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Estimating Remaining BDV and Life Expectancy for Stator Winding Insulation of Rotating Machines by Using Nondestructive Insulation Diagnostic Data

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Abstract: We have investigated an appropriate life expectancy estimating method of the epoxy resin-rich insulation system (Fuji F-class Stabilastic insulation system). We have already collected the BVD and the nondestructive insulation diagnostic data from 30 or more units of the rotating electric machines provided epoxy resin-rich insulation system with the rated voltage of 3.3 to 11kV. We have performed a multivariate analysis on the BVD and the nondestructive insulation diagnostic data of these coils in this time, and have established the estimating method for the remaining BVD and the life expectancy. On the basis of compared results of the measured values with the estimated values, it was proven that this estimating method provides enough accuracy for the actual use.

INTRODUCTION

In 1999, Fuji Electric has established the estimating method on life expectancy [1,2,3] of the F resin/F insulation system in which the epoxy resin is impregnated into individual coils through the multivariate analysis, and is bringing the results. Consecutively, we have investigated an appropriate life expectancy estimating method of the F resin/S insulation system (Fuji F-class Stabilastic insulation system) that is an epoxy resin-rich insulation system. We have already collected the BVD and the nondestructive insulation diagnostic data from 30 or more units of the rotating electric machines provided the F resin/S insulation system with the rated voltage of 3.3 to 11kV.

In this time, we have performed a multivariate analysis on the BVD and the nondestructive insulation diagnostic data of these coils and investigated the estimating method for the remaining BVD and the life expectancy through the multiple regression equation.

MULTIVARIATE ANALYSIS

Correlation between BDV and length of operation

Figure 1 shows correlation between the BVD and the length of operation. The BDV values on vertical-axis are calculated as electric field strength (kV/mm) so as to realize an accurate estimation, and indicated in percentage for easy understanding. The upper line in the figure shows the BVD of the average level, and the lower line shows the BVD of the lower limit level in due consideration of scattering of 3σ. The dielectric strength (2E+1kV) required to continue the reliable operation is in range of 23.1 to 28.8%.

The measured values of numerous rotating machines are plotted in this figure, and it is evident that the remaining BVD lowers in proportion to the length of operation. The insulation life is presented as crossing point of the lower limit level and the dielectric strength 2E+1kV required to continue the reliable operation.

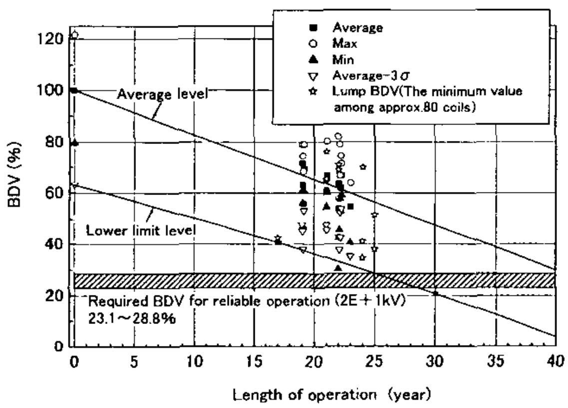

Fig.1. Relation between BDV and length of operation.

Correlation between BDV and variables

The summarized correlation coefficients between the BDV and the variables including individual insulation characteristics determined by nondestructive tests are shown in Table 1. The highest correlation coefficient with the BVD is the length of operation of |0.78| and all other coefficients are lower than |0.5|.

Figure 2 shows the correlation between the BVD and the length of operation. This figure is similar to the Figure 1 and it is evident that the remaining BVD lowers in proportion to the length of operation.

Figure 3 to 5 show correlation between the BDV and the individual insulation characteristics determined by the nondestructive tests such as ΔI12, Δtanδ12, qmax12.

These figures enable to verify that the BDV value reduces together with worsening of the individual insulation characteristics determined by the nondestructive tests in connection with deterioration of the insulation.

Tab.1. Correlation coefficients of BDV and characteristics determined by nondestructive tests.

Variables	Testing voltage	Correlation coefficients
Length of operation	-	-0.78
PI	-	0.17
ΔI12	$1.25*E/\sqrt{3}$	-0.42
ΔI2	E	-0.49
$\tan\delta 0$	1kV, 2kV	-0.45
$\Delta\tan\delta 12$	$1.25*E/\sqrt{3}$	-0.26
$\Delta\tan\delta 2$	E	-0.40
qmax12	$1.25*E/\sqrt{3}$	-0.27

E: Rated voltage

PI: Polarization index

ΔI12:Current increasing ratio at applied voltage of $1.25E/\sqrt{3}$

tanδ0: tanδ at 2 or 1kV

Δtanδ12:Increment to tan δ 0 at applied voltage of $1.25E/\sqrt{3}$

qmax12:Maximum discharge at applied voltage of $1.25E/\sqrt{3}$

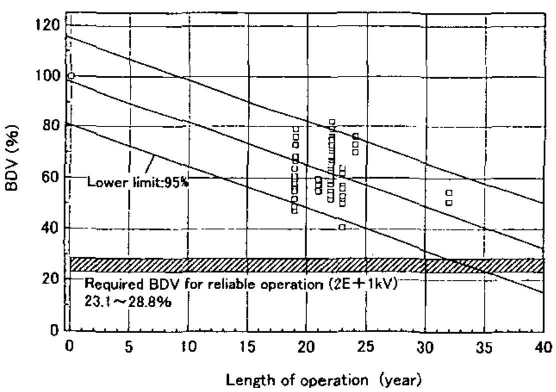

Fig.2.Correlation between BDV and length of operation.

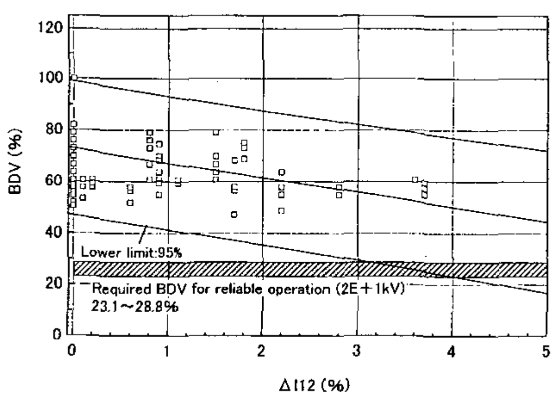

Fig.3. Correlation between BDV and ΔI12.

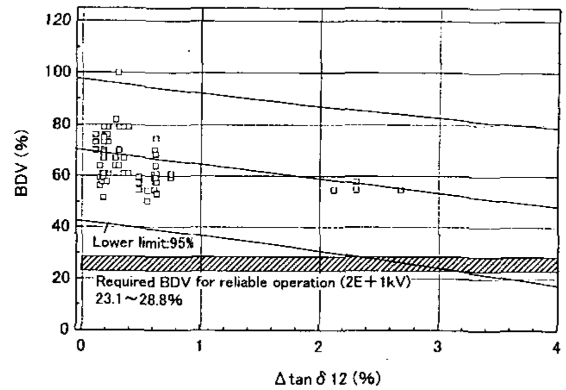

Fig.4. Correlation between BDV and Δtan δ 12.

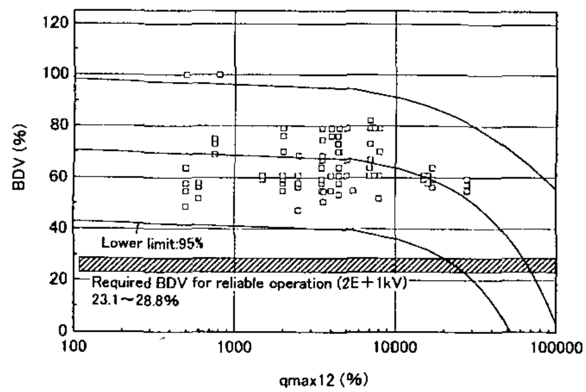

Fig.5. Correlation between BDV and qmax12.

Principal component analysis

The principal component analysis is utilized as a method to find out the synthetic indexes seizing the synthetic correlations and features among the multiple variables. This principal component analysis shall be performed prior to performing the multiple regressive analysis, in order to serve the introduction of the multiple regression equation.

In the analyzed results of the principal component analysis, the eigenvalue and the contributing rate of the principal component shown in Table 2 shall be remarked. According to the data shown in Table 2, we are able to seize the information corresponding to approximately 64% of total, if we remark both of the principal component 1 and 2.

As an important example the factor loading scatter plot of the principal component 1 and 2 is shown in Figure 6. This figure is suggesting that the length of operation and the Δtan δ 12 locating at the opposite side of the BVD are appropriate while the PI is not suitable to estimate the BVD.

Tab.2. Eigenvalue and contribution rate through principal component analysis.

	Eigenvalue	Contribution rate	Cumulative contribution rate
Principal component 1	4.064	0.452	0.452
Principal component 2	1.686	0.187	0.639
Principal component 3	1.306	0.145	0.784

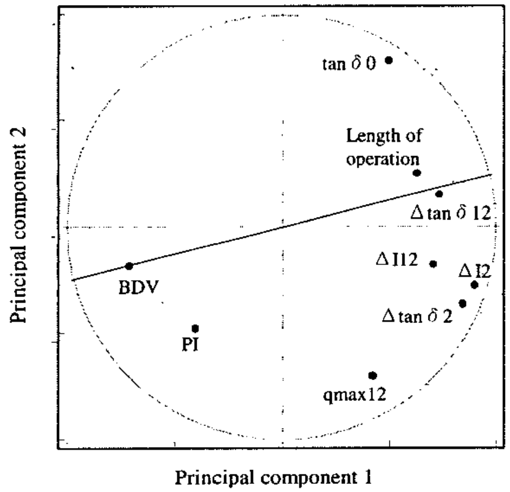

Fig.6. Factor loading scatter plot of principal component 1 and 2.

Inducing multiple regression equation

If the BDV is able to estimate appropriately through a single regression equation, further investigation will not be required, however in order to pursue the improvement of estimating accuracy, the estimation through the multiple regression equation was performed. In case of inducing the multiple regression equation, the most important factor is selection of the variables. In general, because the applied voltage at the insulation diagnosis is not heightened up to the rated one, ΔI2 and $\Delta\tan\delta$ 2 are not able to utilize as the variables.

As a result, length of operation (year), PI, ΔI12 (%), tan δ 0 (%), $\Delta\tan\delta$ 12 (%) and qmax12 (pC) are taken up as the quantitative variables, and cooling method (enclosed type, open type), insulation resistance (< 10000MΩ, ≧10000MΩ) and voltage class (<6, ≧ 6kV) are also taken up as the qualitative variables. Among these variables we have selected the variables that provide excellent estimating computation accuracy, as well as the variables provide commonsense relation with physical phenomena of the insulation deterioration.

Considering the analysis results of the single regressive method and the principal component method mentioned above, we have decided finally as the optimum way that the length of operation, ΔI12, $\Delta\tan\delta$ 12 and qmax12 are selected as the independent variables by which the BVD of mean level that is a dependent variable is estimated. Formula (1) shows the induced multiple regression equation.

$$BDVmav\,(\%) = 98.4 - 1.46\cdot(y) - 2.19\cdot(\Delta I12) - 0.981\cdot(\Delta\tan\delta 12) - 0.000201\cdot(q\max 12)\cdots(1)$$

Where, y is number of years. Formula (2) shows the lower limit BVD considered the scattering of 3 σ, and determined by reducing the scattering width from the formula (1).

$$BDVm3\sigma(\%) = BDVmav - ((100.1 - 1.74\cdot y - 0.000420\cdot y^2) - (63.2 - 1.20\cdot y - 0.00685\cdot y^2))\cdots(2)$$

The required BDV for reliable operation is determined by the following formula.

$$BDVne(\%) = \frac{\left(\frac{2\cdot E+1}{t}\right)}{b}\cdot 100\cdots(3)$$

Where, E is rated voltage (kV), t is thickness of main insulation (mm) and b is coefficient (initial BDV, kV/mm).

Comparison between measured BDV and estimated BDV

Figure 7 shows comparison between the estimated BDV values by the multiple regression equation and the measured BDV values. It is clearly understood by this figure that the estimated BDV value can be computed almost equivalent level with the measured BDV value.

The correlation coefficient determined by the multiple regressive computation is 0.82, and has higher correlation coefficient than the single regression between the BDV and the variables (length of operation, $\Delta\tan\delta$12, qmax12, ΔI12) shown in Table 1.

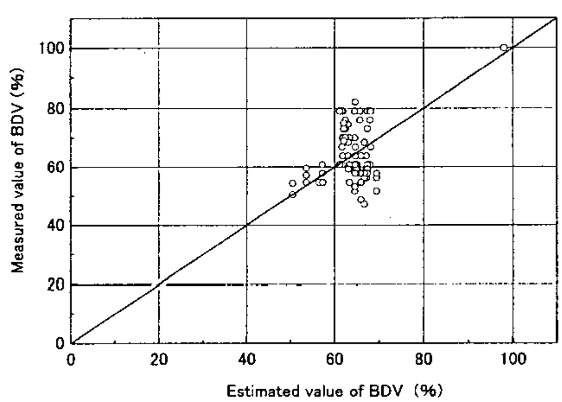

Fig.7. Comparison of BDV between measured values and estimated values.

Computing example

A computing example on 6.6kV insulation using the induced multiple regression equation is presented below. The diagnosis data shown in Table 3 are mean values determined from the insulation diagnosis data of 234 machines.

The computed results are shown in Figure 8 and 9. Figure 8 shows that the deterioration of the stator winding detected by insulation diagnosis are progressing together with the length of operation, and the computed remaining BDV in both average level and lower limit level are also decreasing together with them. The remaining BDV of lower limit level becomes lower than the required BDV of 2E+1kV in the course of approximately 24 years, and therefore it is concluded that the winding must be renewed earlier than this time limit.

Figure 9 shows the relation between the probability that the remaining BDV of windings become less than the required BDV for reliable operation and the length of operation. From this figure, risky degree of the winding insulation depend on the length of operation can be seized.

CONCLUSION

The multiple regressive method presented in this paper provides a merit that the nondestructive insulation diagnosis data are able to reflect directly to estimate the remaining BVD. Thus the life expectancy is determined based on the trend in remaining BVD over time and estimate the appropriate renewal timing of windings.

Judging from comparison results between the computed values with the multiple regression equation and the measured values, it is concluded that this estimating method providing enough accuracy had been established now.

There is a difficulty that numerous data are required to induce the multiple regression equation. However, once the data are collected the appropriate estimation for the remaining BVD is possible considering the deterioration of insulation and arranging to the statistical meaningful data. We will endeavor to improve further the estimating accuracy.

Tab.3. Diagnostic data used for computing BDV.

Length of operation (year)	$\Delta I12$ (%)	$\Delta \tan\delta 12$ (%)	qmax12 (pC)
10	1.90	0.10	1766
20	2.26	0.30	3115
30	2.62	0.50	4465

*Required BDV for reliable operation (2E+1kV) : 28.8%

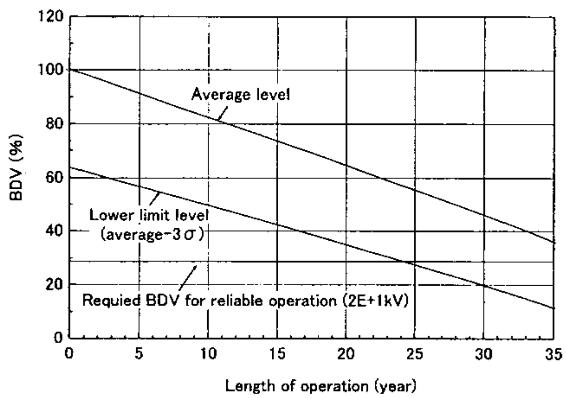

Fig.8. Relation between computed BDV and length of operation.

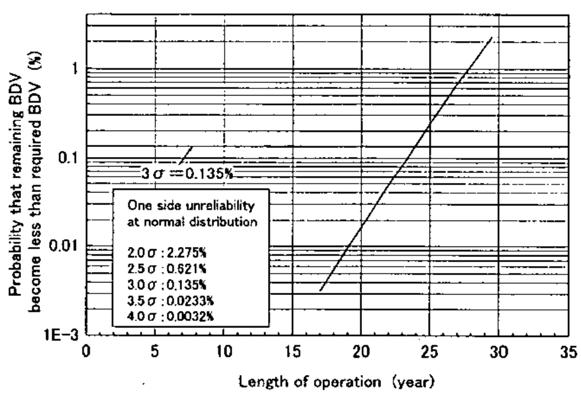

Fig.9. Relation between probability that reaming BDV become less than required BDV and length of operation.

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