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VOLTAGE ENDURANCE OF EPOXY MOLD INSULATION AND EVALUATION OF ITS LIFETIME

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I. INTRODUCTION

Understanding insulation characteristics and voltage endurance lifetime of epoxy resins is very important both for reliability evaluations and reasonable insulation design of high voltage power apparatus. For this purpose, various types of voltage endurance test on epoxy molds have been performed.

However, for the voltage endurance test, theory of electrical deterioration similar to reaction kinetics (Arrhenius law) in thermal deterioration tests is not yet established. Deterioration mode depends on the type of insulation and applied voltage. This test needs a very long time and empirical considerations for estimation of the lifetime. Therefore, a fast and accurate lifetime evaluation method must be established as soon as possible.

In recent years, progress has been made in understanding the electrical deterioration process in mold insulation[1]. Also a considerable amount of data on the voltage endurance, i.e., *V-t* characteristics, have been accumulated. The authors have compiled published *V-t* characteristics data in view of accelerated testing methods and have found features and laws in such characteristics.[2],[3],[4]

This paper presents some of Fuji Electric's research in this field.

First, the statistical treatment of the *V-t* characteristics is explained, and then *V-t* characteristics patterns and laws of their characteristic exponent in various types of voltage deterioration phenomena are described. A few results of voltage endurance tests for various epoxy molds are also presented.

II. STATISTICAL TREATMENT OF *V-t* CHARACTERISTICS

1. Expression of *V-t* Characteristics

When the *V-t* characteristics are plotted on full logarithmic graphs, they are, in many cases, approximated either by a straight line or by a bent line with one or two bends[2]. Due to such super-linear relation, the *V-t* characteristics can be expressed by the following empirical formula.

$$t = K\,V^{-n} \qquad \text{(1)}$$

where: t: lifetime
V: applied voltage
n: characteristic exponent; a constant showing the slope of the straight line in the full logarithmic plots, which is determined by the insulation structure and deterioration factors.
K: constant

In foumula (1), also field E may be used instead of voltage V. In many cases better fitting to measured values is obtained, when (V-V_s) or (V/V_s) is used for V in cosideration of the partial discharge (corona) starting voltage V_s.

However, the Weibull distribution analysis as reliability engineering practice has recently been sucessfully applied to the reliability evaluation of insulation. The inverse n power law (1) is obtained by mathmatical reduction from this Weibull distribution[5]. A Weibull distribution with two random variables, voltage V and time t, can be shown by the following equation:

$$F(V,t) = 1 - \exp\left[\,-\left(\frac{V}{V_o}\right)^{m_v}\left(\frac{t}{t_o}\right)^{m_t}\right] \qquad \text{(2)}$$

where: $F(V.t)$: cumulative breakdown probability
m_v: Weibull form parameter related to voltage V
m_t: Weibull form parameter related to time t
V_o, t_o: constants

When the relation between V and t at a certain cumulative breakdown probability is obtained from equation (2), the following equation can be obtained for constant cumulative breakdown probability.

$$V^{m_v} \cdot t^{m_t} = K \qquad \text{(3)}$$

This can be transformed to:

$$t = K V^{-m_v/m_t} \qquad \text{(4)}$$

When $m_v/m_t = n$, it becomes equation (1).

The *V-t* characteristic shown by equation (1) is known as the inverse n power law. Since the inverse n power law is empirical, its physical meaning is not clear yet. However, the deterioration phenomena which cumulatively progresses in accordance with n power of the stress have been empirically recognized generally in various fields besides electrical deterioration.

2. Acceleration Factors in Voltage Acceleration Tests

When voltage endurance tests are performed, frequency and voltage accelerations are normally used. The acceleration factor in the case of frequency acceleration is known to be given by the frequency ratio (test frequency/operating voltage frequency).[1]

Accroding to the inverse n power law, the acceleration factor can be obtained quantitatively as follows.[2]

When t_1 is an expected lifetime for an operating voltage V_1, a lifetime t_2 for another acceleration voltage $V_2 (=aV_1)$ is expressed as follows:

$$t_1 = KV_1^{-n} \qquad \text{(5-1)}$$

$$t_2 = K(aV_1)^{-n} \qquad \text{(5-2)}$$

From these relations, t_1 and t_2 is related as follows:

$$t_1 = a^n t_2 \qquad \text{(6)}$$

The acceleration factor for the acceleration test performed at a voltage aV_1 is given as a^n.

Table 1 shows calculated values of the voltage acceleration factors for typical values of n. The characteristic exponent of the V-t characteristics depends on the type of deterioration. By using these values, it is possible to estimate quantitatively the degrees of acceleration in the voltage acceleration tests. For example, when the test is performed at 1.5 times the operating voltage the acceleration is 3.4 times for $n = 3$ and 58 times for $n = 10$, and rises to 438 times for $n = 15$.

Table 1 Calculated values of voltage acceleration factor a^n

a \ n	3	10	15
1.2	1.7	6.2	15
1.5	3.4	58	438
2.0	8,0	1×10^3	3.3×10^4

a: voltage ratio n: characteristic exponent

The mode of voltage application in the voltage endurance test includes not only application of a constant voltage for a long period but also application of a voltage rising continuously at a constant rate or stepwise. The lifetimes of these voltage application modes can be related according to the inverse n power law.

For example, the lifetime t under application of a constant voltage V can be related with the breakdown time τ and the breakdown voltage V' for continous increase of applied voltage as following:[6]

$$t = \left(\frac{V'}{V}\right)^n \cdot \frac{1}{n+1} \cdot \tau \qquad \text{(7)}$$

In addition, the following relation can be obtained for the remaining breakdown voltage, i.e., breakdown voltage obtained by a short-term breakdown test after long-term constant voltage application, on the basis of the inverse n power law and the Miner's law of deterioration:

$$V_x = V_o \left(1 - \frac{t_x}{t_a}\right)^{\frac{1}{n+1}} \qquad \text{(8)}$$

where: V_x : remaining breakdown voltage after application of voltage V_a for time t_x
t_a: lifetime at an applied voltage V_a
V_o: initial short-term breakdown voltage

III. *V-t* CHARACTERISTIC PATTERNS AND CHARACTERISTIC EXPONENT FOR EPOXY MOLD INSULATION

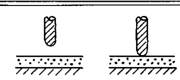
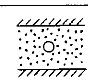
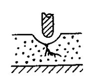
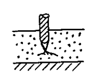
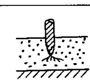
In this section the patterns of the V-t characteristic and the characteristic exponent, n, for various voltage deterioration are described on the basis of the data compiled from the authors' reports and published sources.

Table 2 shows a classification of voltage deterioration in epoxy mold insulation according to the type of the local discharge phenomena involved.

Both partial discharge (corona) deterioration and treeing deterioration are local phenomena. While the former is comparatively uniform, the latter is more locally concentrated.

The V-t characteristics reflecting these type of voltage deterioration show specific patterns and characteristic exponents.

Table 2 Classification of partial discharge phenomena

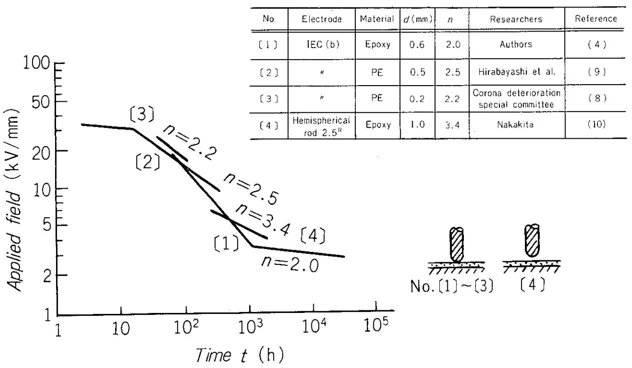
Partial discharge phenomena		Arrangement
Corona deterioration	Surface corona	
	Void corona	
Treeing deterioration	From corona to treeing	
	Treeing for needle-shaped void	
	Treeing without void	

1. *V-t* Characteristics of Partial Discharge (Corona) Deterioration

As shown in *Table 2*, partial discharge deterioration is classified into surface discharge deterioration and internal or void discharge deterioration for which the V-t characteristics of deterioration are different.

1) V-t characteristics of surface discharge deterioration

There have been many studies on the surface discharge deterioration including the work of the Special Standing



No.	Electrode	Material	d (mm)	n	Researchers	Reference
(1)	IEC (b)	Epoxy	0.6	2.0	Authors	(4)
(2)	〃	PE	0.5	2.5	Hirabayashi et al.	(9)
(3)	〃	PE	0.2	2.2	Corona deterioration special committee	(8)
(4)	Hemispherical rod 2.5R	Epoxy	1.0	3.4	Nakakita	(10)

Fig. 1 *V-t* characteristics of surface discharge deterioration.

Committee on Corona Deterioration of Institute of the Electrical Engineers of Japan.[8] Therefore considerable data have been accumulated. *Fig. 1* shows typical *V-t* characteristics for surface discharge deterioration in epoxy and polyethylene films.

Generally, the *V-t* characteristics of surface discharge deterioration have the following three regions which are fitted by straight lines.

The first region is the high field region. In this region, there is strong discharge of streamer type because of the high field applied. The deterioration shows local erosion of treeing type due to discharge concentration. The characteristic exponent in this region is large, about 10. Scattering of the lifetime data is large, and the deterioration pattern obtained by Weibull plots is of random character.

The second region is the medium field region. The typical corona deterioration features in this region. Since partial discharge is stable with respect to both location and time, comparatively uniform erosion occurs. The characteristics exponent which are 2 to 3 in this region, are almost independent of material, electrode shape, and thickness of specimen. Scattering in the lifetime data in this region is comparatively small. The deterioration pattern is cumulative.

The third region is the low field region in the vicinity of the thereshold of partial discharge. In this region, while the discharge deterioration occurs cumulatively, the discharge is weak, irregular, and of low repetition rate. Therefore, progress of the deterioration is retarded and the lifetime is greatly extended. This means that in this region the lifetime shows large scattering. The deterioration pattern is again of random character.

When the applied field is below the discharge threshold field, no voltage deterioration occurs naturally because no discharge does.

Fig. 2 shows an example of transition from the second to third region.[4] *Fig. 3* shows the Weibull plots of lifetimes at various applied voltages in this case. The *V-t* characteristics show a sharp bend at 1.7kV near the corona-starting voltage and a clear change in the Weibull distribution slope (or form parameter m).

2) *V-t* characteristics of internal discharge deterioration

The *V-t* characteristics of the internal discharge deterioration show basically the same pattern as for surface discharge deterioration. However, since the gas is completely enclosed in voids, or has very little passage to the external surface, the discharge is also enclosed within the voids. Therefore, conditions of the internal discharge deterioration are slightly different from the surface discharge deterioration.

Fig. 4 shows various examples of *V-t* characteristics for the internal discharge deterioration. For the internal discharge deterioration of thin material, the pattern is generally very similar to that for the surface discharge deterioration described above. The characteristic exponent is about 4, that is higher than that for surface discharge deterioration.

As the sample thickness increases, the slope of the *V-t* characteristics gradually decreases and the characteristic exponent, n, tends to increase. In patterns [4] and [5] in *Fig. 4*, the characteristic exponents are 6 to 8. This reason

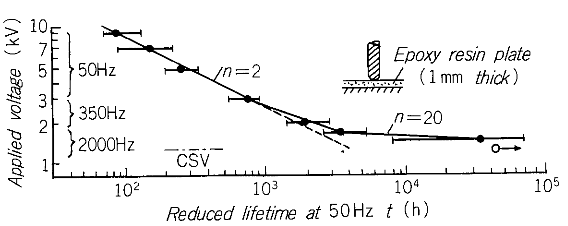


Fig. 2 *V-t* characteristics of surface discharge deterioration in epoxy resin plates.

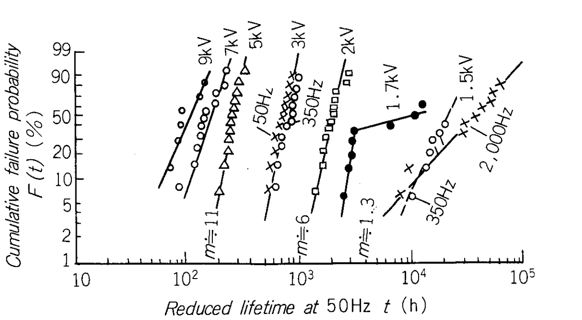
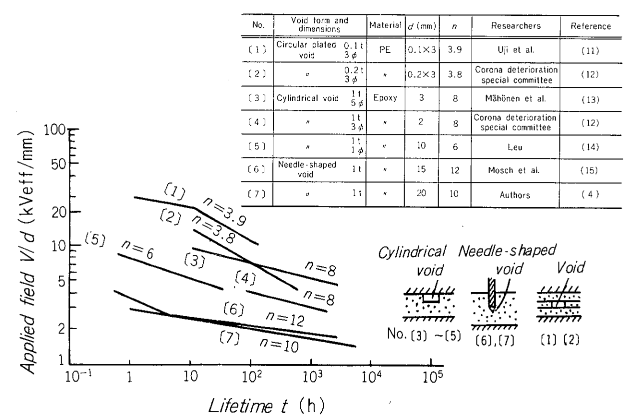


Fig. 3 Weibull plots of lifetimes



No.	Void form and dimensions	Material	d (mm)	n	Researchers	Reference
(1)	Circular plated void 0.1t 3φ	PE	0.1×3	3.9	Uji et al.	(11)
(2)	〃 0.2t 3φ	〃	0.2×3	3.8	Corona deterioration special committee	(12)
(3)	Cylindrical void 1t 5φ	Epoxy	3	8	Mähönen et al.	(13)
(4)	〃 1t 3φ	〃	2	8	Corona deterioration special committee	(12)
(5)	〃 1t 1φ	〃	10	6	Leu	(14)
(6)	Needle-shaped void 1t	〃	15	12	Mosch et al.	(15)
(7)	〃 1t	〃	20	10	Authors	(4)

Fig. 4 *V-t* characteristics of internal discharge deterioration

is assumed to be as follows: While the damage process in the thin samples is uniform corona erosion, the deterioration becomes more localized as the thickness increases and shifts to the socalled treeing deterioration. In fact, tree-like erosion was observed near the void edge in the case [4].(12)

The *V-t* characteristics depend also on the shape of the void. The needle-shaped voids in the cases [6] and [7] in *Fig. 4* are extreme cases. The slopes of the *V-t* characteristics for the needle-shaped voids are even less than that for cylindrical void. The characteristic exponents in this case are 10 to 12. The dependence of the characteristic exponent on the void shape is due to concentration of the discharge to the tip of the void by which the deterioration becomes more localized.

In the needle-shaped voids, the degree of concentration of both discharges and fields is so much high that the lifetime is much shorter than that in an average field (applied voltage/sample thickness). The *V-t* characteristic curves of this case take lower position in the figure than that of the other cases.

2. *V-t* Characteristics of Treeing Deterioration

Fig. 5 shows various *V-t* characteristics for epoxy resin with buried needle electrode without void at its tip.

No.	Electrodes	Material	d (mm)	n	Researchers	Reference
(1)	Needle-hemispherical rod	Epoxy	3	6	Fukushi et al.	(16)
(2)	Needle-flat plate	Epoxy + HHP	1.6	10	Olyphant et al.	(17)
(3)	〃	Epoxy+TPSA	1.6	12	〃	(17)
(4)	〃	Epoxy (Araldite B)	5	26	Hirabayashi et al.	(18)
(5)	〃	Epoxy (Epicoat 828)	5	7	〃	(18)
(6)	〃	Epoxy	25	29	Mosch et al.	(15)

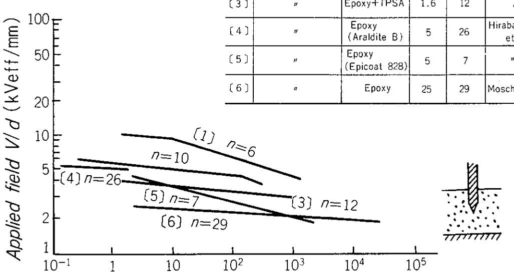


Fig. 5 *V-t* characteristics of treeing deterioration

The *V-t* characteristic pattern in this case is mostly approximated by one straight line. The characteristic exponents showed wide scattering from 6 to 29, and were generally much larger than those for partial discharge.

The reason for the large characteristic exponents and the strong voltage dependency of the lifetime in the treeing deterioration is that, as described in the previous section. the damage process of "deterioration to breakdown" is more locally concentrated than that for partial discharge deterioration.

The large scattering of the characteristic exponent in the data is assumed to well reflect treeing deterioration mechanism. In other words, minute differences in material structure or in sample preparation have strong effects on the factors such as the presence of minute voids at the needle tips, the degree of stress concentration and the space field distribution which control the starting and spreading of the treeing. Therefore, it is assumed that the scattering in the characteristic exponent in the data is due to difference in the deterioration characteristics caused by such effects.

As in the case of partial-discharge deterioration, a lower limit below which the treeing deterioration occurs seems to exist also in the low field region. However, since this has not been confirmed, the *V-t* characteristic pattern of this case is approximated by a straight line.

3. *V-t* Characteristics for Mold Insulation Without Void or Strong Field Concentration

So far, features of *V-t* characteristics in cases of partial discharges and treeing discharge caused by the presence of voids or needle-shaped intrusions have been discussed. The *V-t* characteristics of insulation structures free from these deteriorating factors is described below.

Fig. 6 shows the *V-t* characteristics of epoxy mold test pieces with hemispherical-rod or flat-plate electrodes. In comparison with the case of *Figs. 1* through *5*, the average fields in these *V-t* characteristics are rather high. But the characteristic exponents of the *V-t* characteristics are 10 to 16, and compared to those for treeing deterioration.

When long-term voltage endurance capability is estimated by extrapolating the *V-t* characteristic by a straight line, the breakdown strength at 10^5 hours (about 12 years) is 10 to 20kV/mm which is larger about one order of magnitude than that normally used with epoxy mold insulation.

Fig. 6 shows a comparison of published data with

No.	Electrodes	Material	d (mm)	n	Researchers	Reference
(1)	Hemispherical rod - flat plate 50 ϕ 25 ^{R}	Epoxy + quartz powder	2.7	12	Authors	(4)
(2)	Cylinder - flat plate 15 ϕ	Epoxy	3	15	Nakakita et al.	(19)
(3)	Hemispherical rod - flat plate 10 ϕ 5 ^{R}	〃	1	10	Naito et al.	(20)
(4)	Plate - plate	〃	5	12	Tangen et al.	(21)
(5)	Sphere - plate 7 ^{R}	Epoxy + quartz powder	2	12	Mosch et al.	(15)

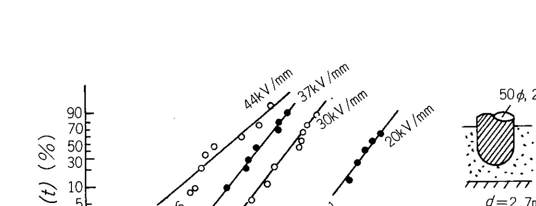


Fig. 6 *V-t* characteristics of epoxy resin molds without void and field concentration

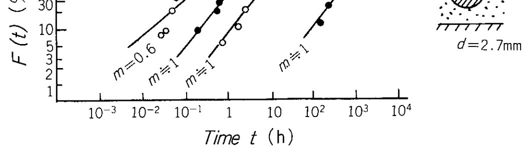


Fig. 7 Weibull plots of lifetimes by *V-t* test of epoxy resin mold

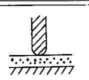
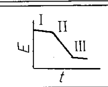
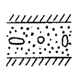
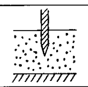
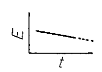
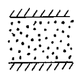
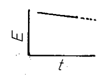
regard to the average field in which differences between the data are unexpectedly small for both absolute levels and slopes of the *V-t* characteristics. In other words, there was comparatively good agreement in the data.

Fig. 7 shows a Weibull plot of the lifetimes at various test voltages.[4] Although the Weibull form parameter m for above mentioned insulation structures usually slightly depends on the applied. field, the presence of fillers, and other factors, the m value is less than one in all cases and deterioration pattern is of initial failure type or random type.

As no deterioration is expected in the low field region for this type of insulation structure, the *V-t* characteristics are assumed to level off. Since, as in the case of treeing deterioration, this has not been confirmed, the *V-t* characteristic pattern is approximated by a straight line on the whole for practical application for assuring reliability.

The above sections have described the *V-t* characteristic patterns and the inverse n power law for various voltage deterioration. These are summarized in *Table 3*.

Table 3 *V-t* characteristics of epoxy resin mold insulation

Type of voltage deterioration		Arrangement	*V-t* pattern	Characteristic exponent n
Partial discharge deterioration	Surface discharge			About 2–3 (No. II region)
	Internal discharge			Thin sample: about 4, thick sample or needle-like voids: n becomes larger (No. II region)
Treeing deterioration				6–29
Voidless or uniform field				10–15

IV. TEST FOR EVALUATING VOLTAGE ENDURANCE OF EPOXY MOLDS

The findings described can be effectively applied to the voltage endurance evaluation of actual products and provide valuable information for development, design and quality control of epoxy mold insulation.

In addition, voltage endurance tests are performed on samples of the same size and shape as actual products on the basis of empirical confirmation of products reliability. Long-term breakdown strengths using test models of actual scale were investigated in order to determine the upper limits of electrical field to which the epoxy mold insulation is practically useable. Photographs of testing apparatus for such purpose are shown below.

Figs. 8 through *10* show the long-term voltage endurance test for verifying the lives of various mold insulation. The tests are performed under the voltage of frequency acceleration for verifying the voltage endurance life over a period of several ten years in a short time. In every epoxy mold insulation, reliability test was sufficiently performed. *Fig. 8* shows a test on a mold used in a SF_6 insulate metal-clad switchgear (VMH).[22] With an arrangement of various types of spacers, operating rods, molded PT, and others just as in the actual product, a long-term voltage endurance test was performed at a voltage much higher than that of the operating voltage. This test is also applied for confirming the overall reliability of gas insualted equipments.

Fig. 9 shows a life test of a molded power transformer.[23] The long-term test was performed by applying an actual load current as well as a voltage.

Fig. 10 shows a long-term test of a mold used as a high voltage bus support in a compact medium voltage metal-clad switchgear (Fuji mini F-clad). In this test the voltage endurance was confirmed by using both voltage and frequency accelerations.

Fig. 11 shows a long-term voltage endurance testing

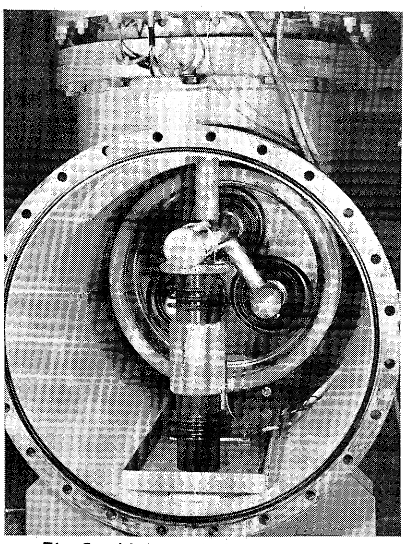


Fig. 8 Voltage endurance test of SF_6-insulated metal-clad switchgear (VMH)

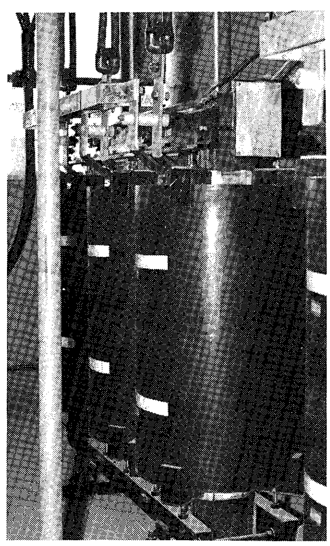


Fig. 9 Voltage endurance test of epoxy mold power transformer

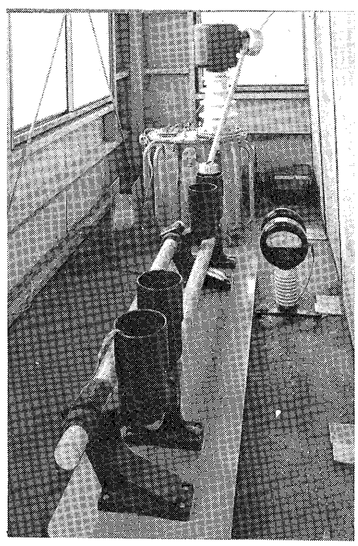


Fig. 10 Voltage endurance test of epoxy resin insulator for 34.5kV metal-clad switchgear

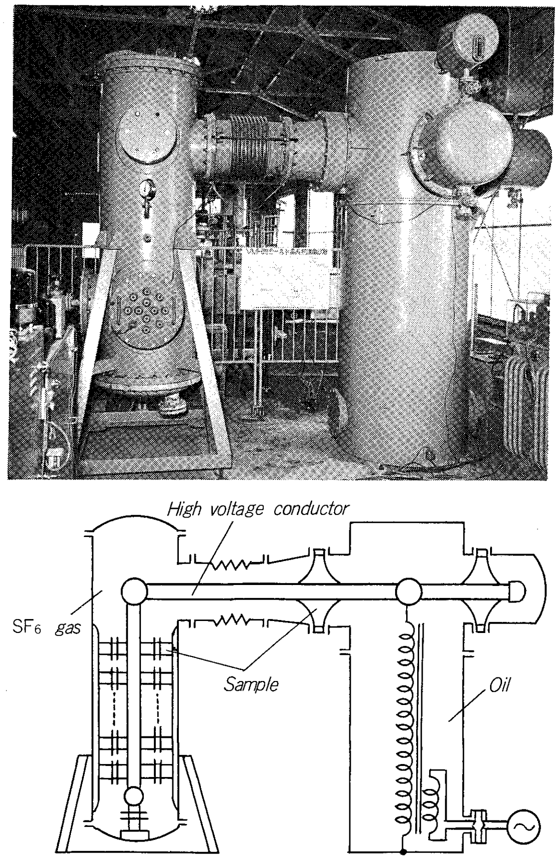


Fig. 11 Testing apparatus for voltage endurance of epoxy resin mold insulation

apparatus used for determining the limit of voltage endurance of the epoxy mold insulation. Several mold support insulators and spacers of actual size are placed in this testing apparatus as shown in the figure. Under an applied field of 5 to 10kV/mm, which is several times the normal operating field, the long-term breakdown strength of the mold is investigated. To obtain empirical data of permissible corona level in actual equipment, samples in which internal corona occurs are also tested in this appratus for voltage endurance. While, as shown in the photograph, this apparatus is rather of large scale, right knowledge about the safe operating voltage limit of molds of actual scale is very useful for determining tolerances with respect to reliability and for designing high voltage power equipments with both greater voltage capacities and better compactness.

V. CONCLUSION

The statistical treatment of the *V-t* characteristics of epoxy mold insulation and the behavior of various types of voltage deterioration are discussed. The *V-t* characteristic patterns are classified in relation to characteristic exponents on the basis of the authors' test results and data published to date. Although the laws obtained are only empirical, they serve as guiding rules for more reasonable voltage endurance evaluations. In addition to this basic study, some examples of actual scale tests on various epoxy molds were presented.

To increase the reliability of mold insulation, it is important to eliminate the various factors which cause deterioration. Therefore, Fuji Electric is making great effort to improve its reliability at every stage of design, manufacturing and testing. At the design stage, electrical, thermal and mechanical stress levels are determined by both computer analysis of electric field distribution and stress analysis techniques, and reasonable constructions of insulation are investigated on the basis of these data. At the manufacturing stage, molding and compounding techniques which eliminate voids or cracks are improved. At the testing stage, severe type tests such as heat cycle and mechanical loading are performed. In shipping test of products the corona test is employed for the quality control. Further efforts will be made to improve various techniques for high quality epoxy mold insulation.

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