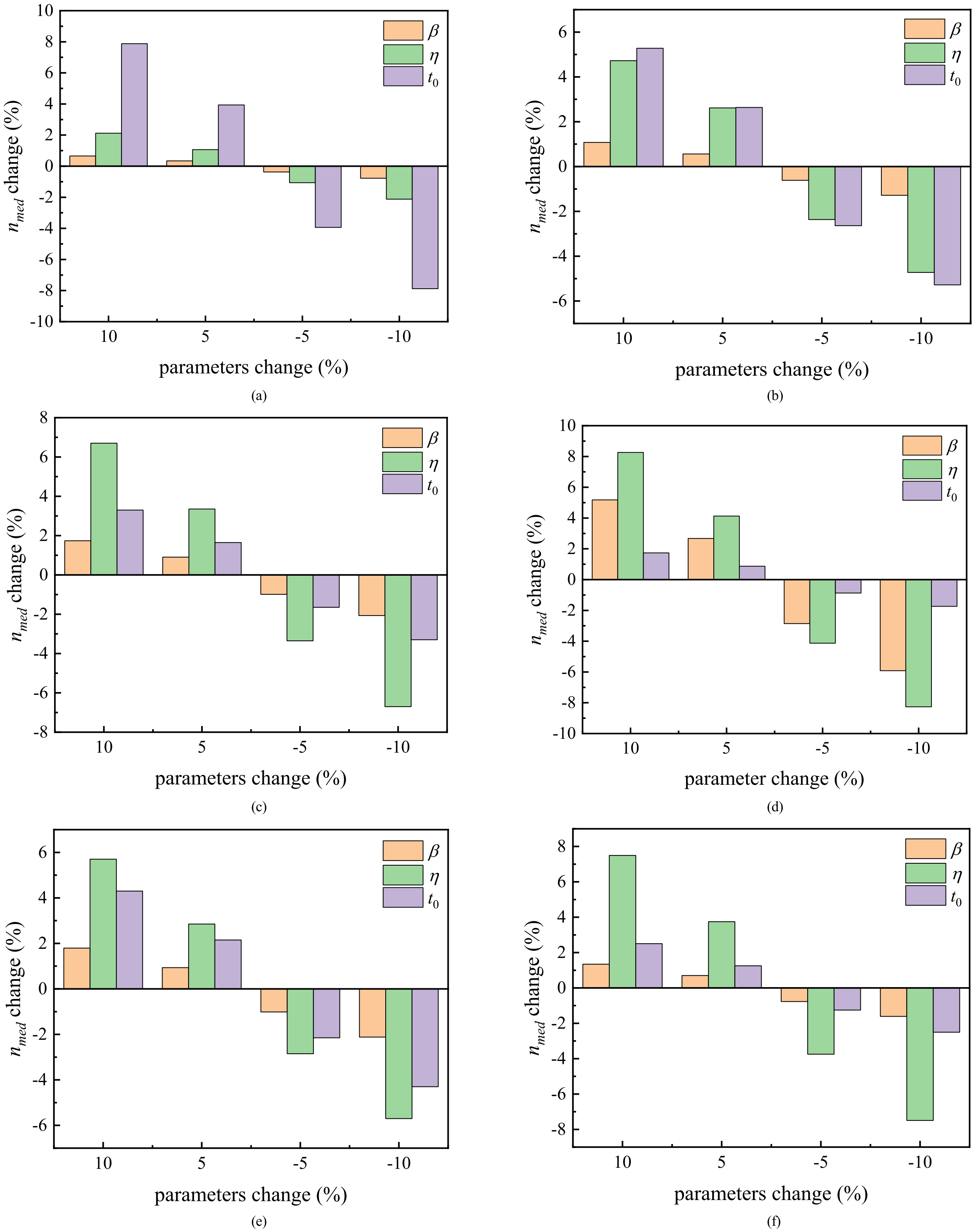

FIGURE 8. **Sensitivity analysis of six groups. (a) Group 1. (b) Group 2. (c) Group 3. (d) Group 4. (e) Group 5. (f) Group 6.**

Because position parameter t_0 is a part of the median life n_{med}, the ratio between t_0 and n_{med} is lager, the sensitivity of n_{med} to t_0 becomes higher. The values of t_0/n_{med} of Group 1, Group 2 and Group 5 are 78.79%, 52.76% and 43.06%, which are much larger than those of other groups. Consequently, the models of these groups are highly sensitive to t_0.

TABLE 12. Sensitivity analysis of position parameter.

Parameter	Change(%)	Group	n_{med}	Change(%)
t_0	10	1	17.81	7.8786
	5		17.16	3.9382
	-5		15.86	–3.9382
	-10		15.21	–7.8786
	10	2	303.28	5.2763
	5		295.68	2.6381
	-5		280.48	–2.6381
	-10		272.88	–5.2763
	10	3	28.20	3.2968
	5		27.75	1.6484
	-5		26.85	–1.6484
	-10		26.40	–3.2968
	10	4	871.91	1.7371
	5		851.14	0.8686
	-5		805.28	–0.8686
	-10		779.92	–1.7371
	10	5	21.83	4.2996
	5		21.38	2.1498
	-5		20.48	–2.1498
	-10		20.03	–4.2996
	10	6	6871.35	2.5062
	5		6787.35	1.2531
	-5		6619.35	–1.2531
	-10		6535.35	–2.5062

Since the value of $e^{-0.3665/\beta}$ in six groups are not quite different, scale parameter η plays an importance role in determining n_{med}. When the ratio between η and n_{med} is larger, the influence of its change on n_{med} becomes greater. The value of η/n_{med} of Group 1 is 29.68%, which is much smaller than other groups. So except Group 1, the models of other groups are highly sensitive to η.

Only the model of Group 4 is highly sensitive to shape parameter β, because the value of β is change between 0 and 2, and the influence of β on n_{med} is limited by η. Only when β is small and η is large, the model will be highly sensitive to β.

VIII. CONCLUSION

In this paper, we propose a method to evaluate the impulse life of MOV based on the Weibull distribution. Through the impulse life test of the MOV samples, the Weibull distribution is used to fit the life test data. The median life of the MOV under different impulse currents is obtained. Combined with the impulse life characteristics of MOV, i.e. the impulse current amplitude borne by MOV has an approximate linear relationship with its impulse life, three basic equations of MOV under short, median and long impulse currents are established. According to these equations, the life of MOV under arbitrary waveform impulse current can be evaluated by the interpolation algorithm. In addition, the validity of the fitting is checked. The results show that the parameter model based on the Weibull distribution has a high degree of matching with the impulse life distribution of MOV. And further sensitivity analysis of the variables has been done to examine the effect of changes in the values of the parameters on the propose model. Due to the difference of failure modes of MOV under different impulses, the magnitude and the equivalent square wave width of impulse current will affect the sensitivity of the model to parameters. It will be the future study about the failure modes of MOV under different impulse currents.

With the proposed method, the impulse life evaluation of MOV becomes applicable in engineering to increase the reliability of MOV. As long as the three basic impulse life characteristic equations of the same type MOV products are established, the impulse life evaluation of these products can be achieved to provide reference for the improvement of the manufacturing process. It is worth mentioning that the failure of MOV caused by impulse current is uncertain, and it is difficult to obtain complete failure data through life tests. In view of the above situation, neutrosophic statistics can be used for improvement in the future study [28]–[30].

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