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EXPERIMENTAL ANALYSIS FOR THE INFLUENCE OF METALLIC AND DIELECTRIC FREE MOVING PARTICLES ON THE BREAKDOWN VOLTAGE OF SMALL OIL GAPS

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تحليل معملى لتأثير الجسيمات المعدنيه والعازله الحرة الحركه على جهد انهيار تغرات الزيت الصغيرة

الخلاصه :-

هذا البحث يقدم تحليل لنتائج تجارب معملية أجريت بواسطة الباحث حول تأثير الجزيئيات الصلبه الحره الحركة على سلوك جهد أنهيار ثغرات الزيت العازلة . التجارب والمشاهدات المعملية أرتبطت باستعمال نوعين من الجزيئيات المعلقه فى ثغرات الزيت الصغيرة (جسيمات معدينة وجسيمات عازله) وذلك لنوعين من الثغرات (بين كرتين متماثلتين كذلك بين كره ولوح) . كما أجريت تجارب أخرى بوضع جسيمات مستقره حره على سطح لوح معدنى للثغرات التى تفصل بين كره ولوح فى وضع رأسى مغمورة فى الزيت كذلك فقد تم اجراء تحليل احصائى لاحتمالات جهد الانهيار فى حالتى استعمال جزئ صلب مفرد واستعمال عديد من هذه الجسيمات ومناقشة تأثير زيادة عدد هذه الجسيمات على احتمالات جهد الانهيار الكهربى

ABSTRACT

This paper introduces experimental investigations about the influence of solid free moving particles on a.c. breakdown voltage behaviour of insulating oil gaps. The experiments and observations have been conducted by means of using suspended metallic and dielectric particles in small oil sphere gaps as well as in sphere-plate gaps. Moreover, another experiments have been carried out using resting free moving conducting particles on a plate in plate-sphere oil gaps. The observed results about the movement of the conducting particles as well as the influence of the particles on breakdown voltage behaviour of the gaps have been recorded and analyzed. Statistical analysis of the breakdown voltage probabilities and the effects of the number of foreign artificial particles have been discussed.

1. INTRODUCTION

The presence of impurity particles in liquid insulations has been recognized to influence the breakdown strength of the liquids [1,2]. However, the general state of knowledge on the behaviour and the effect of such particles on the performances of the liquid insulating materials is less investigated than in the case of gases [3]. One particular dielectric system, for which conductivity can be shown to be especially important, is that of solid particles suspended in a dielectric liquid and causes a motion inside the liquid itself. The presence of solid contaminant in the insulating oils represents a common, although unwanted, situation in many dielectric systems such as transformers and power cable accessories [4].

Metallic and/or dielectric impurities partricles play a major role in the breakdown initiation mechanism of technical grade transformers oil, apart from the possibility of bridge formation [5,6]. However, the hypothysis based on dielectrophoretic phenomena are traditionally applied. This technique assumes an ideal dielectric media and neglects conductivities. Actually, such an assumption can, in some cases, prevent the full understanding of some phenomena [7-10].

As preliminary results, the effect of fixed metallic particles on the dielecric strength of insulating oil gap has been investigated by the author [11]. The results show that, the fixed particles have a significant effect on the electric field uniformity and may consequently lead to different breakdown mechanisms. Resting and suspended free moving particles are expected to distort the electric field strength. Moreover, they are presume to initiate ionization activities due to movement of the foreign particles as well as due to collision between the particles and the electrodes.

This paper investigates experimentally an important analysis to determine the influence of solid free moving particles on the breakdown behaviour of oil insulated gaps. Moreover, observation results of the movement due to artificial suspended and resting particles in small oil gaps have been recorded and discussed. Thereby, the effect of the number of paricles on a. c. breakdown characteristics is statitistically analyzed and useful results have been reported.

2. PHYSICAL BACKGROUND

Some techniques based on a computer model have been used to describe the impurity particle motion in a dielectric liquid

[9,10]. It has been found, in most cases, that the theoretical approach to the problem involved are too complex to be modeled and their nature is essentialy statistical. The reason of complexity is that the size of the particles involved is very small and their electrical and mechanical behaviour during the interaction phase depends strnogly on the local condition of the contact surface.

Generally, in all-oil filled electrical equipment there are zones of divergent electrical field. This is mainly attributed to construction of their equipments. Therefore, the free moving foreign particles can be particulary dangerous in such system, as they move under the action of the electric field, giving rise to its accumulation effects. Then, they can experience breakdown strength between oil gaps, which induce local stress. Thereby, artificial free moving foreign particles can be used, either resting on the electrodes or suspended between the oil gaps. These particles have a size greater than that of a nature impurity particles in oil to observe and recored directly the particle behaviour in the oil gap during its movement. Such technique may be applied for the action due to any defects in construction with the dielectric liquid in presence of impurity particles when investigating the breakdown voltage.

2.1. The Forces Acting on Free Moving Particles

Solid impurities, metallic or dielectric particles are subjected to an electric force, given by [12],

$$Fe = - r^3 \frac{\epsilon_1 - \epsilon_2}{\epsilon_2 + 2\epsilon_1} E \text{ grad } E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where,

r = radius of the particle
ϵ_1= permittivity of the liquid
ϵ_2= permittivity of the particle

It is found, from eqn. (1) that, the force increases as E increases, the force will urge the particle to regions of higher field gradients. Therefore, Particles which are conducting or having higher permitivities than the liquid, for which the force becomes;

$$Fe = r^3 E \text{ grad } E \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

On the other hand, the forces acting on the dielectrophoretic motion are described in ref.[6]. It considers the conductivity of soild suspended particles in a dielectric liquid as an important factor for the particle motion inside the liquid. In this study, the field is created by a point charge q located at a distance d ($d > r$) from the center of the sphere gap, and giving the follwing expression;

$$F(t) = \frac{-q^2 r^3}{4\pi \epsilon_1 d^5} \sum_{n=1}^{\infty} \frac{r^{2n} - 2}{d^{2n} - 2} (n+1) . \frac{n(\epsilon_1 - \epsilon_2)}{2\epsilon_2 + (n+1)} e^{-t/\tau_n} + K \quad ..(3)$$

where,

$$K = \frac{n(\sigma_1 - \sigma_2)}{n\,\sigma_2 + (n+1)\sigma_2}\,(1 - e^{-t/\tau_n})$$

and,

n is the relaxation time, given by

$$n = \frac{n\,\epsilon_2 + (n+1)\,\epsilon_1}{n\,\sigma_2 + (n+1)\,\sigma_1}$$

From eqn.(3), the dielectrophoretic motion process based on the role of permittivities will lead to obtain the force type in the oil gap. This force is poisitive, if $\epsilon_2 > \epsilon_1$ and $t = 0$, i. e. gives rise to an attraction of sphere towards the charge q; a replusion, on the contrary, takes place when $\epsilon_2 < \epsilon_1$. The role of the conductivities is to determine the time duration of the force, and its final value at $t = \infty$. At this time, the force becomes opposite in sign to its initial condition. This occurs, in particular, in the case when $\epsilon_2 > \epsilon_1$ and $\sigma_2 < \sigma_1$ or vice versa.

3. EXPERIMENTAL TECHNIQUES

Experiments have been carried out on transformer oil, class-diala B. The transformer oil used in the experiments has been stored in converted oil drum (taken from Suez Canal Authorithy at Port Fouad). It was kept clean and free from any forign impurities (less than 5000 particles per 100 ml). The moisture contents of the oil has been below 10 ppm and its gas content below 2 % . Moreover, the oil sample has been allowed for a break, stirring between tests and replaced after ten tests.

A 60 - kV oil test set, type BSS/IEC test vessel with semi-automatic set has been used in the experiments. It contains a resin encapsulated transformer with two high voltage output terminals (copper spheres of 13 mm diameter). The mid point of the transformer h. v. winding is earthed. The applied voltage has raised via a motorised variable transformer at a rate of 2 kV/s until breakdown of the oil occurs and the voltage is held in the meter until it is rest.

Plate - sphere oil gaps have been arranged by replacing one of the spheres by a copper disc of 50 mm diameter. Another test vessel has been used, but it is vertically constructed to allow resting of foreign particles on the plate. The electrode surface has been polished to keep it smoothly as possible.

Fig. 1. illustrates, generally, a schematic diagram of the experimental set-up used to investigate the influence of suspended as well as resting particles on the breakdown behaviour of the oil gaps.

Metallic sphere particles of steel with 1 mm, and 3 mm diameter have been used to represent the free moving conducting particles. The dielecric sphere particles of polyethylene (PE), and glass both with 3 mm diameter has also been employed to sample the dielectrophoretic motion in a dielectric oil. Table 1 shows some physical and electrical properties for both metallic and dielectric materials.

Table 1 Some physical and electrical properties for both materials used in the experiment.

Property	Oil (B)	Metallic particle (steel)	Dielectric particles	
			PE	glass
density(gm/cm), ρ	0.875	7.85	0.96	2.5
conductivity ($\Omega^{-1}m^{-1}$), σ	0.6x10 at 90 C	0.11x10	1.25x10	1.1x10
permittivity, ϵ	2.245	-	2.26	5

4. RESULTS AND DISCUSSION

4. 1. Suspended Conducting Particles

In this experiment, copper sphere electrodes of 13 mm diameter and gap spacing of 5.5 mm have been used (Fig. 1. a.). Investigations have been conducted with metallic suspended particles of 1 mm diameter. Every time, the particle has been always balanced in a symmetrical position. Observations of the experimental investigation, under a. c. voltage stress, are obtained and the following remarks may be drawn; (i) initially, after reaching a certain voltage value the particle begins to move towards one of the electrodes which agree with the general eqn. (1); (ii) the particle could, somtimes, reach the electrode at once and thus oscillates between the sphere electrodes; (iii) with voltage raised, the particle has been then repulsed towards the other electrode, at which it leaves the field gap randomly.

Generally, two different kinds of oscillations could be observed, the particle either oscillates and impactes with only of the electrodes or the particle oscillates and impactes with both electrodes. Therefore, the particle oscillations have an irregular nature depending on the two regions of higher field gradients at each sphere of electrode. Whereof, at the beginning of particle oscillations, the particle moves along the axis of symmetry (high electric field strenght line). However. after a couple of collisions, the repulsion forces have been, sometimes, directed so that, a particle rotation around one of the electrodes occured, after which the particle leaves the field gap. Due to collisions between particle and electrodes, about 50% of the suspended particle leaves the field gap away.

The same behaviour has been noticed in the case of sphere-plate electrodes, (Fig. 1. b.), excpet that 15 % only of the suspended particles leavs the field gap. In this case, the observation demonstrates that, the electric force will influence strongly the suspended metal sphere to move to the strongest region of the field. Therefore, it moves and its attracted towards the sphere electrode, according to eqn. (2), at which it leaves the field gap statistically.

In the presence of suspended metallic particle, the breakdown of oil occurs in a sudden way. This process may take place without a clear recognization of inception voltage as that was observed in the case of oil gaps without or with fixed particle on the electrode surface [11]. The only remarkable detectable phenomena before the breakdown were the microdischarges, due to impact between particle and electrode.

The observed irregularity motion of the suspended particle is in our opinion due to the nature of force acting on the paticle as explained above . In addition, the electrostatic driving force is not constant under a. c. voltage, so that position of particle depends on the phase voltage [7]. Thereby, the particle bounces again on the repulsing electrode and do not cross the entire gap until higher voltages are applied or enough energy is accumulated. Such a behaviour has been calculated for moving conducting particles in fluid as well as in SF6-GIS, [9,13].

Fig. 2. illustrates a comparison between the mean breakdown voltages for the same oil sphere gap under three different conditions. First, without particle. Second , with a fixed 1 mm diameter conducting particle. Third , with a 1 mm diameter suspended conducting particle. It is clear from the figure that, suspended conducting particle causes more reduction in the breakdown voltage than that caused by the fixed particle. Assuming that both suspended and fixed particles are causing the same influence on the field strength in the oil gap, the more reduction in the breakdown voltage can lead back to the more initiation of breakdown mechanism due to the particle discharges caused by the movement of the suspended particle.

Similar particle behaviour has been observed with changing the gap spacing from 5.5 mm to 10 mm, wheares, a higher voltage is needed to break the oil gap. Since the suspended particle is not always exactly centered between the oil sphere gap, which consent with the practical cases, a randomly varying particle moving voltage has been recorded. The moving voltage is the voltage at which the particle starts to move. To demonstrate this interesting observation, Fig. 3. shows the suspended conducting particle of 1 mm diameter. The investigations give similar results for both sphere gap as well as plate-sphere oil gap. This behaviour illustrates that, the earlier the motion of the particle caused by the moving voltage occures, the faster is the ionization processes activation in the gap and thus the lower is the breakdown voltage. Therefore, this analysis is more realistic than the analysis which only assume the equilibrium position of suspended particle [6]. Practically, the impurity particles in most-oil filled electrical equipment, has a mechanical transient much slower than the electrical.

Fig. 4. shows the breakdown voltage probabilities for a 5.5 mm oil gap with and without the suspended particle. In the case of suspended conducting particles two size of particle diameters (1 mm, and 3 mm) are used. It is seen from the figure that, the breakdown voltage increase slightly in the case of 3 mm than that of 1 mm due to that, such large particle needs a higher moving voltage. This means that the ionization activities caused by the larger suspended particle begin later than that caused by a lighter particle. Moreover, the smaller particle causes a higher field strength elevation. Fig. 4. shows, also a comparison of the breakdown voltage probabilities between suspended and fixed particle for the same oil gap. The suspended free moving particle initiates partial discharge and breakdown phenommena faster than that of the fixed particle. This is mainly attributed to the moving voltage of suspended particle.

4. 2. Suspended Dielecric Particles

In this section, the effect of dielectric free moving particles on the breakdown behaviour has been experimentally investigated. In this experiment, two different dielectric spheres,polyethylene (PE), and glass of suspended particle with a 3 mm diameter have been used. The particle is suspended also in a symmetrical position between electrodes as previously mentioned, (Fig. 1.).

The following remarked observation, under a. c. voltage stress, may be also withdrawn; (i) the dielectric sphere is observed to have initially, the toward higher field region, the same as the metal sphere. After reaching a certain voltage value, the dielectric particle begin to move to region of lower field gradients. Moreover, it moves towards one of the electrodes; (ii) with increasing the applied voltage, automatically with the rate of 2 kV/s, a microdischarge leads to sparks between dielectric particles and the lower field electrodes (for experiment, plate electrode), and then it leaves to another position depending on the repulsion forces in the oil gap.

Accordingly, the observation demonstrates that, the suspended dielectric behaviour in the oil gap consent in most cases with computational model of dielectrophoretic motion given by eqn.(3). This observation clearifies that, the dielectric particle with a certain voltage value begin to move and be attracted as the metal particle and fast enough to reverse its direction to lower voltage gradient (agree with the condition $\epsilon_2 > \epsilon_1$ in eqn. (3). After that, limiting adherence force to detach the particle from an electrode has been observed. This limiting adherence force depends on the repulsion forces after a period of time(like also the behaviour of dielecrophoretic motion in eqn. (3) at $\epsilon_2 < \epsilon_1$). At that time, limiting adherence force causes the microdischarge between the particle and electrode surface which leads to a spark between them until the particle leaves the field gap away.

Generally, earlier limiting adherence force, caused by a certain adherence voltage, leads to; (i) faster the microdischarge process, (ii) microdischarge initiates spark activation between particle and electrode surface until the particle leaves the field gap away, (ii) lower breakdown voltage (Fig. 5.).

Both suspended dielectric particles (PE, and glass) gives, statistically different behaviour in the oil gap. It is seen from the Fig. 5 that, the adhered voltage is nearly occured at the 30% of the breakdown voltage. Moreover, they have different earlier limiting adherence force values. Fig. 6 shows that, the breakdown voltage probabilities in the case of PE particle are higher than that of glass particle, at the same adherence voltage. This behaviour above 13 kV adhered voltage is not true. In this case the breakdown probabilities in the case of PE particle is lower than that of glass. This is mainly attributed to the mechanical and electrical behaviour in the oil gap depending on the physical and electrical properties of dielectric materials; (i) the particle density ρ , where ρ(glass) > ρ(PE) , (ii) the permittivity, ϵ where ϵ(oil) < ϵ(glass) > ϵ (PE) , (iii) the conductivity σ , where σ(oil) < σ(PE) > σ (glass).

4.3. Resting Free Moving Conducting Particles

The experimental set up has been shown above in Fig. 1. c. The electrodes used are a plate of 50 mm diameter and a 13 mm diameter sphere. Conducting particles of 1 mm, and 3 mm have been investigated in the 10 mm oil gap (Fig. 7.). It is seen that, the 50 % breakdown voltage without any particles has been found to be 42 kV. The existance of one particle resting on the plate causes a significant reduction in the breakdown voltage, from 42 kV to 28 kV (about 33 % for 1 mm and 29 % for 3 mm diameter particles). In the other hand, comparing suspended and resting later particle, it is noticed that , the particle could not be elevated of oil gaps, on the contrary of SF6-GIS [3]. So that, gravity force affects the particle motion in the gap.

For a number of particles up to 4, the influence on the breakdown voltage is almost similar. For a higher number of particles (greater than 4 particles), the influence becomes significant. Fig. 8. explains the effect of number of particles on the breakdown voltage probabilities.

The theoretical calculations of the withstanding probability have been carried out generally using the magnification law, for any number of particles. Good agreement has been obtained previsouly for the case of SF6-GIS [14]. When applying this technique in the case of higher number of resting particles, no agreement has been achieved as explained in Fig. 9.

The disagreement may be attributed to that, in oil insulating liquids there are different mechanisms of breakdown phenomena at different ranges of probability regimes and different field strength. Other word, the disagreement, in the author opinion, is due to the unpossibility resting free moving conducting particles to elevate the field oil gap.

5. CONCLUSIONS

Suspended free moving solid particles as well as resting free moving particles have been found to cause a serious reduction in the breakdown voltage probabilities of the oil gaps. From the experimental analysis under-taken in this work, the results are summarized as follows:-

1- The moving voltage acting on the suspended metallic particles initiates partial discharge and causes a breakdown voltage faster than that in case of fixed particle.

2- The dielectric particles give , statisttically, different breakdown voltage probabilities in the oil gap depending on some behaviours of mechanical and electrical stress.

3- The breakdown occurs suddenly, in the presence of suspended metallic particles, without a clear recognization of inception voltage.

4- Suspended conducting particles cause higher reduction in the breakdown voltage compared with that of fixed particles. This is due to that, it dominates the role of particles discharges by the initiation of breakdown process.

5- The resting and suspended particles cause a reduction of breakdown voltage. This reduction is proportional reversely with the size of the particles.

6- On the contrary of SF6-GIS, no agreement has been achieved between the experimental and theoritical results applying magnification law on the withstanding probability of oil insulating gaps with n. number of conducting particles.

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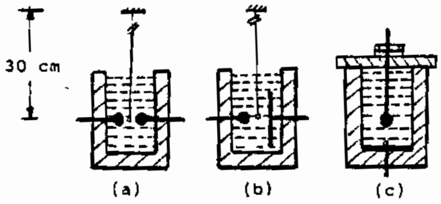

Fig. 1. Schematic diagram of the experimental set-up,
(a) Sphere gap, (b) Sphere-plate electrodes,
(c) Vertical construction of sphere-plate electrodes.

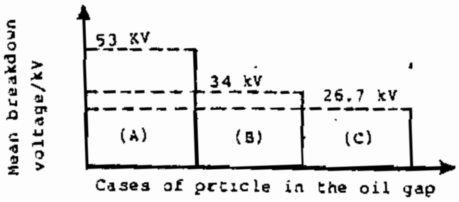

Fig. 2. Comparison between the mean breakdown voltages in different cases: (A) Oil gap without particle, (B) With a fixed particle, (C) With a suspended particle.

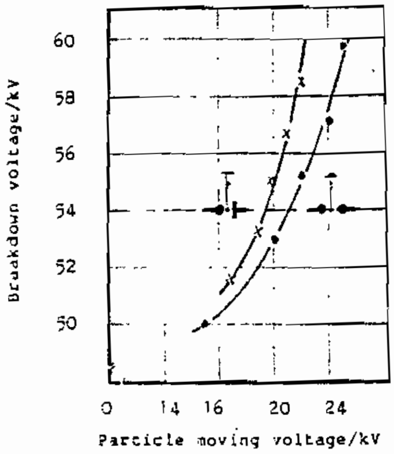

Fig. 3. Breakdown voltage versus particle moving voltage. for a 1 cm gap in presence of 1 mm diameter suspended particle.

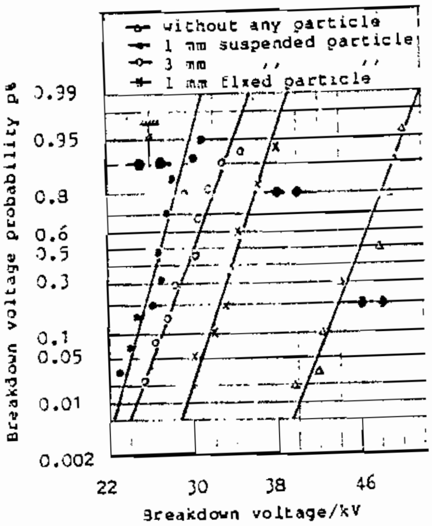

Fig. 4. Breakdown voltage probabilities for a 5.5 mm oil gap.

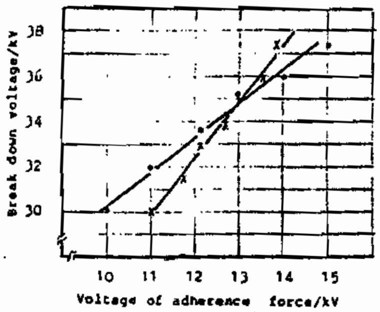

Fig. 5. Breakdown voltage versus adhered voltage.

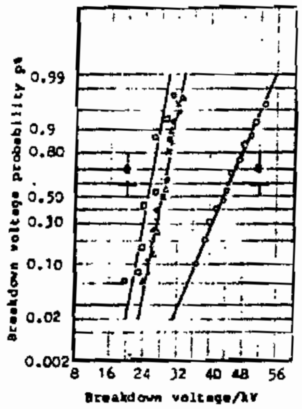

Fig. 7. Breakdown voltage probabilities for 3-cases: a)without any particle
b) with resting particles of 3 mm -•- 1P, -•- 2P, -o- 4P
c) with resting particle of 1 mm -o- 1P.

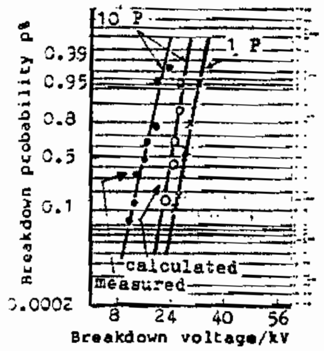

Fig. 9. Comparison between the experiment and estimated breakdown probability using the magnification law for n number pariclea.

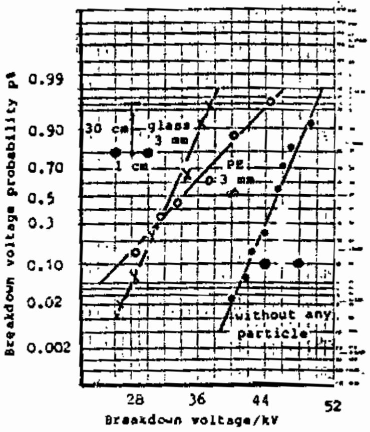

Fig. 6. Breakdown voltage probabilities for both suspended dielectric particles (PE and glass).

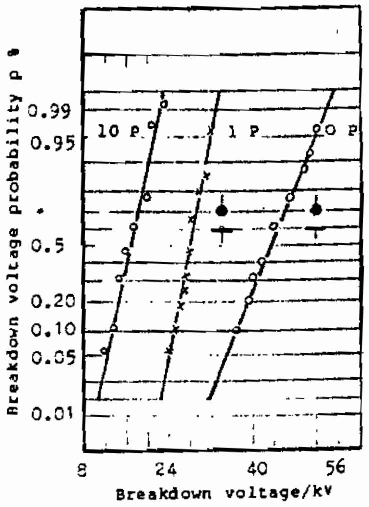

Fig. 8. A comparison between voltage probabilities. a)with particle b)with 1P, and with number of particlea (10 P).