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STATISTICAL ANALYSIS OF ELECTRICAL AND MECHANICAL BREAKDOWN STRESS FOR INSULATION PERFORMANCE IN HIGH VOLTAGE POWER TRANSFORMER

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Original scientific paper
In electrical power system, variety of solid, liquid and gaseous materials are used for insulation target to protect the incipient failure inside the high voltage power transformers. The insulation is practically ended when the insulation system has become fragile enough to flourish cracks under the electrical and mechanical stresses to which it is subjected. The electrical and mechanical stresses are induced by short circuit currents, thermal expansion and contraction of the conductors and vibration. The dielectric strength of insulation is not vitally diminished by brittleness alone, but electrical breakdown will rapidly follow the improvement of ensuing cracks. The purpose of this paper is to briefly cover the methods favourable for determining the insulating value of the insulation on high voltage power transformer windings and bushings. Many failures of insulation are caused by the entrance of moisture. Insulating materials used on high voltage power transformer windings have a high affinity for moisture from the surrounding atmosphere or oil. Effects of the stressed oil volume and stressing time on the breakdown stress of high voltage power transformer insulation were experimentally investigated. The factors influencing the effects and the results obtained based on them were statistically analysed and systematized by the Weibull distribution method. A Four-dimensional volume theory allowing good estimation of breakdown stress in terms of specific probable values has been established.

Keywords: *breakdown stress, high voltage insulation, power transformer, Weibull distribution method*

Statistička analiza učinka električne i mehaničke probojne čvrstoće na karakteristike izolacije kod transformatora snage visokog napona

Izvorni znanstveni članka
U elektroenergetskom se sistemu koristi niz krutih, tekućih i plinovitih materijala za izolaciju u svrhu zaštite od početnog proboja u transformatorima snage visokog napona. Izolacija praktički više ne postoji kad izolacijski sistem postane toliko krhak da se pojave napukline kod električnih i mehaničkih naprezanja kojima je izložen. Do električnih i mehaničkih naprezanja dolazi zbog struje kratkog spoja, termalne ekspanzije i kontrakcije vodiča te vibracije. Dijalektrička čvrstoća izolacije vitalno se ne smanjuje samom krhkošću, već će električni proboj uslijediti ubrzo nakon poboljšanja nastalih pukotina. Svrha je ovoga rada ukratko dati pregled metoda koje pomažu određivanju vrijednosti izolacije na namotima i uvodnicama transformatora visokog napona. Do mnogih kvarova izolacije dolazi zbog vlage. Izolacijski materijali na namotima transformatora visokog napona lako upijaju vlagu iz okolne atmosfere ili ulja. Eksperimentalno su istraživani učinci volumenskog napona ulja i vremena napona na probojnu čvrstoću izolacije transformatora visokog napona. Faktori koji djeluju na učinke i dobiveni rezultati statistički su analizirani i sistematizirani Weibull metodom distribucije. Postavljena je Četiri-dimenzijska teorija volumena koja omogućuje dobru procjenu napona kod električnog proboja u odnosu na moguće specifične vrijednosti.

Ključne riječi: *izolacija visokog napona, probojna čvrstoća, transformator snage, Weibull metoda distribucije*

1 Introduction

Nowadays, going on increasing in scale is requiring still higher voltage and power transformers; 500 kV, 250 MVA units have already been put to service. It is expected for electric power sources in future to be located much farther from service areas and to be much larger in capacity. In view of this situation, researches have already started to develop power transformers capable of bearing 1000 kV, a voltage presumed for next stage. On the other hand, the conditions of location for substations have become worse year by year. This places more severe requirements for transportation, which necessitates smaller size of equipment. It is required of the equipment to have much higher reliability because its failure might give a grave consequence to the community [1]. So a lot of electrical equipment production corporations have been positively engaged in theoretical analyses and fundamental studies on such problems as insulation, countermeasures against stray load loss caused by electromagnetic force, leakage magnetic flux and effective internal cooling of power transformers [2] and applied the results of these analyses and studies to actual equipment in order to grasp the problems observed as the result of the application and to inspect the performance of the objective equipment.

An oil immersed power transformer has complex insulation structure composed of mineral oil and solid dielectrics [3 ÷ 5]. It is well known that, in such a power transformer, the partial discharge inception and dielectric breakdown will be predominantly affected by the breakdown strength of the insulating oil. Therefore, power transformer designers should have explicit figures regarding the stress exerted on the power transformer oil and the breakdown stress of the oil. Calculating techniques of stress exerted on the oil have made remarkable progress in recent years, but estimating techniques of breakdown stress seem to involve many problems to be solved.

Breakdown stress of power transformer insulation cannot be easily estimated because of its likelihood of fluctuating and dispersing. Probably, these phenomena are caused by the presence of a measurable amount of impurities in the power transformer oil. Insulating oils used in power transformers contains 10 to 10 000 pieces of solid impurities per 100 ml [4 ÷ 7]. These impurities, considered to be factors causing discharges in the oil, thus demonstrate the probabilistic phenomena, such as the stressed oil volume effect or stressing time effect on the breakdown stress. I experimentally investigated these factors and effects on the breakdown of power transformer insulation, and systematized them on a statistical basis. The efforts have now led the work to the establishment of a four dimensional volume theory which is the concept allowing breakdown stress of power transformer insulation to be estimated with high accuracy in terms of specific probable values. This study reports some of the research achievements as to insulation techniques for high voltage power transformers, which constitute the basis for rational design contributing to the improvement of their reliability and ability to bear higher voltage, and to the solution of the problem of limitations on their size.

2 Volume effect on breakdown stress of power transformer insulation

Insulating oil has long and widely been used as the excellent insulator, but there still are many unknown factors in its dielectric breakdown mechanism and no definite theory on it has been established. As far as permitted from an economic point of view, the insulating oil used in a power transformer is refined and filtrated industrially and then is sealed in the power transformer fabricated and assembled under high level dust control. However, no oil can be absolutely free from dust and impurities when it is sealed in. For high reliability design of an oil insulated power transformer, it is very important to know the effects of the impurities contained in the oil on its dielectric breakdown characteristics, and the field intensity that causes the oil used in normal state to dielectrically breakdown [6]. In addition, the designer should grasp these data both with precision about values and understanding of the condition of dispersion. A series of surveys have disclosed the following [8 ÷ 12];

The dielectric breakdown probability distribution of oil gaps may be considered normal if the probability ranges from 10 % to 90 %. However, when a breakdown probability less than several per cent, important for insulation design, is considered as a problem, it seems more appropriate to use a Weibull distribution.

The shape parameter of the Weibull distribution, which is an index for the size of dispersion, is 15 ≈ 22 for the lightning impulse region, 19 ≈ 67 for the switching impulse region, and 15 ≈ 39 for alternative current system. This signifies that greater dispersion occurs for longer time of voltage application.

For alternative current system, a dielectric breakdown is likely to occur immediately after voltage is applied. It is for this reason that the $V-t$ curve becomes flat in the long time range.

2.1 Theoretical volume effect

As described in the previous section, the power transformer oil contains a large number of impurities that can become a factor causing its breakdown. Hence, breakdown model is assumed based on the concept that breakdown will occur at the weakest point.

1. If a uniform field oil gap is divided into equal volume units, they have the same probability of breakdown.
2. The breakdown of any one micro unit resulting from such equal division triggers the breakdown of other units, leading to that of the entire gap.

If the probability of breakdown for the entire oil gap is P and that of each volume unit is P_0, then equation 1 is justified from the multiplication theorem of probability based on the above assumption 2.

$$1-P=(1-P_0)^V. \tag{1}$$

If the gap is split into the possibility smallest units, the above equation can be rewritten as Eq. (2) below;

$$In(1-P)=-VP_0, \tag{2}$$

where, P_0 can be expressed in terms of a function of stress E, that is, $P_0 = f(E)$ [11]. Weibull perceived that this relation could be approximated to a gradually increasing curve, and substituted $(E/E_1)^m$ for P_0. In this term, E_1 is a constant that determines the substantial strength of material, called "scale" parameter, and m is a coefficient regarding to the uniformity of micro defects, called "shape" parameter [12 ÷ 17]. Therefore;

$$In(1-P)=-V\left(\frac{E}{E_1}\right)^m. \tag{3}$$

The probability density function can be given by Eq. (4) which results from p being differentiated by E [9];

$$g(E)=\frac{V}{E_1^m}mE^{m-1}\exp\left[-V\left(\frac{E}{E_1}\right)^m\right]. \tag{4}$$

Fig. 1 shows breakdown stress distributions relative to parameter m with E_1 and V normalized to 1.

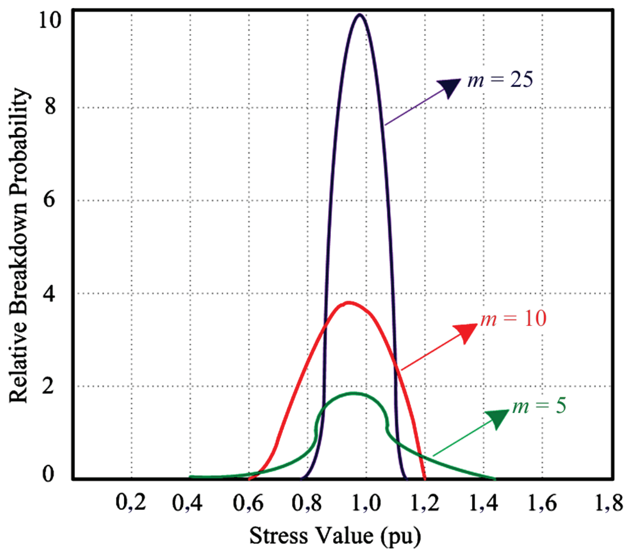

Figure 1 Relativebreakdown stress distributions

As can be understood from this graph, the sharpness of distribution depends on parameter m and the distribution itself is asymmetric between the right and left with a spreading skirt of lower stress. Nearly normal distribution is obtained in the range of m between 8 and 12. The average distribution E_g that can be given by Eq. (4), and the variation factor σ are given by Eqs. (5) and (6), respectively:

$$E = \int_0^{+\infty} E_g(E)\mathrm{d}E = D_1(V)^{-\left(\frac{1}{m}\right)} \lambda\ell\left(\frac{1}{m}\right), \tag{5}$$

$$\sigma = \sqrt{\frac{\lambda\ell\left(\frac{2}{m}\right)}{(\lambda\ell)^2\left(\frac{1}{m}\right)} - 1}, \tag{6}$$

where, $\lambda\ell$ (1/m) is a Gauss law $\lambda\ell$ function. Theoretical volume effect of breakdown stress is shown in Fig. 2.

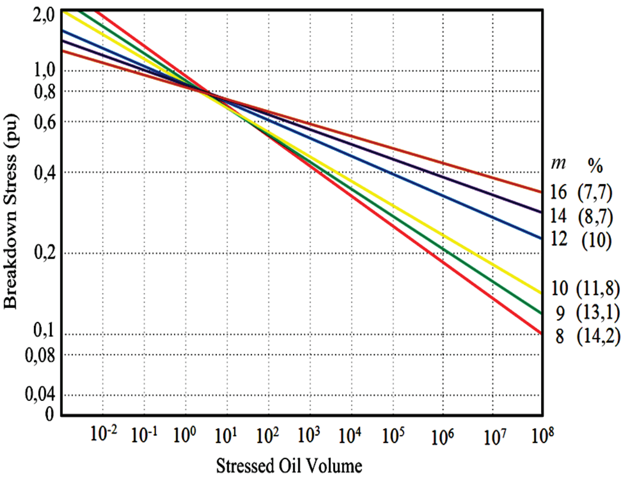

Figure 2 Theoretical volume effect of breakdown stress

This implies that, as indicated in Fig. 2, the average breakdown stress of volume V is reversely proportionate to (1/m) of V. The m in this term can be given by a function of the oil breakdown variation coefficient as is shown in Eq. (6). Dispersion of oil breakdown stress is said to be 10 to 15 % in terms of the variation coefficient σ, which corresponds to 8 to 12 in terms of parameter m. In other words, if m = 10 (equivalent to 11,8 % in terms of σ), the breakdown stress will reduce to 40 % when the stressed oil volume increases 10 000 times (See in Fig. 2). According to Eq. (5), the breakdown stress will decrease infinitely as the volume increases infinitely. Physically, however, there is a certain limit to the reduction of breakdown stress. Eq. (7) represents a theoretical volume effect involving the location parameter E_0 which is defined in Weibull distribution [15].

$$E = E_0 + (E_1 - E_0)\cdot V^{-\frac{1}{m}}, \tag{7}$$

where, E_0 is a converged value of breakdown stress when the stressed oil volume is infinite, in other words average breakdown stress cannot be lowered less than E_0.

2.2 Effects of impurities in power transformer oil

Since the oil in a power transformer is streaming, minute impurities may safely be considered to be straying in the oil. Thus, the effects of impurities in the oil on the power transformer insulation should be elucidated in terms of the relationship of them with the oil flow [10]. Fig. 3 shows the result of the streaming characteristics of dielectric breakdown of a coaxial cylindrical oil gap (⌀90 × ⌀110 × 300 mm), with the filtration accuracy used as the parameter.

In each of the curves, higher breakdown voltage occurs in the normal velocity range of oil flow (at the point of 7,5 cm/s) than in the case of still oil. The cause is that the bridged impurities are carried away by the oil flow. In the high velocity area, a reduction in breakdown voltage occurs and this is contributed by an increased volume of impurities passing through the electrodes, i.e., the volume effect. The short time during which the impurities are passing through the electrodes also helps the breakdown voltage rise, but the volume effect gives a greater influence. It is understood that a certain reduction in breakdown voltage will result as the combined effect.

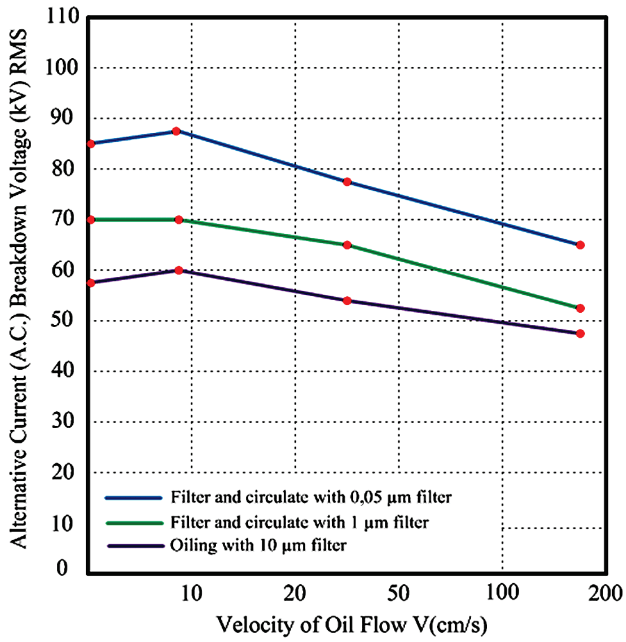

Figure 3 Velocity of oil flow A.C. breakdown voltage of oil gaps

Curves (circulate with 0,05 μm filter and circulate with 1 μm filter) of Fig. 3 show breakdown voltages raised by the control of impurities straying in oils; obviously, the volume of impurities in oil has big effects on its breakdown voltage. It may safely be said that all of these results verify the concept that, in the volume theory regarding oil breakdown, impurities straying in the oil gap are one of the factors for breakdown.

2.3 Experimental results

In order to investigate what volume effects could be expected for uniform field oil gaps, breakdown stress was experimentally measured with the stressed oil volume varied in the range from 10^{-7} to 10^{6} (cm^3) by changing the size of Rogowski oil gaps [13 ÷ 18]. The breakdown stresses were measured for the lightning impulse, the switching impulse, the ramp function voltage, the one minute, and the 30 minute alternative current voltages. The experimental results are shown in Figs. 4 and 5, accompanied by regression equations approximated by Eq. (7).

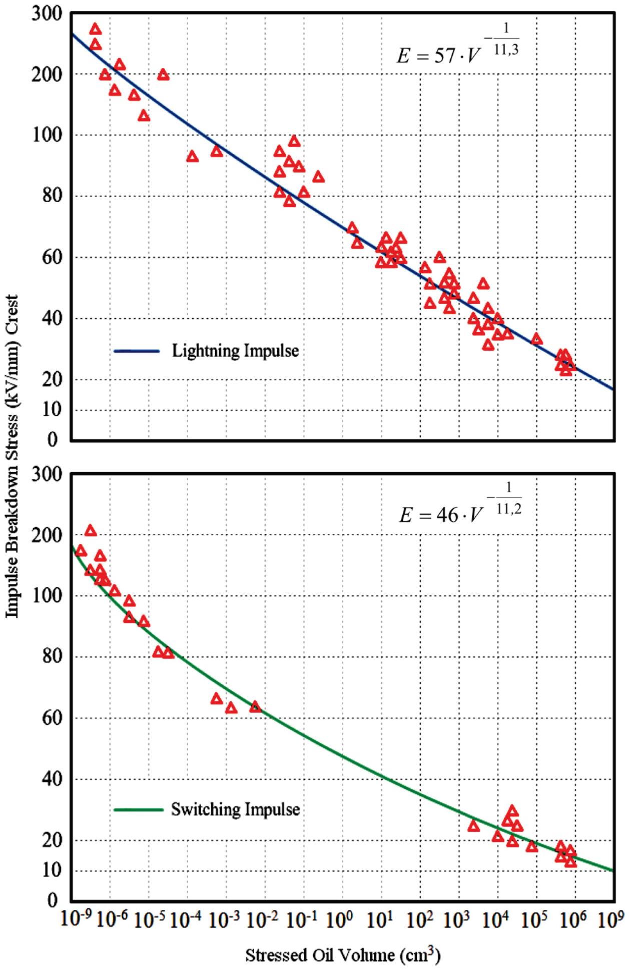

Figure 4 Stressed oil volume of impulse breakdown stress

They show that breakdown stress does not converge in the case of lightning impulses or switching impulse voltage, but converge at around several kV/mm in the case of alternative current (A.C.) voltages. The empirical formula on the stressed oil volume and the breakdown stress of power transformer oils are listed in Tab. 1

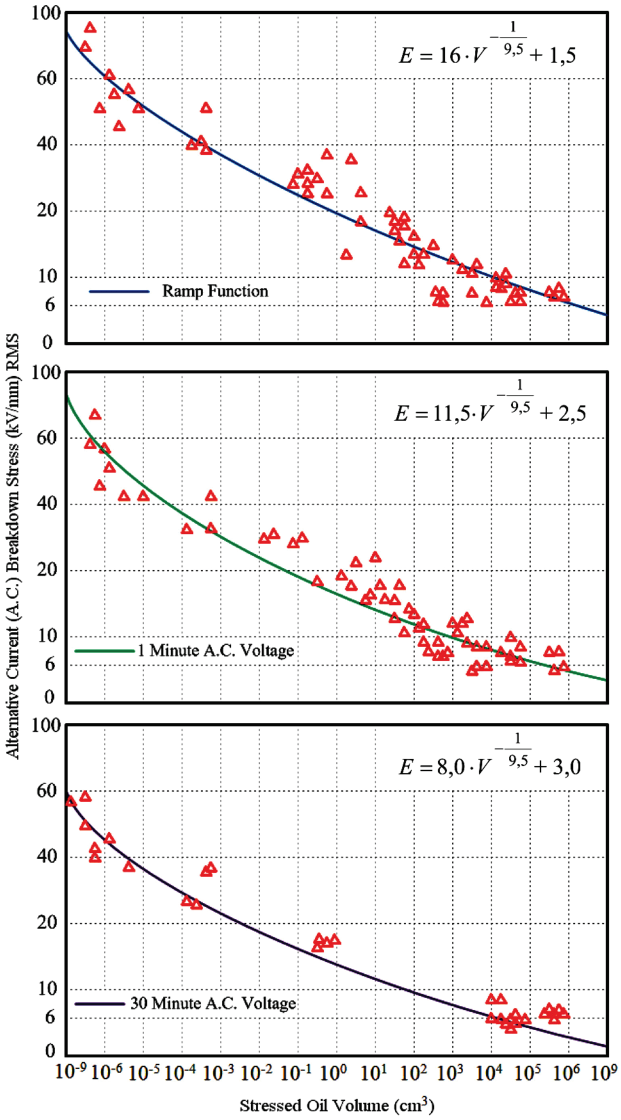

Figure 5 Stressed oil volume of alternative current (A.C.) breakdown stress

Table 1 Regression equations of volume effect on breakdown of power transformer oil

Voltage		Regression Linear Equations	Shape Parameter / m	Scale Parameter F_r / kV/mm	Position Parameter E_0 / kV/mm
Impulse	Lightning	$E = 57 \cdot V^{-(1/11,3)}$	11,3	57	–
	Switching	$E = 46 \cdot V^{-(1/11,2)}$	11,2	46	–
Alternative Current (A.C.)	Build up Method	$E = 16,0 \cdot V^{-(1/9,5)} + 1,5$	9,5	17,5	1,5
	1 Minute Method	$E = 11,5 \cdot V^{-(1/9,5)} + 2,5$	9,5	14,0	2,5
	30 Minute Method	$E = 8,0 \cdot V^{-(1/9,5)} + 3,0$	9,5	11,0	3,0
Direct Current (D.C.)	Build up Method	$E = 11,25 \cdot V^{-(1/10,95)} + 2,75$	10,95	14,0	2,75
	1 Minute Method	$E = 6,35 \cdot V^{-(1/10,95)} + 3,25$	10,95	9,6	3,25
	30 Minute Method	$E = 5,25 \cdot V^{-(1/10,95)} + 2,75$	10,95	8,0	2,75

Calculation of the stressed oil volume from the above mentioned test data enables the dielectric breakdown voltage of oil gaps to be estimated from the equations shown in Tab. 1. This concept is called the volume theory [14]. Such volume effects are caused by the fact that dielectric breakdown is based on the weakest point theory; as the stressed oil volume increases the breakdown voltage becomes low in probability because of the presence of impurities straying in the oil.

For 1 minute alternative current (A.C.) voltage, the breakdown stress is 70 kV/mm if the stressed oil volume is 10^{-7} cm^3, but reduces to 5 kV/mm for a 10^6 cm^3 stressed oil volume. From these findings it is understood that breakdown stress of power transformer insulation depends on a stressed oil volume [10 ÷ 16]. Conversely, calculation of a stressed oil volume permits us to estimate the breakdown stress to be estimated. It has been accepted that the breakdown stress for non-uniform field oil gaps presents curves nearly similar to those shown in Figs. 4

and 5. Here, the stressed oil volume of non-uniform field oil gap means the oil volume where the stress is in excess of 90 % of the maximum stress.

3 Insulation inside the power transformer winding

A problem which has long been wrestled with is how to predict a potential occurring inside the power transformer winding when impulse voltage is applied to it. However, when the power transformer winding has non-uniform inductance and/or capacitance, or when the power transformer has many windings, the prediction cannot but rely on numerical analysis; this field of technique has made great strides along with the expanded use of computers.

3.1 Electric field calculation

Conventional field mapping technique is based on the finite element method and the charge-simulation method. The procedures for calculation are as follows:

1) A power transformer winding is given in terms of an equivalent circuit which consists of self – inductance, mutual inductance, series capacitance, and parallel capacitance. Equivalent circuit for power transformer winding is shown in Fig. 6.
2) Circuit constants of the equivalent circuit are determined from the data of the windings, and circuit equations are formed.
3) The circuit equations represented in terms of simultaneous differential equations are numerically analysed.

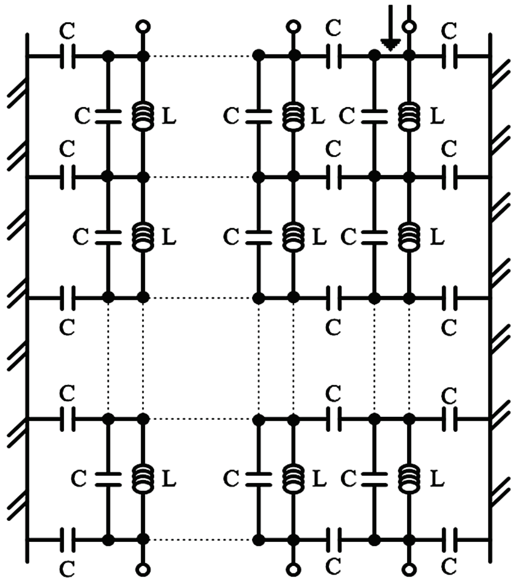

Figure 6 Equivalent circuits for power transformer winding

The above-mentioned calculation can be applied to power transformers with complicated winding structure and to the case where impulse voltage of non-standard waveform is applied to windings. The technique thus demonstrates its full capabilities in improving the reliability of power transformer insulation in its interior windings.

Electric field calculation by charge-simulation method is shown in Fig. 7. It provides direct calculation of electric fields from virtual charges superposed inside the electrode, the quantity of such charges being selected so that the required electrode shape may have a certain potential. The method if suitably applicable to the calculation of a two dimensional or revolving symmetrical field [19] where there are few insulating media, is particularly characterized by the fact that a local field can be calculated with high accuracy by arranging charges densely in that location.

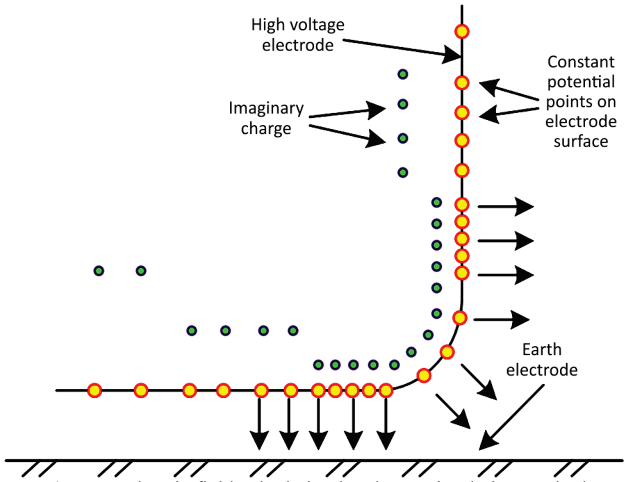

Figure 7 Electric field calculation by charge simulation method

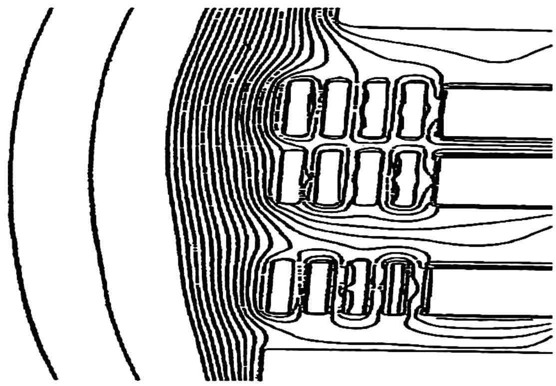

Figure 8 Potential distributions within disc winding

Another big feature of the method is the short time required for calculation because it involves no repetitive calculation. In contrast, the finite element method was initially used for structural analysis and has recently been applied to the analysis of electric/magnetic fields [20]. It is suitable for field analysis where there are many insulating media, and complicated electrode shapes are used, or space charges must be taken into account. Figure 8 gives an example of calculation, by the charge simulation method, of electric fields at the section ends of an interleaved disc winding when lightning impulse voltage is applied to it.

A significant concentration of electric fields is observed at the section end because of the superposition of radial and axial fields. The fact that it has become possible to grasp localized fields within windings is very meaningful for applying impulse breakdown characteristics in localized regions within windings to the design of real power transformer units.

3.2 Impulse corona

Fig. 9 shows the corona starting voltage and breakdown voltage characteristics of a turn to turn insulation model.

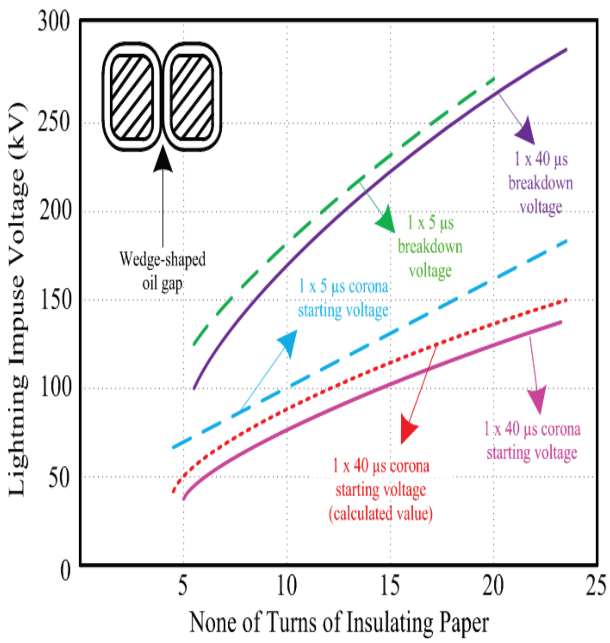

Figure 9 Impulse corona breakdown characteristics of turn insulation

The curves of breakdown voltage for 1 × 5 µs and 1 × 40 µs, nearly agree with each other, but the corona starting voltage for 1 × 5 µs is about 1,3 times greater than that for 1 × 40 µs. The ratio of corona starting voltage to breakdown voltage is 55 ≈ 70 % for 1 × 5 µs and 45 ≈ 60 % for 1 × 40 µs [14 ÷ 17]. This may be attributable to the fact that, whereas the corona starting voltage depends on the oil breakdown in the wedge shaped portion between turns, and its *V*−*t* characteristics follow those of the oil, the breakdown voltage depends on the withstand voltage of the paper and its *V*−*t* characteristics follow those of the paper. The electric fields applied to the wedge shaped oil gap calculated by the charge simulation method for two insulation media are shown in Fig. 9. They agree well with the measured corona starting voltage data. This signifies that the above mentioned concept holds true.

Fig. 10 shows the ratio of corona starting voltage to breakdown voltage of an inter coil insulation model, with the proportion of the insulating paper to the insulation distance between sections plotted on the abscissa. 100 % on the abscissa corresponds to the turn to turn insulation model [13]. As the proportion of the oil path between sections increases, the ratio of corona starting voltage to breakdown voltage comes close to unity.

In regard to these impulse corona characteristics between coils sections, too, it has been confirmed that, from the correspondence with the result of calculation of field mentioned above, the corona starting stress is 30 ÷ 40 kV/mm in the normal conductor insulation range, and that it is in a proportionate relation of $R-1/n$ with the rate of conductor insulation increase. From the above discussion, it may well be said that designers cannot offer high reliability power transformers incorporating properly designed interior insulation without the use of calculations for voltage transition and electric fields as well as inter coil insulation characteristics.

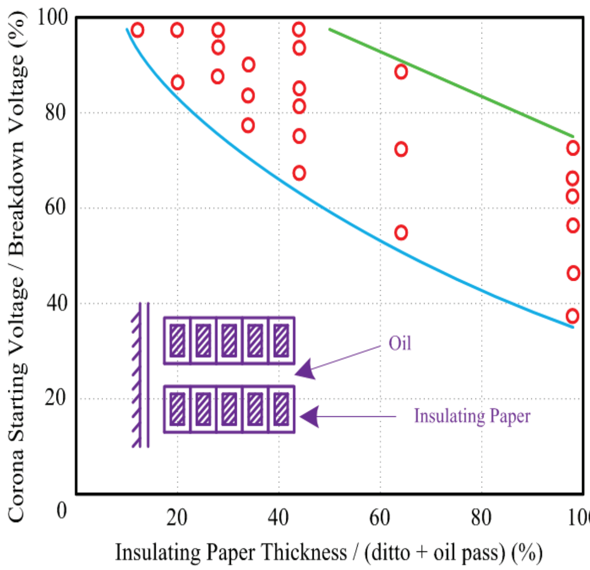

Figure 10 Impulse corona levels of inter coil insulation

4 Insulation around the power transformer winding

4.1 Insulation of leads

It has already been elucidated that the insulation of leads can be systematically analysed by the volume theory. By rearranging this in terms of relations between the size of the leads and breakdown stress, one can find that, as shown in Fig. 11, there exists one constant factor n, for both bare and insulated leads, which is given by the Eq. (8).

$$E = K \cdot R^{-\frac{1}{n}}. \tag{8}$$

Fig. 12 shows the difference in breakdown voltage between 100 samples each of bare and insulated leads in the normal volume range. For the insulated samples, in order to check the effects of the grounded side, comparative examination was made between two cases of the grounded side with and without insulation barriers. From Fig. 12, it is understood that a difference is seen in breakdown voltage between insulated and bare high voltage electrodes even for the same volume.

In the case of bare leads, transfer of charges between impurities and the surface of electrodes seems to have an effect on breakdown voltage levels. For the grounded side, on the other hand, the presence or absence of barriers makes no significant difference in terms of average values. However, the dispersion remains unchanged at the minimum value but becomes greater at the maximum value for leads having barriers. This is attributable to the fact that higher stress increases the probability of breakdown on the grounded side. Such a phenomenon is more conspicuous when the test is conducted with larger sized leads.

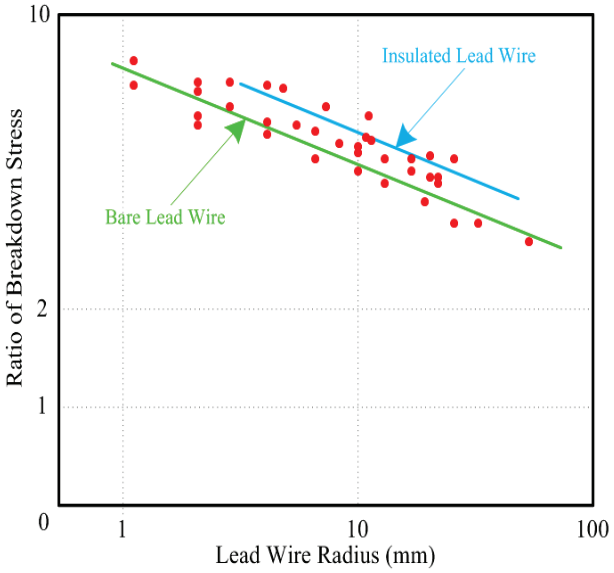

Figure 11 Breakdown characteristics of leads

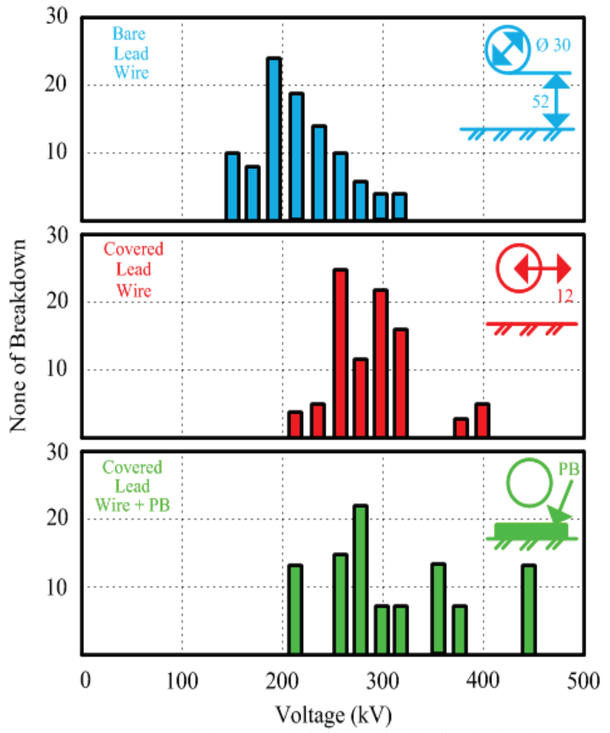

Figure 12 Breakdown probabilities distribution in leads

In an example of leads having a size of 90 mm with a distance of 33 mm, the presence or absence of insulation on the high voltage side gives no effect on the breakdown voltage level, but the insulation on the grounded side seems to make breakdown voltage higher. The effect of insulation applied to electrodes tends to become greater as electric field concentrates on the electrode, and to become smaller as the field is unified. For high voltage leads, the insulated leads are surrounded with insulation barriers to segregate the oil [8 ÷ 21], thereby improving its breakdown characteristics. As generally known, a smaller oil gap between barriers will increase the oil breakdown stress, being nearly proportional to $d^{(-1/3)}$.

4.2 Ground insulation

Since the insulation between the coil and tank breaks down in a nearly uniform field oil gap, the data obtained by the volume theory covering up to a huge amount of oil can be applied to the insulation between the coil and tank. However, since the coil side is insulated, breakdown voltage levels depend greatly on the condition of the grounded electrode. Consider, as an example, a tank whose inner wall is coated. The mean breakdown value will not be much influenced by presence or absence of coating, coating materials, and coating technique. But a defect on the coated surface may increase the dispersion of breakdown voltage, decreasing the minimum breakdown value. When the tank is coated with magnetic shielding, the effect of the silicon steel band edge will reduce the breakdown voltage as compared with a flat wall. Therefore, in case magnetic shielding is to be applied to high voltage power transformers, various techniques are contrived for preventing decrease in breakdown voltage.

5 Breakdown distribution of power transformer insulation and *V* – *t* curves

5.1 Four dimensional volume theory and equal probabilistic *V* – t characteristics

A four dimensional volume theory can be derived from the volume effect of breakdown stress, $V\!-\!t$ characteristics and probability distribution. Fig. 13 shows four dimensional volume theory concepts. Now obtainable from this chart are p % breakdown probability stresses for stressed oil volume of V_1 with duration time t_1.

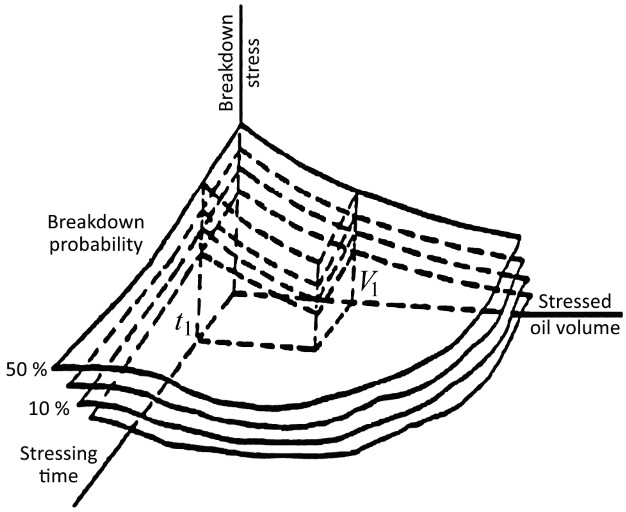

Figure 13 Four dimensional volume theory

Breakdown probability distributions for each voltage applied for the five different durations were obtained as mentioned in above section. From these distributions, equal probabilistic $V\!-\!t$ characteristics could be obtained. Fig. 14 shows the $V\!-\!t$ characteristics plotted on a full logarithmic chart.

It may safely be concluded that the $V\!-\!t$ characteristics at low breakdown probability are parallel with those at 50 % probability. As shown in Fig. 14, the breakdown voltage of oils reduces with a certain gradient for the initial 10 minutes but the gradient becomes flat thereafter. The gradient of the V–t curves is shown by time range (n) of Eq. (9), and is listed in Tab. 2.

$$V = t^{-\frac{1}{n}}. \tag{9}$$

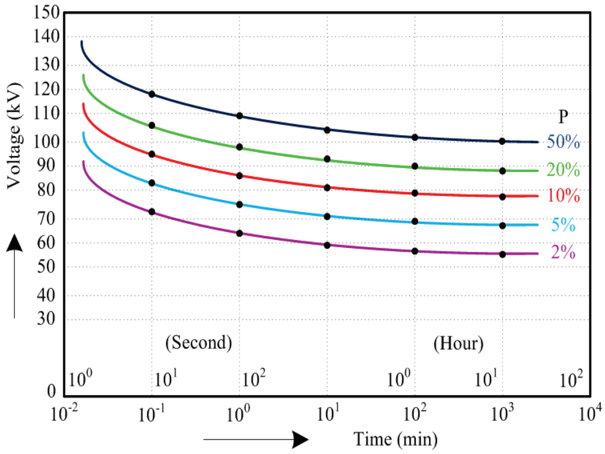

Figure 14 Equal probabilistic V–t characteristics of oil

Table 2 The gradient n of V–t characteristics of oil

Time Range	10 second 1 minute	1 minute 10 minute	10 minute 1 hour	1 hour 10 hour
n	18	18	21	37

Tab. 3 provides p % breakdown probabilistic voltages for each holding time with the 50 % breakdown probability voltage (applied for one minute) normalized to 1,0.

Table 3 Normalized breakdown voltages of transformer insulation

Durations of test voltage		10 second	1 minute	10 minute	1 hour	10 hour
P Risk of failures	50 %	1,11	1,00	0,88	0,81	0,76
	10 %	0,88	0,78	0,69	0,63	0,59
	5 %	0,80	0,71	0,63	0,58	0,54
	3 %	0,75	0,67	0,59	0,54	0,51
	2 %	0,71	0,63	0,56	0,51	0,48
	1 %	0,65	0,58	0,51	0,47	0,44
	0,5 %	0,60	0,53	0,46	0,43	0,40

5.2 Oil breakdown probability distributions

Probability distributions of breakdown stress for the oils artificially maintained in the same condition as on site power transformer oils were investigated. The oil gap under test was that of Rogowski; 250 mm in diameter and 10 mm in length [18]. Applied alternative current (a.c.) voltage (50 Hz) was increased rapidly to the target level, maintained at the same level for a certain time, and then lowered to zero. The target voltage was held for five different durations; 10 seconds, 1 minute, 10 minutes, 1 hour, and 10 hours. Voltages in the same mode were applied 100 to 500 times, and a breakdown stress probability distribution was measured for each voltage. Close analysis of the distributions obtained has shown that they present a good match if approximated by the Weibull distribution which can be given by Eq. (10).

$$P(V) = 1 - \exp\left[-\left(\frac{V}{V_1}\right)^m\right]. \tag{10}$$

The two parameters in Eq. (10); m and V_1 were obtained as shown in Tab. 4.

Table 4 Estimated parameters of Weibull distribution

Durations of test voltage	m	V_1
10 second	8,05	131,6
1 minute	7,70	119,0
10 minute	7,60	104,6
1 hour	7,75	96,0
10 hour	8,35	90,2

The Weibull distribution function in Eq. (10) can be given linearly on probability chart. Fig. 15 shows real data plotted on Weibull probability chart.

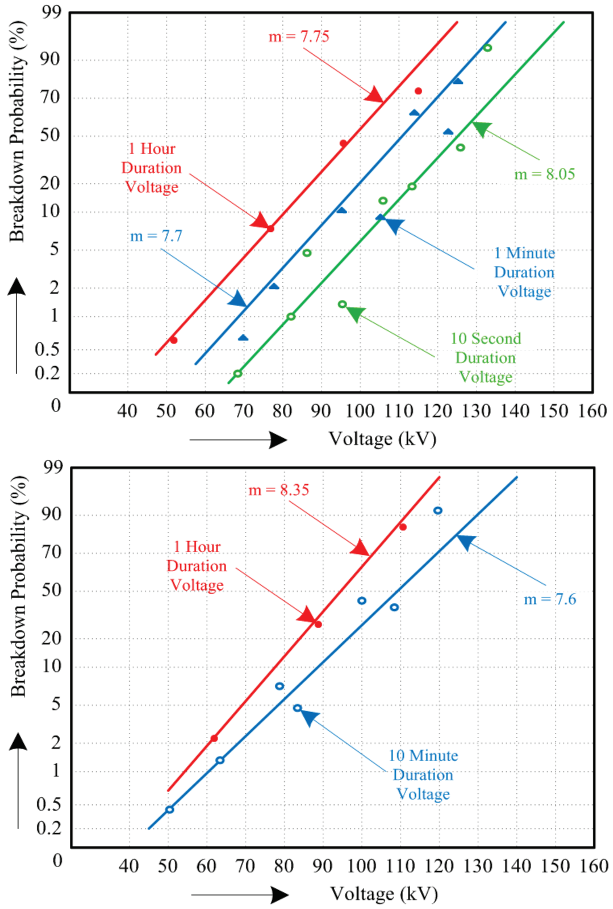

Figure 15 Breakdown probability distribution of uniform field oil gap

6 Conclusion

The shape parameter α appearing in Tab. 4 and Fig. 15 signifies the gradient of regression lines on the Weibull chart. In other words, this parameter gives the spread of the probability distribution (or the magnitude of dispersion). As shown in Fig. 15, m is some 8,0 (equivalent to 14,2 % in terms of variation coefficient) and seems to be rather independent of the voltage holding time.

The total experience of oil absorbed power transformers hinges on the long period experience of the oil paper isolation system from first to last continuous function. Studying the credibility evaluation procedures for oil paper isolation is able to help designate the credibility level of power transformers exactly, and assure their reliable and stable function. All of the measurements indicate that both depolarization and polarization currents are severely impressed by water content of oil and paper and ageing time. The consequences have informed that maximum compensatory voltage of paper/oil isolation system and tensile strength of paper isolation in power transformers alter significantly and permanently according to ageing temperatures and ageing time.

The Weibull distribution credibility curve cluster of oil paper isolation is sketched under several conditions by which an oil paper isolation credibility evaluation procedure is suggested. In order to obtain substantially compact yet highly reliable power transformers, the most authoritative approaches have been exercised; first, grasping the basic insulation characteristics for potential and field calculation and for expanded application to actual design efforts, and next, determining most appropriate insulation structures and verifying them on full scale models. Incessant efforts will continue to develop more satisfactory insulation techniques and to fabricate power transformers with higher reliability. Recently, the combined technique of electric field calculation and the volume theory has made it possible to design power transformer with very sophisticated insulation structures.

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