Česká společnost pro nedestruktivní zkoušení materiálu
37. mezinárodní konference **DEFEKTOSKOPIE 2007**
Praha, 7. - 9. 11. 2007

THE APPLICATION OF MULTIFACTOR ANALYSIS OF VARIANCE IN RVM DIAGNOSTICS OF PAPER-OIL INSULATION

Stefan Wolny **Józef Kędzia** **Maciej Zdanowski**
Opole University of Technology
Faculty of Electrical Engineering, Automatic Control and Computer Science
Institute of Electrical Power Engineering
Poland

ABSTRACT

The paper presents the method of a multifactor analysis of variance in its application for the assessment of the paper-oil insulation condition of power appliances (mainly power transformers) using a parametric analysis of the return voltage runs (RVM method). This method makes it possible to cut down significantly the cost of the research work carried out and to make it less time-consuming. The conclusions were based on the laboratory test results of the return voltage phenomenon of the insulation samples which had been prepared earlier and which differed in the degree of aging and dampness. The method presented can be successfully applied in diagnostics of the insulation condition of electric power appliances, performed on real objects.

KEYWORDS: paper-oil insulation, RVM diagnostic, multifactor analysis of variance, power transformers

1. INTRODUCTION

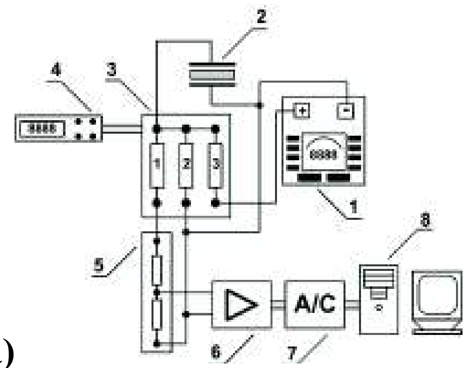
A paper-oil insulation system has been used in the construction and structure of power transformers for over 120 years. With the increase of the power of transformers it was subject to modernization not only from the point of view of construction but also from the technological point of view. The increase of electrical parameters that characterize such a system sometimes led to the occurrence of new hazards. Such a problem constituted, for example, static electricity generated by a forced flow of insulation oil. It reached such a level that could affect insulation electrical strength [1, 2]. The research work carried world-wide made it possible to limit this hazard. The issue that has been subject to research work since the very beginning of using paper-oil insulation system is the process of insulation aging and chemical reactions connected with this process which condition the formation of water. Water can have a disastrous effect on the strength of the transformer insulation system.

Diagnostic research on the changes taking place in paper-oil insulation systems is a complex issue. The factors that significantly influence their process are: long duration of aging processes, high financial outlays, interaction of factors. Taking all these into account, it seems that the application of the tools of modern statistics could be purposeful for the research result analysis. They can limit the time and costs of the research work and also help obtain the results which would be impossible to obtain without their application.

2. REASEARCH WORK CHARACTERISTICS

The aim of the research work carried out was to determine how the aging processes and the content of water in paper-oil insulation influence the return potential measured.

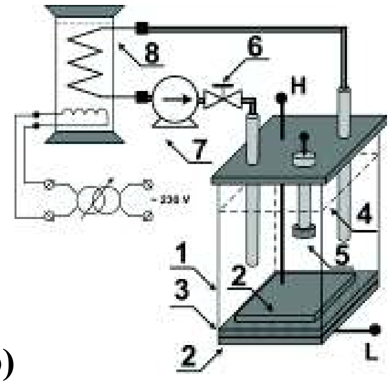
The parameter characterizing such voltage results obtained was its maximum value (U_{max} – Fig. 1.c) [3, 4, 5]. A single insulation sample consisted of 10 layers of electrotechnical cable paper (size 100x100mm) impregnated with fresh mineral insulation oil. Fresh samples and samples subjected to accelerated thermal aging were used for the research purposes. The paper aging process consisted in holding the samples at a temperature of 150 and 170^{o}C for 25 hours with the presence of air. Impregnation with insulation oil (Nynas 10BGN) was performed only after this stage. The content of water [5, 6] was an additional factor which modified the properties of the samples. It changed within 1.5 to 4.1% [6, 7]. The process of paper dampening consisted in a controlled by weight absorption of humidity from the surrounding air. Once the assumed weight of a sample was obtained (dampness level), impregnation with insulation oil was carried out. Figure 1 shows a measuring system (Fig. 1.a), a container in which the samples of the insulation under study were immersed (Fig. 1.b) and voltage runs occurring during the research tests (Fig. 1.c).



a)

Fig. 1.a Laboratory measuring system for diagnostics of paper-oil insulation with RVM method

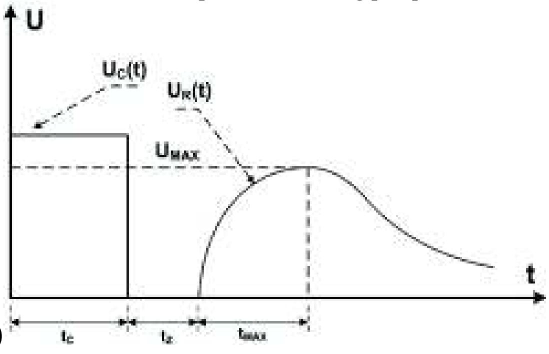
1- voltage source, 2- insulation sample under study, 3- reed relay switches, 4- time controller, 5- voltage divider, 6- amplifier, 7- A/C transducer, 8- computer



b)

Fig. 1.b Container for testing paper-oil insulation samples

1- glass container, 2- metal electrodes (stainless steel), 3- insulation sample, 4- insulation oil level, 5- temperature and humidity sensor, 6- valve, 7- oil circulating pump, 8- water heater



c)

Fig. 1.c Voltage runs occurring during diagnostics with RVM method

U_C- charging voltage, t_C- charging time, t_Z- fault time, U_R- return voltage, U_{MAX}- return voltage maximum value, t_{MAX}- time of obtaining value U_{MAX}

A two-factor analysis of variance was applied for the analysis of the return voltage results obtained, which changed due to two factors – aging and humidity content. The calculations were made in STATISTICA program. A dependent variable was return voltage $\mathbf{U_{max}}$, and independent variables were dampness marked as **(A)** and aging degree **(B)**. Two levels of dampness were assumed for the variance analysis (1, 2) and three aging levels – (1, 2, 3). Level (**A-1**) contained dampness measurement results from the range 1.5 ÷ 3.0 %. The other level (**A-2**) contained the results from the range 3.1 ÷ 4.1 %. In factor **B** characterizing aging hazard, level (**B-1**) referred to fresh samples. The level marked as (**B-2**) is connected with connected with the samples subjected to thermal hazard in temperature 150°C within 24 hours. The samples in which the temperature of hazard was increased to 170°C, were connected with level (**B-3**).

3. STATISTICAL ANALYSIS OF THE RESEARCH RESULTS

The application of the multifactor variance analysis [8] for the results obtained from the paper-oil insulation tests makes it first of all possible to determine which of the factors – dampness or aging – influences significantly the maximum value of return voltage ($\mathbf{U_{max}}$). It was also possible to determine whether the influence of these factors is independent or whether there exists interaction in this scope. The results of the variance analysis are shown in Table 1.

Table 1. Analysis of Variance for $\mathbf{U_{max}}$ - Type III sums of Squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	p-Value
Main effects					
Factor **A**	43923,3	1	43923,3	13,16	0,0055
Factor **B**	21903,5	2	10951,7	3,28	0,0850
INTERACTIONS **AxB**	3068,22	2	1534,11	0,46	0,6455
RESIDUAL	30033,3	9	3337,03		
TOTAL (CORRECTED)	96483,1	14			

All F-ratios are based on the residual mean square error

The values of the Fisher statistics and corresponding probability levels, at the assumed significance level 5% show that the content of water has a significant influence on value $\mathbf{U_{max}}$.

This is confirmed by a low p-Value (lower than the significance level assumed). The effect of the aging process is negligible. Also the interaction of the two factors is of little significance. Table 2 shows a collective listing variance $\mathbf{U_{max}}$ values for each factor level, standard errors and uncertainty intervals.

Differences in dispersion and confidence intervals can be analyzed additionally by Multiple Range Tests. Table 3 shows the results of such an analysis for factor **A**. They indicate that the differences in the levels of this factor are significant and the groups under study are not homogeneous. Also in the case of factor **B** (Table 4), levels 1, 2 are characteristic of a statistically significant difference. The results listed in the tables are also shown in Figures 4 and 5 in the form of mean values and confidence intervals. The lack of interaction of the two factors is shown in Figures 6 and 7.

Table 2. Table of Least Squares Means for $\mathbf{U_{max}}$ with 95,0 Percent Confidence Intervals

Level			Count	Mean	Stnd. Error	Lower Limit	Upper Limit
GRAND MEAN			15	159,233			
Factor **A**							
	1		7	104,004	22,2345	53,7063	154,303
	2		8	214,462	20,7985	167,413	261,512
Factor **B**							
	1		6	187,210	23,5833	133,861	240,559
	2		5	104,535	26,3669	44,8887	164,181
	3		4	1285,955	28,8835	120,616	251,294
A by B							
	1	1	3	126,633	33,3518	51,1861	202,081
	1	2	2	69,690	40,8475	-22,7136	162,094
	1	3	2	115,690	40,8475	23,2864	208,094
	2	1	3	247,787	33,3518	172,339	323,234
	2	2	3	139,380	33,3518	63,9328	214,827
	2	3	2	256,220	40,8475	163,816	348,624

Table 3. Multiple Range Tests for $\mathbf{U_{max}}$ by **A**

Method: 95,0 percent LSD Factor **A**	Count	LS Mean	Homogeneous Grups	
1	7	104,004	X	
2	8	214,462	X	
Contrast			Difference	+/- Limits
1 - 2			*-110,458	67,6325

*denotes a statistically significant difference

Table 4. Multiple Range Tests for $\mathbf{U_{max}}$ by **B**

Method: 95,0 percent LSD Factor **B**	Count	LS Mean	Homogeneous Grups	
2	5	104,535	X	
3	4	185,955	XX	
1	6	187,210	X	
Contrast			Difference	+/- Limits
1 – 2			*82,675	79,1297
1 – 3			1,255	84,3526
2 – 3			-81,420	87,6618

*denotes a statistically significant difference

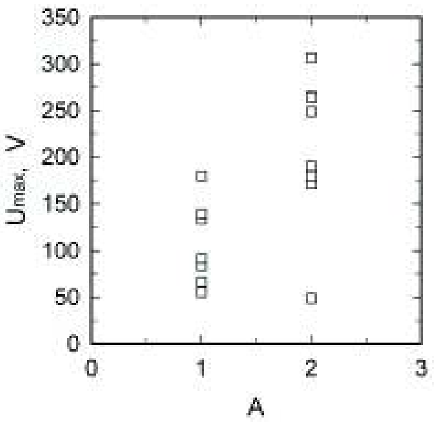


Fig. 2. Dispersion of value U_{max} for various levels of Factor **A**

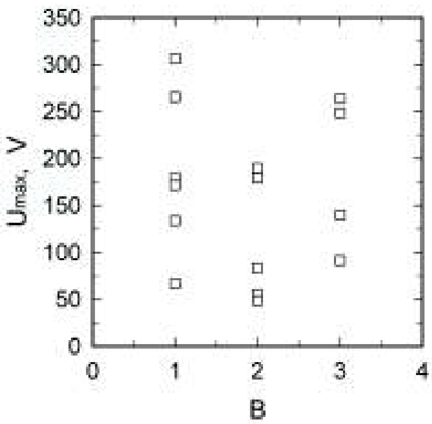


Fig. 3. Dispersion of value U_{max} for various levels of Factor **B**

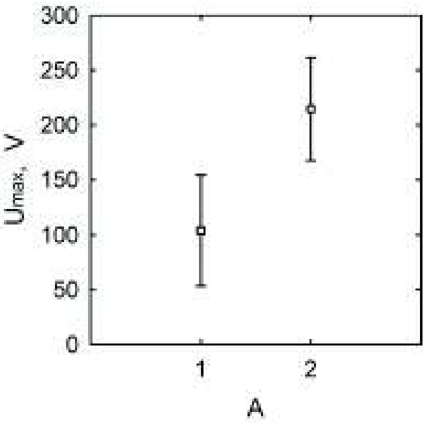


Fig. 4. Mean values and uncertainty intervals U_{max} for various levels of Factor **A**

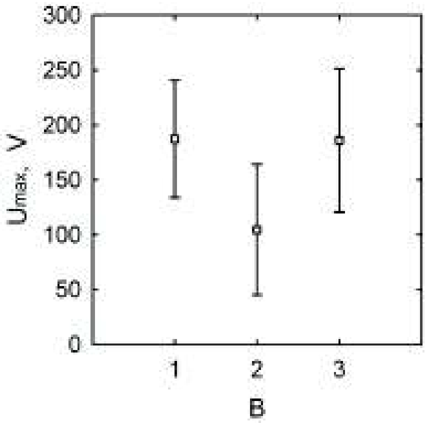
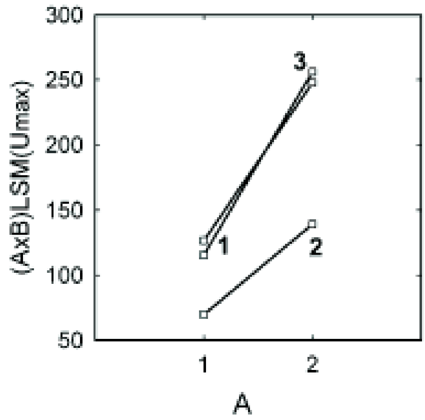


Fig. 5. Mean values and uncertainty intervals U_{max} for various levels of Factor **B**



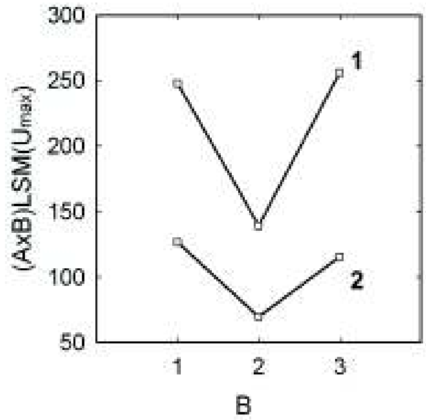


Fig. 6. Interaction **A×B** for various levels of Factor **A**

Fig. 7. Interaction **A×B** for various levels of Factor **B**

4. SUMMING-UP

Multifactor and multidimensional variance analysis is a very useful research tool, widely used in various branches of research work. The research analysis carried out by using this method made it possible to assess the influence of two factors on $\mathbf{U_{max}}$ of the return potential measured. It was proved that it is dampness that has a statistically significant influence and not the processes taking place due to thermal hazard. The analysis carried out made it also possible to rule out mutual interaction of these factors. The Multiple Range Tests make the assessment of the homogeneity of the results obtained possible.

LITERATURE

[1] M. Zdanowski, S. Wolny, D. Zmarzły, J. Kędzia, The Analysis and Selection of the Spinning Disk System Parameters for the Measurement of Static Electrification of Insulation Oils, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 14 No. 2, April 2007, pp. 480-486

[2] S. Wolny, J. Kędzia, M. Zdanowski, Analiza elektryzacji strumieniowej w ujęciu modeli przepływu laminarnego i turbulentnego, *Przegląd Elektrotechniczny- Konferencje v.4 1/2006*, VIII Ogólnopolskie Sympozjum Inżynieria Wysokich Napięć, Będlewo 8-10 maja 2006, pp. 276-278

[3] Saha T. K., Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers, *IEEE Trans. on Dielectr. and Electrical Insul.,* Vol. 10, October 2003, 903-917

[4] S. Wolny, Analiza zaniku napięcia powrotnego izolacji papierowo-olejowej, *Przegląd Elektrotechniczny-Konferencje v.4 1/2006*, VIII Ogólnopolskie Sympozjum Inżynieria Wysokich Napięć, Będlewo 8-10 maja 2006, pp. 272-275

[5] S. Wolny, The Influence of Temperature and Dampness on the Value of the Main time Constant of Paper-Oil Insulation Determined by Using Deby's Model, *Physics and Chemistry of Solid State V. 7 No. 3 2006*, pp. 572-576

[6] S. Wolny, D. Zmarzły, Wpływ temperatury i wilgotności na wybrane parametry napięcia powrotnego izolacji papierowo-olejowej, *Energetyka - Zeszyt Tematyczny nr VI*, kwiecień 2005, Konferencja Naukowo-Techniczna „Transformatory w eksploatacji", Kołobrzeg 20-22 kwietnia 2005, pp.59-61

[7] S. Wolny, The influence of temperature and humidity on time-constant of paper-oil insulation determined by using the recovery voltage model, *IV International Conference NEET'2005*, Zakopane 21-24 June 2005, pp. 215-217

[8] A. Luszniewicz, T. Słaby, Statystyka z pakietem komputerowym STATISTIKA PL, *C.H. Beck Warszawa 2003.*