와이블 분포식을 이용한 에폭시 복합체의 절연 신뢰도 분석

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Analysis of Insulating Reliability in Epoxy Composites using Weibull Distribution Equation

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ABSTRACT

The dielectric breakdown of epoxy composites used for transformers was experimented and then its data were applied to Weibull distribution probability. First of all, speaking of dielectric breakdown properties, the more hardener increased, the stronger breakdown strength became at low temperature because of cross-linked density by the virtue of ester radical. The breakdown strength of specimens with filler was lower than it of non-filler specimens because it is believed that the adding filler forms interface and charge is accumulated in it, therefore the molecular motility is raised and the electric field is concentrated. In the case of filled specimens with treating silane, the breakdown strength become much higher. Finally, according to Weibull distribution analysis, reducing breakdown probability of equipment insulation lower than 0.1 % level requires the allowable field intensity values to be kept under 21.5 MV/cm.

키워드

cross-linked density, treating silane, Weibull distribution method

I. Introduction

To supply the safe and reliable electric energy efficiently, electric insulation techniques should be established. For this, intense research and development of insulation material should be extended. Meanwhile, refining materials, developing manufacturing process for removal of various defects and examining dielectric degradation require theoretical analysis based on the study of material properties. That is, to improve existing materials and develop new materials, precise understanding of insulation in microscopic perspective and establishment of base information should come first thereby enabling development of superior dielectric material and extending influences on the development of electric and electronic study area[1].

Although organic high molecular materials possess superior dielectric characteristics fit to be utilized in areas requiring insulation as well as in electric power systems, generally, as time goes by, constituent materials are subject to degradation and performance decrease leading to possible accidents. Therefore, constructing a stable system requires knowledge of overall phenomena covering thermal, mechanical, chemical and aging degradation and researches on degradation diagnosis.

Currently, installment of extra high voltage in transmission/distribution system is under way and many researches are in progress to increase stability in every transmission and distribution system. Concerning the technology of high voltage or high electric field, data of dielectric breakdown or service life and data relating non-dielectric breakdown to dielectric breakdown form a very important set of information. However, these data of service life and dielectric breakdown generally lack focus and scatter requiring quantitative estimation by a consistent statistical treatment[2].

This study presented statistical data treatment method of aging degradation for deciding insulation safety by estimating an allowable electric field intensity applied at an allowable arbitrary breakdown probability using Weibull distribution, which is frequently used for life estimation and breakdown statistics getting data out of tests performed for five specimens of epoxy resin with predefined combination of mixtures.

II. Experimental

This study took normally liquid Bisphenol-A type epoxy resin and acid anhydride hardener MeTHPA(Methyl Tetra Hydro Phthalic Anhydride) with low viscosity and good suction stability mixing them with a constant composition[3] and going through the first hardening(100℃, 2 h) and the second hardening (140℃, 6 h) and improved impact and tensile strength with addition of five wt % of DY-040. Further, to supplement mechanical and thermal characteristics, silica (SiO2) of 9.5 to 38 μm radius was added as filler material[3].

Because thermal expansion coefficient differs greatly between organic base resin and inorganic filler material, for the purpose of improving material characteristics of the composite, amino silane N-(N-(β-Aminoetyl)-γ-Aminopropyltrimetoxy-Silane), taken as a coupling agent was diluted with 1 % concentration in water solution and was used in treating silica surface with silane. Table 1. shows Formulation ratio and curing condition of samples.

Weibull distribution is widely used in degradation statistics of high voltage equipment, which requires determination of statistical quantities such as average and standard deviation σ because average value together with standard deviation telling degree of scattering forms a very important set of factors in actual equipment design practices.

Generally, given n data with i-th component Xi (i=1,2,...,n), average X and standard deviation σ becomes:

$$X=(X_1+X_2+\cdots+X_n)/n$$

$$\sigma=\sqrt{((X_1-X)^2+(X_2-X)^2+\cdots+(X_n-X)^2)/n}$$

Weibull distribution is also referred to as the weakest point breakdown probability distribution and the accumulated probability distribution taking an effective value of a probability variable X as x becomes:

$$F(x) = 1-\exp\left[-\left(\frac{x-x_l}{x_s}\right)^m\right] \quad (x \geq x_l)$$
$$= 0 \quad (x < x_l)$$

This means that the probability of effective values of X to fall below x equals F(x), in which xl, xs and m represents parameter for position, scale and shape. xl represents the lowest value for occurrence of dielectric breakdown and xs refers to an average breakdown strength equivalent to an accumulated breakdown rate of 63.2 %. And m is a parameter determining distribution shape of accumulated breakdown probability distribution, using large value of which reduces scattering leading to a near exponential distribution when m is approximately unity and near normal distribution when m is more than around four.

The silane treated filler-added specimen was produced by removing impurities through heat treating silica at 500 ℃ for 5 h and drying in vacuum oven at 80 ℃ for 4 h after treating with boundary coupling agent. After mixing the silane filler with liquid epoxy, the mixture was

Table 1. Formulation ratio and curing condition of samples.

Samples	Epoxy	Hardener	DY-040	Filler	Curing Condition
H80FN	100	80	5	0	▶1st Curing : 100℃, 2 h ▶2nd Curing : 140℃, 6 h ☞ S : silane
H90FN	100	90	5	0	
H100FN	100	100	5	0	
H100F60	100	100	5	60	
SH100F60	100	100	5	60	

put into a vacuum heating agitator to stir it up for about one hour at 80 ℃ to distribute the filler material evenly and hardener was added. The compound epoxy was poured into a preheated die-cast and hardened for two hours at 100 ℃ and secondly hardened at 140 ℃ for 6 h.

The dielectric breakdown test equipment is constructed as is depicted in Figure 1. to measure voltage soaked in degased silicon oil, for prevention of discharge at contiguous surfaces, varying temperature through 20 ~ 160 ℃ range and rising voltage at 1 kV/s until dielectric breakdown takes place. And as for the number of measurement, voltage measurements for ten specimens under the same condition were averaged to yield an average breakdown voltage.

The specimen for dielectric breakdown test was constructed by molding 3 ㎜ thickness epoxy between 4 ㎜ diameter stainless electrode and upper electrode placing them 200 ㎛ apart to form a sphere-to-flat surface electrode system.

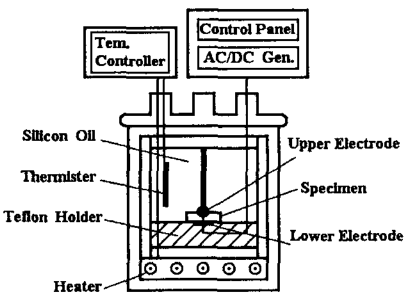

Fig. 1 Experimental apparatus.

III. Results and discussion

Figure 2. shows DC dielectric breakdown strength subject to variation of hardening agent proportion in secondly hardened non-filler specimen.

At low temperature, breakdown strength goes up as the percentage of hardening agent increases while, near 110 ℃, abrupt decrease of breakdown strength is noticeable, which implies that the temperature range is in thermal transformation regime bringing about active molecular motion. Breakdown strength increases according to the highest order of hardener content at low temperature below 90 ℃, which is considered to be the result of dielectric strength growth which is caused by augmented cross-linked density following the increase of ester radical due to the addition of hardener. Also in high temperature area, Joule heat of conducting current causes heat generation and reduces dielectric strength by letting the added hardener act as a defect thereby decreasing the dielectric strength, which explains high strength value for the specimen with less hardener[4].

Figure 3. represents DC breakdown strength for non-filler specimen(H100FN), filler specimen(H100F 60) and filler/ silane - treated (SH100FN) specimen produce by mixing epoxy and hardener with the ratio of 1:1.

The specimen with filler shows overall low strength value compared with non-filler specimen, which is estimated to be caused by electron avalanche following the build-up of bonding interface as a result of filler addition.

In the case of improving bonding status through silane treating, specimen with filler addition only reveals higher strength, in which treating silane is considered to constrict the growth of interface eventually strengthening dielectric strength[5].

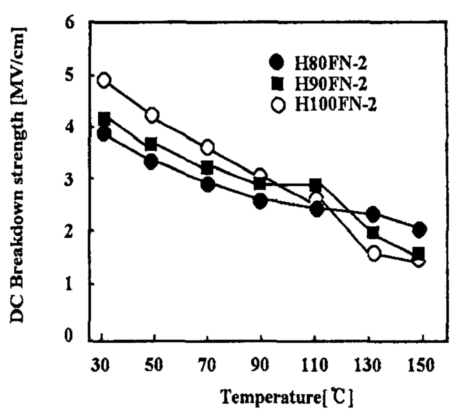

Fig. 2 DC breakdown strength according to ratio of adding hardener.

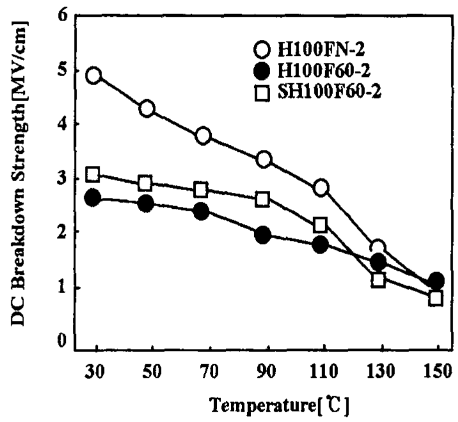

Fig. 3 DC breakdown strength according to adding filler and treating silane coupling agent.

Table 2. summarized simulation results using parameters found out in DC dielectric breakdown test.

IV. Concluding remarks

Applying more percentage of hardener increases ester radicals and cross-linked density leading to improvement of dielectric breakdown strength at low temperatures and at high temperature such as 110 ℃ near free transition state, where molecular motion is activated, dramatical decrease of strength occurs as a result of adding more hardener.

Adding filler forms bonding boundary between epoxy and silica, letting electric field converge at the boundary and accelerate electron reducing overall breakdown strength compared to the non-filler case. Treating silane, however, improves boundary bonding resulting in higher strength than specimen with filler added only. Therefore, when using epoxy composites as insulation material, silane treating is required to constrain boundary growth and increase insulation property.

According to Weibull distribution analysis, it can be reasoned that reducing breakdown probability of equipment insulation lower than 0.1 % level requires the allowable field intensity values to be kept under 21.5 MV/cm.

Reference

[1] B. A. Rozenberg, "Kinetics, Thermodynamics and Mechanism of Reactions of Epoxy Oligomers with Amine : Epoxy Resin and Composites II, K. Dusek Edit.", Springer-Verlag, Berlin Heidelberg, pp. 113-166, 1986.

[2] X. M. Chen and B. Ellis, "Coatings and Other Applications of Epoxy Resina-Chemistry and Technology of Epoxy Resins, Bryan Ellis, Edit.", Blackie Academic & Professional, pp. 303-327, 1993.

[3] L. Simoni, "A General Approach to the Endurance of Electrical Insulation under Temperature and Voltages", Colloid & Poly-mer Sci., 260, pp. 297-302, 1982.

[4] S. S. Sastry, G. Satyanandam, "Effects of Fillers on Electrical Properties of Epoxy Composites", J. Appl. Poly. Sci., Vol. 26, pp. 1607-1615, 1988.

[5] J. D. Reid, "Dielectric Properties of an Epoxy Resin and its Composite II", J. Appl. Poly. Sci., Vol. 33, pp. 2293-2303, 1987.

Table 2. The values of each parameter obtained from DC breakdown data.

Parameter / Samples	Shape Parameter(m)	Measuring Parameter(E_s)	The Values of Applied Field (Allowed Breakdown Probability=0.1[%])
H80FN-2	3.73	124	19.46 MV/cm
H90FN-2	3.47	155	21.17 MV/cm
H100FN-2	3.44	159	21.34 MV/cm
H100F60-2	3.42	161	21.36 MV/cm
SH100F60-2	2.83	246	21.43 MV/cm