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Evaluation of the Martin Empirical Formulae for Transformer Oil: Statistical Meaning of the Time Parameter

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***Abstract*—To study the statistical meaning of the time parameter $t_{63\%}$ in the Martin empirical formula, we took Kunlun 25# transformer oil as the liquid insulating dielectric and utilized an impulse voltage generator, the impulse width of which could range from 50 ns to 1000 μs, along with the corresponding measuring equipment. The relationships between the breakdown voltage, the breakdown time lag and the discharge probabilities were acquired through experiments under impulses with quasi-uniform field. The results show that the discharge probabilities of different voltage levels under the fixed impulse waveform and the breakdown time lag under the same voltage level both could be well fitted to the three-parameter Weibull distribution functions, whose shape parameter was a constant only correlated to the electrode geometry. Meanwhile, on the basis of the Weibull distribution functions and corresponding impulse waveforms, we defined the effective duration and show the statistical meaning of the time parameter $t_{63\%}$.**

Keywords—transformer oil; Weibull distribution function; effective duration; time parameter in the Martin formulae

I. INTRODUCTION

With the development of the electric power and pulsed power system, higher requirements for reducing the cost of equipment and the security margin of insulation designs are put forward by equipment manufacturers, which calls for better estimation of the dielectric strength. As one kind of the significant liquid dielectrics, transformer oil has been studied for a very long time [1-4]. However, considering the fact that the mechanism of liquid discharge is not clear yet, the empirical formulae of the dielectric strength of transformer oil are quite valuable to scientific researches or insulation designs [5].

At present, the empirical formulae provided by J. C. Martin are the most frequently used to estimate the dielectric strength of transformer oil in project site or lab, of which the application ranges are comparatively wider and the results are accurate to some degree [6, 7]:

$$E^{3/2} \cdot t_{63\%} = 0.08 \tag{1}$$

$$E \cdot t_{63\%}^{1/3} \cdot A^{1/10} = 0.5 \tag{2}$$

where E is the maximum average electrical field in MV/cm, $t_{63\%}$ is the temporal width of the impulse at 63% of the peak voltage in μs and A is the effective area in cm^2.

Equation (1) is suitable for when the impulses are applied in quasi-uniform field, and time parameters $t_{63\%}$ could only range from 100 ns to 150 ns; equation (2) extends the upper limit of the time range to 10 μs, but it demands the electrical field to be uniform.

Though the estimated results of equation (1) and (2) are comparatively accurate, the absence of the physical meaning of the time parameter $t_{63\%}$ limits its further applications. It Is of great significance to reveal the meaning of the time parameter.

In [8], the three-parameter Weibull distribution has been introduced to characterize the liquid discharge and the shape parameter m_E in the Weibull probability plot of breakdown field strength was considered only correlated to the gap geometry, which played the role of amplifying the effects of the major discharge elements and weakening the effects of the minor discharge elements. It was reasonable to utilize the shape parameter to represent some physical quantities.

In this paper, based on the weak-link theory [9], we will prove that the breakdown field strength and the breakdown time lag under different experimental conditions with quasi-uniform field can both be well fitted to the three-parameter Weibull distribution functions and their shape parameters are constants only correlated to the gap geometry. The effective duration will be defined and the meaning of the time parameter $t_{63\%}$ in the Martin empirical formulae will be clarified by statistics.

II. EXPERIMENTAL SETUP

Figure 1 shows the circuit of the 200 kV Marx generator. The adjustment of the output waveforms can be conducted by changing the main capacitors C, front resistor R_f or tail resistor R_t. Triggering of the circuit is controlled by the gas switch S. Examples of output voltage waveforms are shown in Figure 2.

Figure 3 shows the schematic diagram of test cell. It was made of PMMA, which has a good chemical compatibility with the liquids used. The radius of the stainless steel

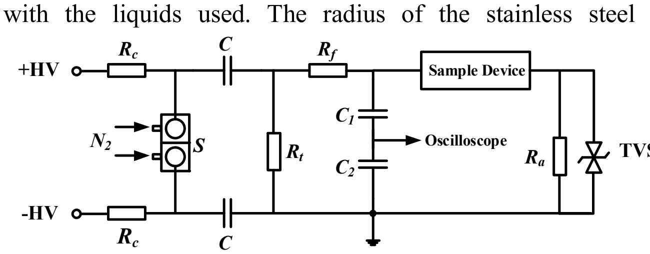

Fig.1. Circuit schematic diagram of 200 kV impulse generator

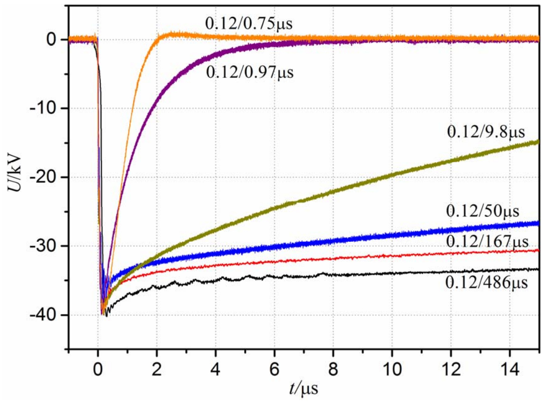

Fig.2. Output voltage waveforms

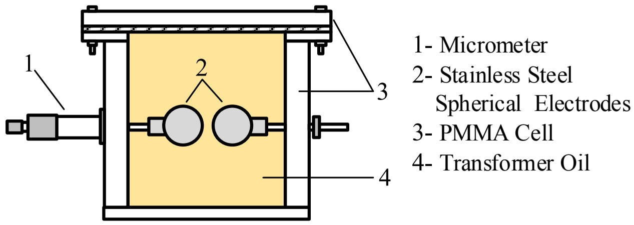

Fig.3. Schematic diagram of the sample device

spherical electrodes was 15 mm and they would be polished through same processes before each series of experiments. The transformer oil used in this experiment was Kunlun KI25X and would be replaced by new one after 50 breakdown to weaken the effects of carbide particles induced by discharges. All new oil had been dried in a vacuum drying oven, (100 Pa, 80 ℃, 24 h), to make sure the water and gas content less than 15mg/L and 1%. The withstand voltage of new oil is above 60 kV. The gap length between electrodes can be adjusted by the micrometer and was set as 500 μm in this paper.

III. Weibull Distributions of Discharge Time Delay and Breakdown Field Strength under the Same Volatge Waveform

Based on the weak-link theory, the Weibull distribution model is suitable for analyzing the phenomena that partial failures could lead to the loss of the whole function. Meanwhile, the situation that formation of any conducting channels could contribute to the failure of the liquid insulating medium resembles the theory. Hence, the Weibull distribution model can characterize the breakdown behaviors of liquid dielectrics.

A. Weibull Distribution of Discharge Time Delay

The two-parameter and three-parameter time-dependent Weibull distribution functions could be expressed as [8]

$$P_W(t) = 1 - \exp\left[-\left(\frac{t}{t_0}\right)^{m_t}\right] \tag{3}$$

$$P_W(t) = 1 - \exp\left[-\left(\frac{t - t_{\min}}{t_0}\right)^{m_t}\right] \tag{4}$$

where $P_W(t)$ is cumulative discharge probability, defined as the probability that discharge will occur when the discharge time delay is shorter than t; $t_{\min}$ is the location parameter; t_0 is the scale parameter; m_t is the shape parameter.

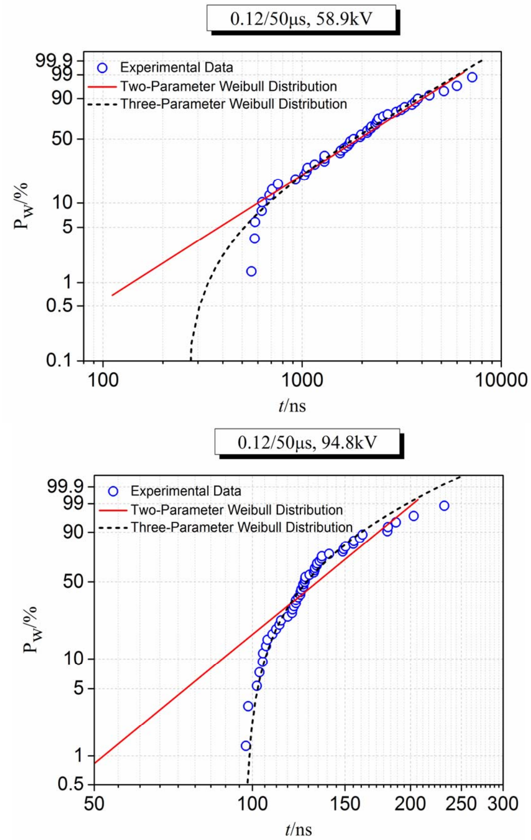

Fig.4. Weibull plot of time lag

Experimental data of discharge time delay corresponding to different voltage levels were acquired under 0.12/50 μs impulse voltage and the cumulative discharge probabilities were calculated. Figure 4 shows some fitting results of equation (3) and (4).

It is evident from Figure 4 that the fitting results of the three-parameter Weibull distribution function are better than the two-parameter Weibull distribution function. Thus, we will utilize the three-parameter Weibull distribution functions to analyze the following experimental data. Table Ⅰ shows the parameter values of the three-parameter Weibull distribution functions under different voltage levels.

TABLE I. Parameter Values of the Three-Parameter Weibull Distribution Functions

Voltage Level /kV	Fitted Value		
	Location Parameter $t_{\min}$	Scale Parameter t_0	Shape Parameter m_t
58.9	253.9	2015	1.448
69.8	121.1	587.1	2.272
94.8	96.47	38.16	1.578
120.8	84.33	34.17	1.815

Taking the data in Table Ⅰ and corresponding researches into consideration [8,11], it can be easily found that the shape parameter m_t is always around 1, hardly affected by voltage levels and waveforms. Below we take the shape parameter a constant only related to the gap geometry, as mentioned above.

B. Weibull Distribution of Breakdown Field Strength

The two-parameter and three-parameter field-dependent Weibull distribution functions could be expressed as [8]

$$P_W(E)=1-\exp\left[-\left(\frac{E}{E_0}\right)^{m_E}\right] \tag{5}$$

$$P_W(E)=1-\exp\left[-\left(\frac{E-E_{\min}}{E_0}\right)^{m_E}\right] \tag{6}$$

where $P_W(E)$ is cumulative discharge probability, defined as the probability that discharge will occur when the field strength is smaller than E; $E_{\min}$ is the location parameter; E_0 is the scale parameter; m_E is the shape parameter.

Step method [10] is utilized to obtain the values of $E_{\min}$, E_0 and m_E under 0.12/50 μs impulse voltage, as well as the discharge probabilities with different applied field strength. Figure 5 shows the fitting results of equation (5) and (6).

As with the time delay, the fitting result of the three-parameter Weibull distribution function is much better and can be expressed as

$$P_W(E)=1-\exp\left[-\left(\frac{E-0.5993}{0.8205}\right)^{2.897}\right] \tag{7}$$

where E is in MV/cm.

Due to the high fitting accuracy of the three-parameter Weibull distribution function (both the breakdown field strength and the discharge time delay), the probability of main insulation breakdown in oil-immersed equipment under practical field can be predicted through the fitting curve of the data obtained from previous working conditions or accidents. Then, the security margin could be determined more appropriately and the insulating structures can be further optimized.

IV. Relationship between the Effective Duration and the Time Parameter in the Martin Empirical Formulae

A. Physical meaning of the shape parameter

The shape parameter m in the Weibull distribution plays the role of controlling the mathematical morphology and the larger the parameter, the narrower the distribution of the random variables, which means that the shape parameter m represents the independent variables' "contributions" to the dependent ones [9].

The active area A_a, which refers to the largest area where breakdown may occur, was defined as [8]

$$A_a=\oiint\left(\frac{E_i}{E_{\max}}\right)^{m_E}\mathrm{d}S \tag{8}$$

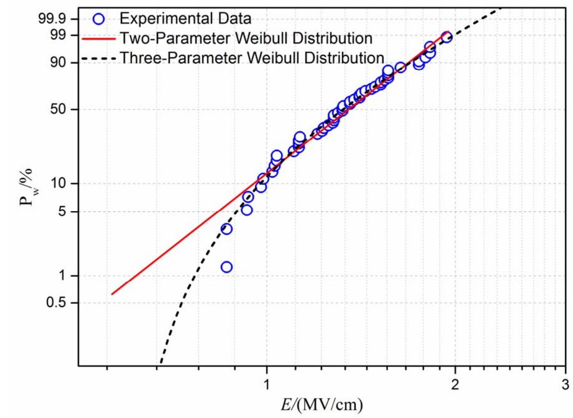

Fig.5. Weibull plot of breakdown field strength

where E_i is field strength of anywhere on the electrode surface; $E_{\max}$ is maximum field strength on the electrode surface; m_E is the shape parameter; dS is the surface area element.

For physical quantities like A_a in equation (8) which is under the action of the field strength, m_E plays the role of amplifying the major discharge elements and weakening the minor discharge elements. Thus, in this paper, we classify m_E as the electrical-acting factor under specific gap geometry, which can be used to define the effective duration.

B. Definition of effective duration

Similar to the definition of the active area, the effective duration t_{eff} under specific impulse is defined as the time region in which an electrical breakdown can take place and can be derived from

$$\int_0^{\infty}\left(\frac{E_i}{E_{\max}}\right)^{m_E}\mathrm{d}t=\int_{t_1}^{t_2}\left(\frac{E_i}{E_{\max}}\right)\mathrm{d}t$$
$$\xrightarrow{U=Ed}\int_0^{\infty}\left(\frac{U_i}{U_{\max}}\right)^{m_E}\mathrm{d}t=\int_{t_1}^{t_2}\left(\frac{U_i}{U_{\max}}\right)\mathrm{d}t \tag{9}$$

$$t_{\mathrm{eff}}=t_2-t_1 \tag{10}$$

where E_i and U_i are the average electrical field strength and the gap voltage at any time; $E_{\max}$ and $U_{\max}$ are the maximum average electrical field strength and the maximum voltage; η is the effective factor; t_1, t_2 is the lower time and upper time, derived from $E_i=\eta E_{\max}$; d is the gap distance; m_E is the shape parameter.

For that the shape parameter m_E is assumed only correlated to the gap geometry, m_E=2.897 in equation (7) can be used to analyze the voltage waveforms shown in Figure 2. Table Ⅱ shows the values of the effective factor η and corres-

TABLE II. Values of Effective Factors and Effective Duration under Different Waveforms

Voltage Waveform	$U_{\max}$ / kV	$\eta\cdot U_{\max}$ / kV	η / %	t_1 / ns	t_2 / μs	t_{eff} / μs	$t_{63\%}$ / μs
0.12/486 μs	-34.4	-21.6	62.8	128	269	269	260
0.12/167 μs	-57.3	-34.9	60.9	56.0	88.0	88.0	74.2
0.12/50 μs	-119	-73.4	61.7	54.0	23.2	23.2	29.6
0.12/9.8 μs	-54.2	-34.4	63.5	55.6	5.52	5.46	5.52
112/970 ns	-47.9	-31.8	66.4	50.6	0.633	0.582	0.629
37.3/111 ns	-39.1	-25.8	66.0	0.300	0.048	0.0478	0.0515

ponding effective duration t_{eff}.

It is evident from Table that effective factor η is always around 63%, whatever the voltage levels and the waveforms are adopted. Thus, the effective duration t_{eff} is equal to the the temporal width of the impulse voltage at 63% of the peak voltage.

C. Physical meaning of the time parameter in the Martin empirical formulae

From the statistical analysis above, we can find that the defined effective duration is approximately equal to the time parameter in the Martin empirical formulae in value, shown in Table (the parameter $t_{63\%}$ is directly derived from the recorded waveform).

Thus, the time parameter in the Martin formulae $t_{63\%}$ physically has the meaning of effective duration, and is reasonably to be applied in the *E-t* empirical formulae. What's more, the successful application in the definitions of effective duration and the active area illustrates that the shape parameter m_E does have the role of amplifying the major discharge elements and weakening the minor discharge elements.

V. CONCLUSION

We acquired the relationships between the voltage levels, the breakdown time lag and the discharge probabilities through experiments under impulse voltages with quasi-uniform field and analyzed the results with statistical methods. The conclusions are as follows:

1) The discharge probabilities of different voltage levels under the single waveform and the different discharge time delay under the same voltage level could both be well fitted to the three-parameter Weibull distribution functions.

2) The shape parameter m_E in the three-papameter field-dependent Weibull distribution function is a constant only correlated to the gap geometry and plays the role of amplifying the major discharge elements and weakening the minor discharge elements

3) The time parameter in the Martin formulae $t_{63\%}$ physically has the meaning of effective duration, and is reasonably to be applied in the *E-t* empirical formulae.

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