Copper Particle Effect on the Breakdown Strength of Insulating Oil at Combined AC and DC Voltage

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Abstract – Converter transformer is the key equipment of high voltage direct current transmission system. The solid suspending particles originating from the process of installation and operation of converter transformer have significant influence on the insulation performance of transformer oil, especially in presence of DC component in applied voltage. Under high electric field, the particles easily lead to partial discharge and breakdown of insulating oil. This paper investigated copper particle effect on the breakdown voltage of transformer oil at combined AC and DC voltage. A simulation model with single copper particle was established to interpret the particle effect on the breakdown strength of insulating oil. The experimental and simulation results showed that the particles distort the electric field. The breakdown voltage of insulating oil contaminated with copper particle decreases with the increase of particle number, and the breakdown voltage and the logarithm of particle number approximately satisfy the linear relationship. With the increase of the DC component in applied voltage, the breakdown voltage of contaminated insulating oil decreases. The simulation results show that the particle collides with the electrode more frequently with more DC component contained in the applied voltage, which will trigger more discharge and decrease the breakdown voltage of insulating oil.

Keywords: Converter transformer, Insulating oil, Copper particle, Combined AC and DC voltage, Breakdown strength, Weibull distribution, Particle trajectory

1. Introduction

Converter transformer is the key component connecting the AC power grid and DC power grid in the high voltage direct current (HVDC) transmission systems, and the insulating oil of converter transformer simultaneously withstands AC voltage and DC voltage [1]. The insulating performance of transformer oil is quite sensitive to solid particles suspending in the transformer insulating oil, which originate from the mechanical vibration, aging and partial discharge of converter transformer insulation [2]. The particles in transformer insulating oil will move to the high electric field region and form impurity bridges due to the electric field force, which will reduce the breakdown strength of the insulating oil [3]. The motion of particles at combined AC and DC voltage is different from that at AC voltage, which will lead to different breakdown characteristics of contaminated insulating oil [4]. Investigation into the breakdown characteristics of transformer insulating oil contaminated with solid particles at combined AC and DC voltage is conducive to the understanding of breakdown mechanism of insulating oil used in converter

transformer in presence of particle contamination.

The particle type, particle concentration and the external electric field are the key factors influencing the breakdown strength of insulating oil [5]. The CIGRE report [6] suggested that particle identification and counting were found to be necessary procedures of condition monitoring of converter transformers. In view of the research progress of the particle effect on the breakdown of insulating oil, focus was made on the particle types [7-9], voltage types [10, 11] particle movement [12, 13] under electric field, and partial discharge [10, 13] in insulating oil. Reference [7, 8] observed that conducting particles affect the dielectric strength much more than insulating particles, and larger particles reduce the breakdown voltage even more significantly. Reference [9] obtained insulating oil with different content of carbon particles through different numbers of lightning discharge and investigated the influence of carbon particle concentration on the breakdown voltage of insulating oil at AC voltage. Reference [10] investigated the influence of conductive particle with different particle sizes on the breakdown voltage of insulating oil at DC voltage, and it was found that larger particle has significant influence on the breakdown of insulating oil. References [12] investigated the motion of conductive particle at AC voltage. The AC breakdown strength of insulating oil contaminated with different copper particle concentrations was obtained. Reference [13] also investigated the motion of single steel particle in

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insulating oil at AC voltage and obtained the relationship between the PDs on particle and the motion of particle in insulating oil. Most publications investigated particle effect on the breakdown characteristics of insulating oil at individual AC voltage and individual DC voltage. Relatively few publications dealt with the influence of particle on the breakdown voltage at combined AC and DC voltage. Most publications analyzed the influence of particle on the breakdown voltage of insulating oil by means of the mass weight or concentration. However, the number of particles was seldom precisely considered, let alone the relationship between particle number and breakdown voltage at combined AC and DC voltage.

The objective of this paper is to investigate the influence of copper particle on the breakdown characteristics of insulating oil at combined AC and DC voltage and analyze the mechanism behind it with the simulation result of the copper particle movement trajectory. Firstly, insulating oil with different numbers of copper particles were prepared. Subsequently, the breakdown strength of insulating oil contaminated with copper particles at combined AC and DC voltage with the ratio of AC to DC component equal to 1 and 1/3 were measured, and breakdown strength at individual AC and DC voltage were also measured for comparison. The Weibull distribution was used to analyze the breakdown strength of contaminated insulating oil. Lastly, the electric field distribution near a single copper particle in the insulating oil was calculated and the particle movement trajectory is simulated to interpret the breakdown characteristic of contaminated insulating oil at combined AC and DC voltage.

2. Experiments

2.1 Experimental setup

The experimental set up is shown in Fig. 1, which consists of a function generator, an amplifier, a voltage divider and an oscilloscope. The input signal was provided by the function generator with the voltage types of AC, DC and combined AC and DC voltage. Reference [14]

Fig. 1. Wiring diagram of insulating oil breakdown test system

analyzed the voltage type that the converter transformer valve windings withstands and it found that the ratio of maximum value for AC and DC component is mainly 1 and 1/3. In this paper, the combined AC and DC voltage with the ratio of AC to DC equal to 1 and 1/3 were adopted during the experiments. The output signal of the signal generator is amplified by the high voltage amplifier. The electrode system in the oil cup is designed according to ASTM D877 [15], as shown in Fig. 2.

2.2 Experimental samples

The Karamay 25# transformer insulating oil provided by China National Petroleum Corporation was used as the insulating oil for experiments. The basic physical and chemical properties of the insulating oil are shown in Table 1. In order to eliminate water and particle effect, the transformer insulating oil was firstly filtered by a membrane with the pore size of about 0.8 μm . The filtered oil satisfies the “clean oil” standard [5], namely, the number of particles whose diameter larger than 5 μm is less than 300 per 100 ml in the oil sample. Then the insulating oil was degassed and dried at 80 $^{\circ}\text{C}$ for 48 hours to make sure that the water content in the insulating oil is less than 15mg/L.

The particle in insulating oil has a wide range of diameter, mainly ranging from 1 μm to 100 μm [5]. Copper particles are typically metallic particles found in insulating oil. Therefore, copper particles were used in this experiment to investigate the metallic particle effect on the breakdown strength of insulating oil. Their median diameter is 25 μm

Fig. 2. The plate-plate electrode system

Table 1. Basic physical and chemical properties of Karamay 25# transformer insulating oil

Parameter	Mineral oil
Appearance	Transparent
Density (20 $^{\circ}\text{C}$)/ $\text{kg}\cdot\text{m}^{-3}$	<0.895
Kinematic viscosity (40 $^{\circ}\text{C}$)/ $\text{mm}^2\cdot\text{s}^{-1}$	≤ 13.0
Pour point/ $^{\circ}\text{C}$	<-22
Flash point/ $^{\circ}\text{C}$	≥ 135
Acid value/ $\text{mgKOH}\cdot\text{g}^{-1}$	<0.03
Interfacial tension/ mN/m	47
Dissipation factor (90 $^{\circ}\text{C}$)	0.1%
Relative permittivity (90 $^{\circ}\text{C}$)	2.2
Volume resistivity (90 $^{\circ}\text{C}$)/ $\Omega\cdot\text{m}$	7×10^{11}

Fig. 3. Particle size distribution of copper

and the particle size distribution range is 1-100 μm . The median diameter is a criterion to evaluate the overall particle size distribution of particles. It means the diameter at which the cumulative size distribution percentage reaches 50%. The copper particle size distribution is shown in Fig. 3.

In this experiment, insulating oil with five copper particle concentrations were prepared. N was used to represent the particle number in per 100 ml oil. N was fixed at 10000, 100000, 500000, 1000000 and 5000000, symbolized as $N1$, $N2$, $N3$, $N4$ and $N5$, respectively. N was determined by measuring the mass weight of copper particles. The relationship between the particle number and particle mass weight is illustrated in appendix.

2.3 Testing procedures

The experiments of breakdown strength of contaminated oil were carried out as per ASTM D877 [15]. The increasing speed of voltage is about 2 kV/s. In order to get plenty of experimental data for statistical analysis, three series of 6 breakdown voltages were measured. During the test interval, an electromagnetic stir was used to stir the oil sample to ensure the homogeneity of particle distributions in the insulating oil, and the standing time of 2 minutes between two successive breakdowns was adopted to make the particles back to state of homogeneous distribution. The breakdown voltage of insulating oil contaminated with five copper particle concentrations was measured at AC voltage, DC voltage and combined AC and DC voltages.

3. Experimental Results

3.1 Weibull distribution analysis

Statistical methods (parametric and non-parametric) have been used to study the breakdown voltage distribution of transformer oil [16]. The common distributions are normal distribution, Gumbel distribution and Weibull distribution. Previous study showed that Weibull distri-

Fig. 4. Weibull probability plot of breakdown voltage of insulating oil contaminated with copper particles at AC voltage

Fig. 5. Weibull probability plot of breakdown voltage of insulating oil contaminated with copper particles at DC voltage

Fig. 6. Weibull probability plot of breakdown voltage of insulating oil contaminated with copper particles at AC/DC=1

bution has some advantages over other distributions to analyze breakdown voltage data of insulating oil [17]. In this paper, the two-parameter Weibull distribution model was used to analyze the breakdown voltage. The two-parameter Weibull distribution is shown in Eq. (1), where $F(u)$ is the probability of breakdown, α is the scale parameter and β is the shape parameter and u is breakdown

Table 2. Characteristic parameter of Weibull distribution of breakdown voltage

Voltage type	Weibull parameter	N1	N2	N3	N4	N5
AC	α	46.39	43.36	40.85	38.91	35.64
	β	12.44	10.51	10.89	9.71	7.37
DC	α	44.04	39.38	36.25	33.81	30.80
	β	10.85	10.43	6.88	6.11	6.09
AC/DC=1	α	44.52	42.22	39.34	37.16	33.29
	β	15.03	14.22	14.24	8.32	6.88
AC/DC=1/3	α	44.12	40.64	37.63	35.28	31.96
	β	11.97	11.03	10.04	8.69	7.91

Fig. 7. Weibull probability plot of breakdown voltage of insulating oil contaminated with copper particles at AC/DC=1/3

voltage of insulating oil.

$$F(u) = 1 - e^{-(u/\alpha)^\beta} \quad (1)$$

Figs. 4-7 show the Weibull distribution of the breakdown voltage of insulating oil contaminated with copper particles. The Weibull distribution of breakdown voltage in Figs. 4-7 show that the breakdown voltage data of contaminated oil are distributed in both sides of the Weibull probability straight line, which indicates that the breakdown voltage data of contaminated oil almost satisfy the Weibull distribution.

The scale parameter α and shape parameter β of the breakdown voltage were calculated with maximum likelihood estimation. The results are shown in Table 2. The scale parameter α of Weibull distribution of the breakdown voltage was adopted as the characteristic breakdown voltage.

3.2 Fitting results

The relationship between the copper particle concentration and the breakdown voltage was depicted in Fig. 8. A linear function was used to fit the above relationship, as shown in Table 3, where U is the characteristic breakdown voltage of contaminated oil and $\lg N$ is the

Table 3. Fitting expressions of the breakdown voltage of insulating oil

Voltage type	Fitting expression
AC	$U = -3.9697 \lg N + 62.7843$
DC	$U = -4.9559 \lg N + 64.0097$
AC/DC=1	$U = -4.1562 \lg N + 62.0789$
AC/DC=1/3	$U = -4.5420 \lg N + 62.8155$

Fig. 8. Breakdown voltage of insulating oil contaminated with copper particles

logarithm of the copper particle number in per 100 ml of insulating oil.

It can be seen from Fig. 8 and Table 3 that the breakdown voltage decreases with the increase of particle concentration. The above changing tendency demonstrates that the copper particle concentration has significant influence on the breakdown voltage of insulating oil, regardless of voltage type. The breakdown voltage reduces with the increase of the DC component at the same particle concentration, i.e. breakdown voltage at AC voltage is the largest while breakdown voltage at DC voltage is the smallest, and breakdown voltage at combined AC and DC voltage is medium.

Fig. 8 presented the fitting results of breakdown voltage of contaminated insulating oil versus particle number. The breakdown voltage reduces almost 3.5-5kV with tenfold increase in copper particle number. The decreasing speed of the breakdown voltage at combined AC and DC voltage is medium. The decreasing speed of the breakdown voltage at AC voltage is the smallest while DC voltage largest.

4. Discussions

4.1 Simulation model

According to the electrode system, a simulation model with single copper particle was established with the COMSOL simulation software to investigate the electric field distortion caused by the single copper particle and the copper particle trajectory, as shown in Fig. 9. The COMSOL software provides two module called "Particle

Table 4. Material parameter

Material	Relative permittivity	Resistivity/($\Omega \cdot m$)
Metallic electrode	10^5	$1.7 \cdot 10^{-8}$
Insulating oil	2.2	$7 \cdot 10^{11}$
Copper particle	10^5	$1.7 \cdot 10^{-8}$

Fig. 9. COMSOL simulation model of copper particle

Tracing” and “AC/DC”, which are enough to accomplish this task. The copper particle was placed in the axis of symmetry of the high voltage electrode and the low voltage electrode. The diameter of copper particle is $25\mu m$. The insulation around the electrode and copper particle is transformer insulating oil. The peak value of applied voltage on the high voltage electrode is 10kV. The low voltage electrode is grounded. The material parameter of the simulation model is shown in Table 4.

The forces applied on the copper particle in this simulation are drag, electrostatic and gravitational forces. Reference [18] found that the conductive particle in an electric field will be charged by contacting the electrode. The charge on the copper particle is calculated by Eq. (2) [19].

$$q = \frac{2}{3} \pi^3 \epsilon_m \epsilon_0 \left(\frac{d_p}{2} \right)^2 E \quad (2)$$

where ϵ_m , ϵ_0 , d_p and E are the relative permittivity of the liquid, the permittivity of vacuum, the diameter of copper particle, and the electric field, respectively.

The trajectory of copper particle is also influenced by the gravitational force and drag force during the course of movement in the insulating oil. The gravitational force F_g and drag force F_d are given by Eqs. (3) and (4) respectively.

$$F_g = m_p g \frac{(\rho_p - \rho)}{\rho_p} \quad (3)$$

where g is the acceleration of gravity, m_p is the mass of the

Fig. 10. The electric field distribution around copper particle at AC/DC=1

particle, ρ_p is the mass density of copper particle, and ρ is the mass density of insulating oil.

$$F_d = \frac{18\mu}{d_p^2 \rho_p} m_p v \quad (4)$$

where μ is the viscosity of insulating oil, v is the velocity of copper particle.

4.2 Electric field analysis

Fig. 10 shows the simulation results of the electric field distribution around a single copper particle at combined AC and DC voltage with the ratio of AC to DC equal to 1. Results show that the electric field between the two electrodes is uniform except for the regions around the particle and the value is 4kV/mm. There is a distortion in the electric field around the copper particle. The maximum of the distorted electric field is about 7.32kV/mm and the distorted area exists above and below the copper particle. The simulation results show that the introduction of copper particles will lead to the distortion of local electric field strength in the insulating oil. This phenomenon is also observed at other types of voltage. The uniformity coefficient of electric field can be calculated by Eq. (5) [20].

$$f_{Cu} = \frac{E_{max}}{E_{mean}} = 7.32 / 4 = 1.83 \quad (5)$$

where E_{max} represents the maximum electric field, and E_{mean} represents the mean value of electric field.

Fig. 11 shows the electric field distribution around copper particle in one period at AC voltage, DC voltage, and combined AC and DC voltage. The DC component has significant influence on the electric field. As the increase of the DC component in combined AC and DC voltage, the electric field strength around copper particle will increase while the maximum value stays the same and the volatility of electric field strength will reduce.

Fig. 11. The electric field distribution around copper particle

Table 5. Copper particle trajectories

Voltage type	Particle trajectories
AC	
AC/DC=1	
AC/DC=1/3	
DC	

The trajectories of the copper particle between the high voltage electrode and low voltage electrode at AC voltage, DC voltage and combined AC and DC voltage are shown in Table 5. The particle trajectory of simulation result at DC voltage is similar with the experimental result obtained in [21] and [22]. The particle trajectories show the path that copper particle pass through between the plate electrodes. It can be concluded from Table 5 that the copper particle collides with the electrode more frequently at DC voltage and the numbers of collisions at combined AC and DC voltage is medium. With the increase of the DC voltage component in applied voltage, the copper particle collides with the electrode more frequently. In summary, the voltage type has significant influence on the particle movement and the DC voltage will increase the collision probability with electrode.

4.3 Mechanism analysis

The influence of copper particle on the breakdown

voltage of insulating oil can be explained with the simulation results as follows.

The electric field simulation results show that a certain amount of charge will be induced in the two sides of the copper particle when reaching the electrode. These charges will form an additional electric field around the copper particle. The additional electric field and original electric field in insulating oil will cause the electric field distortion, namely, the electric field near the copper particle will obviously increase.

As the copper concentration is low, it can be considered that the breakdown of insulating oil is caused by individual particle. Reference [21] found that particles will move to high electric field and contact the electrode due to the effect of electric force. From the simulation results, it is clear that the electric field in insulating oil with the existence of a copper particle is much larger than that without a copper particle. When the particle moves to the area with larger electric field, the electric field will be distorted further. In that case, it is easier to trigger discharge. When the electric field strength exceeds the breakdown strength of insulating oil, the insulating oil breakdowns [18, 23]. Even if the electric field strength around particle surface is not large enough, the particles will move to the electrode that carries charge with the opposite polarity due to the effect of electric force. When the particle reaches the area near the electrode, the electric field strength between the particle and electrode will increase, which will cause partial breakdown and finally lead to the entire breakdown of the oil gap [12].

As the copper particle concentration of insulating oil is large, more and more particles will concentrate in electrode area with a strong electric field due to the electric force, which leads to the increase of copper particles concentration. Then the collision frequency with electrode of copper particles will increase. A large amount of copper particles movement will form a phenomenon which is similar to the impurity bridge [24].

As to the difference between the AC voltage and DC voltage, the copper particle will withstand an electric force with a constant polarity at DC voltage and combined AC and DC voltage. The particles are easier to gather in the high electric field area, including the electrode surface [25]. The copper particles are much easier to contact the two electrodes, as shown in Table 5. Therefore, the breakdown voltage of insulating oil at DC voltage, combined AC and DC voltage is smaller than that at AC voltage. This phenomenon is in accordance with the experimental results.

For converter transformers, the valve side winding withstands combined AC and DC voltages. Because the copper particle has larger influence on the breakdown voltage of insulating oil when subjected to DC voltage, special attention should be paid to the insulating performance of insulating oil used in converter transformers. In presence of particle and DC component, the insulation design and maintenance should be differentiated compared

to that in traditional transformers to ensure the insulating performance of insulating liquids. The electric field allowance for the insulation should be different from that of insulation used in conventional AC transformers and the particle limit for insulating oil used in converter transformers should be strictly controlled in case of the electric field distortion induced by particle which may further cause breakdown of insulation.

5. Conclusions

This paper investigated the copper particle effect on the breakdown strength of insulating oil at combined AC and DC voltage. The main conclusions are summarized as follows.

1) The breakdown strength of insulating oil contaminated with copper particles reduces with the increase of the copper particle concentration. There is a liner relationship between the breakdown voltage and logarithm of the copper particle concentration.

2) The experimental and simulation results show that the copper particle will distort the electric field in insulating oil and the uniformity coefficient of electric field will increase, which will increase the breakdown probability of insulating oil and lead to the decline of breakdown voltage.

3) The DC component in applied voltage has significant influence on the breakdown voltage of contaminated insulating oil. The simulation results show that the copper particle collides with the electrode more frequently with more DC voltage component contained in applied voltage, which brings about more times of discharges and decrease the breakdown voltage. For insulating oil used in converter transformers which withstands combined AC and DC voltage, special attention should be paid to its insulating performance.

Appendix

This appendix illustrates the calculation method of particle number estimation of copper particle with respect to its mass weight.

Assume that the diameter of copper particles of different numbers obey the same diameter distribution illustrated in Fig. 3 and the copper particles are all spheres and uniformly distributed. The copper particles can be classified into i categories by means of their diameters. Define V as the overall volume of copper particles in all diameter ranges and N as the number of all copper particles. The upper and lower boundary of each diameter range are defined as r_{imax} and r_{imin} , respectively. r_i is the average diameter of the i th diameter range and it can be calculated by the following equation

$$r_i = (r_{imax} + r_{imin}) / 2 \quad (A1)$$

According to the size distribution of copper particle, volume proportion of particles in each diameter range can be calculated, defined as α_i . Define N_i as the number of corresponding particles in each diameter range and V_i as the particle volume of particles in each diameter range. Then the following relationships are obtained.

$$V_i = V \alpha_i = 4/3 \pi r_i^3 N_i \quad (A2)$$

$$\sum V_i = V \quad (A3)$$

$$\sum N_i = N \quad (A4)$$

Define ρ as the density of copper particle, the mass weight of particles in each diameter range, defined as M_i , can be calculated with Eq. (A5).

$$M_i = \rho V_i \quad (A5)$$

Define r_{eq} as the equivalent diameter of all the copper particles, which can be calculated by Eq. (A6).

$$4/3 \pi r_{eq}^3 N \rho = \sum M_i \quad (A6)$$

According to Eq. (A1)-(A6), the relationship between the number of copper particles and the mass weight can be obtained by Eq. (A7).

$$M = 4/3 \pi r_{eq}^3 \rho N \quad (A7)$$

Therefore, the particle number N can be estimated and controlled with the mass weight of the copper particles M .

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