A Ccombined TOPSIS and FA Based Strategic Analysis of Technical Condition of High Power Transformers

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Abstract. *The paper presents mathematical model – TOPSIS method, which was utilized on insulating state of distribution transformer to analyze and sensibility of individual measurements methods mutual comparison. We can uniquely determine the importance of these measurements methods with this mathematical apparatus in these measurements methods in insulating state of transformers.*

Keywords

Assigning indicators, high power transformers, TOPSIS method.

1. Introduction

With regard to the development of the world and national economies, also control, maintenance and its analysis by mathematic calculations becomes an important subject [1], [2], [4], [19], [20], [21], [22], [26]. This sphere also includes power transformers, where their proper function has a positive impact on the trouble-free supply of electricity and heat for industries and households. It is therefore necessary, in the absence of scientific and research potential in distribution utilities, to achieve the objectives of the proposed activities, i.e. in-depth analysis of undesirable impacts on devices condition, design of measurements and their verification, and design of new diagnostic procedures for improving reliability of power transformers.

In case we want to determine the real insulating state of a transformer and then lifetime of insulation, is necessary to analyze some measurements in individual types of assays and then determine their exactness and reliability with mathematical models. We can exactly prove the importance of these assays by mathematical and statistical models in the field of analysis of the insulating state of transformers [23], [24].

For mathematical analyzing these assays measurements we chose within the frame of comparison of the degree of sensitivity in single methods of the insulating state of distribution transformers 110/22 kV:

- insulation resistance and polarizing index R_{60}/R_{15},
- dissipation factor and capacity: $\tan\delta$ and C,
- relative change of short-circuit voltage $\mathrm{d}U_k$.

2. Description of Chosen Measurements

The oldest and easiest method of inspecting the state of insulators is by means of insulation resistance measuring. The main disadvantage of this method is that insulation resistance does not only depend on the state of insulation but also on its type and dimensions. Insulation resistance method can be used to evaluate the state of insulation of electric device only on the basis of previous experience with the same insulation on the same devices.

The method is based on the following principle: change in insulator state causes a change in time dependence of a current flowing through the insulator by DC voltage [8]. A current flowing through an insulator consists of a time-decreasing absorption element and stabilized element. The more water content there is in the insulation, more apparent increase of the stabilized element of a current is the observed comparing to the absorption element. The absorption element of a current has a low effect on the characteristics of time dependency in relation to the current as well as the resistance, and flattens with increasing humidity (Fig. 1).

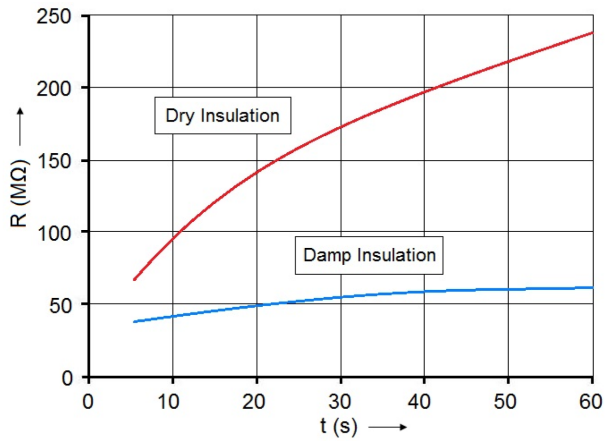

Fig. 1: Time dependence of the insulation resistance.

Utilizing this knowledge for evaluation of the insulation state does not require determining the full time dependence of a current. It is enough to determine the value of a current (resistance) in two different moments from the time of connection to DC voltage. The ratio of these two values defines the state of insulation and is called the polarizing index. Since it is a non-dimensional parameter, it does not depend on the dimension of insulation. Polarizing index is measured after 1 and 10 min or after 15 and 60 s.

So for the better illustrate the change in values of the polarizing index, it needs to be expressed by both elements of a current - absorption element i_a and stabilized element i_∞:

$$p_i = \frac{R_{60}}{R_{15}} = \frac{i_{a15} + i_\infty}{i_{a60} + i_\infty}. \tag{1}$$

The humid and contaminated insulation is determined by i_∞, therefore numerator and denominator are very close values and their ration tends towards 1. On the other hand, the dry and clean insulation which is in good condition has a very low stabilized current and the time dependent element i_a is dominant. Thus, the fraction value is noticeably higher than 1. The polarizing index of new transformers before usage in operation should reach at least 1,3.

The measurements of the dissipation factor (tan δ) and the capacities of transformer windings are used for additional determination of the insulation quality as whole or only of some parts of the transformer. The value of tan δ indicates the presence of polar and ion compounds in oil and it also determinates the aging of oil. The degree of oil humidity can be measured by temperature dependence of tan δ [8].

Changes in the state of short-circuit voltage dU_k (impedance) express geometrical winding movements and their construction changes in transformers. This technical condition depends on the thermal and mechanical effects of short-circuit currents.

By means of measurement of short-circuit voltage we can identify the mechanical and insulating deformation of the winding of a transformer.

Absolute value of short-circuit voltages usually are not sufficient to qualify the condition of winding without knowledge of their evolution in time, so the analysis is based on comparison of values for a specified time of operation of a transformer.

3. Composite Indicator and TOPSIS Method

A composite indicator (CI) is a mathematical aggregation of a set of individual indicators that measure a multi-dimensional concept [25]. There are m comparised alternatives, each alternative consists of n sub-indicators x_{ij}. For each alternative is evaluated CI. CI is used for the performance measurements, benchmarking, via providing an aggregated performance index in various fields such as Human Development Index, Road Safety Index [2], [3], [16], [17], [18], [27].

The graphical representation of CI construction is illustrated on Eq. (2). There are m comparised alternatives, each alternative consist n sub-indicators x_{ij}. For the each alternative is evaluated CI. Sub-indicators usually have no common measurable units.

The TOPSIS method is used to analyze a multi-criteria decision making problem with m alternatives with n criteria. In the TOPSIS method, the best alternative should have the shortest Euclidean distance from the positive ideal solution (PIS) and the longest distance from the negative ideal solution (NIS). The PIS is a hypothetical solution which maximum values from the database of all alternatives, and the NIS is a hypothetical solution which minimum values from the database of all alternatives. TOPSIS defines an index called relative closeness to the PIS and remoteness from the NIS [7]. This index can be used as a CI of alternatives.

Generally, the structure of CI can by expressed by the Eq. (3):

$$\begin{array}{c} alternative\ \ 1 \\ alternative\ \ 2 \\ \vdots \\ alternative\ \ m \end{array} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \rightarrow \begin{bmatrix} CI_1 \\ CI_2 \\ \vdots \\ CI_m \end{bmatrix}. \quad (2)$$

$$CI = \sum_{i-1}^{n} w_i I_i, \quad (3)$$

where w_i means weight assigned to indicator i.

The main procedure of the TOPSIS method is described in the following steps:

Step 1: Define a decision matrix:

The decision matrix **D** of $m \times n$ dimension consists of values of n sub-indicators for m alternatives.

Step 2: Normalize the decision matrix:

The values of sub-indicators are normalized to a scale 0–1. In case of "benefit type" indicators, what means a higher value is better, as is used in the formula:

$$x'_{ij} = \frac{x_{ij} - min_i\{x_{ij}\}}{max_i\{x_{ij}\} - min_i\{x_{ij}\}}. \quad (4)$$

With "cost type" sub-indicators, what means the lower value is better. They are normalized in the following way:

$$x'_{ij} = \frac{max_i\{x_{ij}\} - x_{ij}}{max_i\{x_{ij}\} - min_i\{x_{ij}\}}. \quad (5)$$

As a result is obtained the normalized decision matrix **D'**.

Step 3: Compute the weighted normalized decision matrix:

Elements of the normalized decision matrix **D'** are multiplied by weight vector **W**, which consist of n weight factors w. These factors express the relatively importance of criteria. The elements of weighted normalized decision matrix **V** are expressed as:

$$v_{ij} = w_j x'_{ij}. \quad (6)$$

Step 4: Identify the PIS and NIS:

The positive ideal solution A^+ and the negative ideal solution A^- can be expressed as:

$$A^+ = (max_i\{v_{i,1}\}, .., max_i\{v_{i,n}\}) = \left(v_1^+, ..., v_n^+\right), \quad (7)$$

$$A^- = (min_i\{v_{i,1}\}, .., max_i\{v_{i,n}\}) = \left(v_1^-, ..., v_n^-\right). \quad (8)$$

Step 5: Calculate the distance to PIS and NIS:

For each alternative i the Euclidean distance d_i^+ to the positive ideal solution and distance d_i^- to the negative ideal solution is defined [7].

Step 6: Compute the relative closeness data to CI:

Values d_i^+ and d_i^- are combined to relative closeness index C_i:

$$C_i = \frac{d_i^-}{d_i^+ - d_i^-}. \quad (9)$$

The C_i is a composed indicator CI of alternative i.

4. Composite Indicator and TOPSIS Method

To express the subjectiveness and imprecision of the evaluation process, the sub-indicators and weights are represented by a triangular fuzzy number [7]. A triangular fuzzy number $\tilde{n}$ can be define by a triplet (a, b, c) shown in Fig. 2. The membership function $\mu_{\tilde{n}}$ is defined as:

$$\mu_{\tilde{n}}(x) = \begin{cases} \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0 & otherwise \end{cases}, \quad (10)$$

where $a < b < c$. The b is the most possible value of a fuzzy number.

Let two triangular positive triangular numbers $\tilde{n}_1 = (a_1, b_1, c_1)$, $\tilde{n}_2 = (a_2, b_2, c_2)$ and a positive real number r. Similarly as in the case of real numbers, the operations of positive fuzzy numbers can be defined as follows [7]:

$$\tilde{n}_1(+)\tilde{n}_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2), \tag{11}$$

$$\tilde{n}_1(\times)\tilde{n}_2 = (a_1 a_2, b_1 b_2, c_1 c_2), \tag{12}$$

$$\tilde{n}_1(/)\tilde{n}_2 = (a_1/a_2, b_1/b_2, c_1/c_2), \tag{13}$$

$$1/\tilde{n}_1 = (1/c_1, 1/b_1, 1/a_1), \tag{14}$$

$$r * \tilde{n}_1 = (ra_1, rb_1, rc_1). \tag{15}$$

The distance between fuzzy numbers can be defined:

$$D(\tilde{n}_1, \tilde{n}_2) = \sqrt{\frac{1}{3}\left[(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2\right]}. \tag{16}$$

Used fuzzy-TOPSIS model is similar to classic TOPSIS method. In step 1 decision matrix is generated, in step 2 this matrix is normalized. After normalization, the real values in the decision matrix and weight values are converted into fuzzy numbers. The 7-level scale of fuzzy numbers expressed in linguistic terms that are used (Tab. 1).

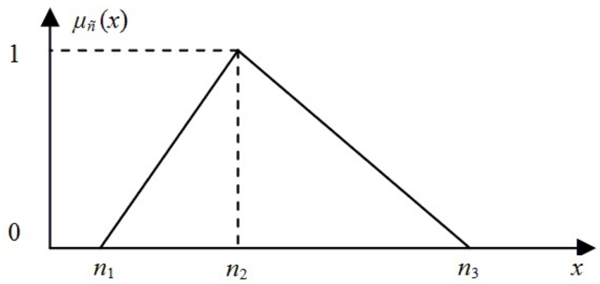

Fig. 2: Triangular fuzzy number $\tilde{N}$.

Tab. 1: Table of conversion real values into the fuzzy values.

Real value x	Linguistic value	Fuzzy value $\tilde{n}$
$0 \leq x \leq 1/7$	Very Low	$(0, 0, 1/6)$
$1/7 \leq x \leq 2/7$	Low	$(0, 1/6, 2/6)$
$2/7 \leq x \leq 3/7$	Medium Low	$(1/6, 2/6, 3/6)$
$3/7 \leq x \leq 4/7$	Medium	$(2/6, 3/6, 4/6)$
$4/7 \leq x \leq 5/7$	Medium High	$(3/6, 4/6, 5/6)$
$5/7 \leq x \leq 6/7$	High	$(4/6, 5/6, 1)$
$6/7 \leq x \leq 7/7$	Very High	$(5/6, 1, 1)$

The calculations in step 3 are proceeding with the fuzzy values. In step 4, the fuzzy values of PIS and NIS are defined as:

$$A_j^+ = \left(max_i \tilde{n}_{ij}^1, max_i \tilde{n}_{ij}^2, max_i \tilde{n}_{ij}^3\right), \tag{17}$$

$$A_j^- = \left(min_i \tilde{n}_{ij}^1, min_i \tilde{n}_{ij}^2, min_i \tilde{n}_{ij}^3\right), \tag{18}$$

where $\tilde{n}_{ij}^1$, $\tilde{n}_{ij}^2$, $\tilde{n}_{ij}^3$ are fuzzy values of fuzzy normalized decision matrix. In step 5 is calculated the distance to PIS and NIS by formula Eq. (18), in step 6 the relative closeness in the estimate by Eq. (11).

5. Assigning Indicators Weights by Factor Analysis

The values of the weights will be assigned by factor analysis. Factor analysis method is based on a reducing the dimensions of the problem, where the n dimensions are transformed into a p smaller number unobserved variables called factors. The idea of factor analysis can be described by the formula:

$$X = FY + E, \tag{19}$$

where **X** – matrix of the input data, **Y** – matrix of uncorrelated common factors, **F** – matrix of factor loadings, **E** – matrix of the specific factors.

The dimensionality of matrix **F** depends on the selected number of factors. Each factor explains a part of the variance of the input data.

The approach to the calculations of weight factors suggested in [2] consist the following steps:

Step 1: Define a number of factors:

Chosen factors should explain 70–80 % of the variance of the input data. Usually there are 2 or 3 factors.

Step 2: Define squared factor loadings:

Squared factor loadings can be described by the formula:

$$u_{ij} = \frac{a_{ij}^2}{\sum_{k=1}^{m} a_{kj}^2}, \tag{20}$$

where m – the numbers of the factors.

Step 3: Calculate preliminary weights:

The preliminary values of the weights can be expressed as:

$$w_j' = \frac{max_k u_{kj}}{e_k'}, \tag{21}$$

where e'$_k$ is the relative variation explained in the data sheet:

$$e'_k = \frac{e_k}{e}, \quad (22)$$

where e is total variation explained by chosen m number of the factors, e_k is variation explained by the k factor.

Step 4: Rescaling of the weights:

The final values of the weights are described by the formula:

$$w_j = \frac{w'_j}{\sum_{i=1}^{m} w_j}. \quad (23)$$

6. Results of the Calculation

Assigning of the weights of the criteria by factor analysis was the first step of the calculation. Two factors in factor analysis were chosen: factor 1 represents the parameters R_{60}/R_{15} and C, and explains 38 % of the total variance; factor 2 represents the parameters dU_k and tangent delta, and explains 34 % of the variance. The values of weights are presented in Tab. 2.

Tab. 2: Calculated values of the weights.

Parameter	Weight
R_{60}/R_{15}	0,24
dU_k	0,36
tangent delta	0,17
C	0,22

Assigned weights of the criteria were applied to fuzzy TOPSIS model. Tab. 3 presents the results of the calculations as well as the data for four sub-indicators.

To investigate the impact of criteria weights was realized the sensitivity analysis – were calculated values of CI for different sets of weights. The 11 experiments were conducted, the sets of weights are presented in Tab. 4, the results of the sensitivity analysis is showed in Fig. 3. There is shown range of standard deviation of CI calculated for 11 sets of weights and CI calculated in the previous part of the paper.

It is noticeable, that the assigned values of CI are placed in the range of the standard deviation, what confirm the reliability of the fuzzy TOPSIS method. In Fig. 4 is presented sensitivity analysis regarding the final outcome ranking – the technical condition of each transformer referred to the other transformers.

Better position in ranking means better technical condition – higher CI. The average position in sensitive analysis in every case is located closely to position based on the previous assigned value of CI. In some cases is visible significant between the maximal and the minimal position – columns T8, T10, T12. It can be explained by the disproportion between several technical parameters of transformer. That fact indicates a prerequisite of ill natured technical condition of transformer and can be used to identify a failure.

To investigate the accuracy of presented fuzzy TOPSIS method was realized the cluster analysis. Cluster analysis is a multivariate technique which informs about the similarity in the data set. Clustering is a task of assigning objects into groups – cluster. The objects in the same cluster are more similar to each other than to those in other clusters.

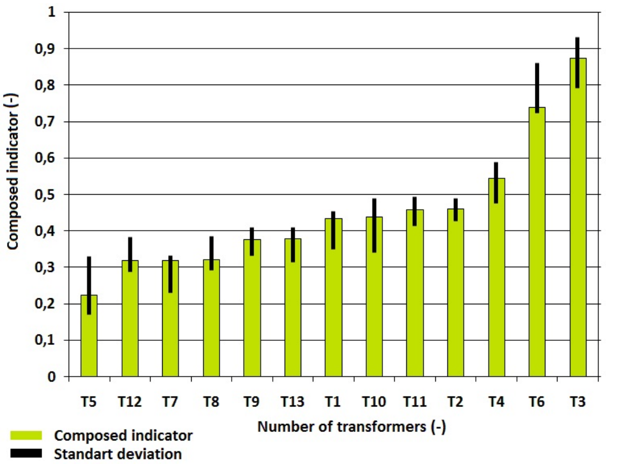

Fig. 3: The results of the sensitivity analysis - values of CI and standard deviation.

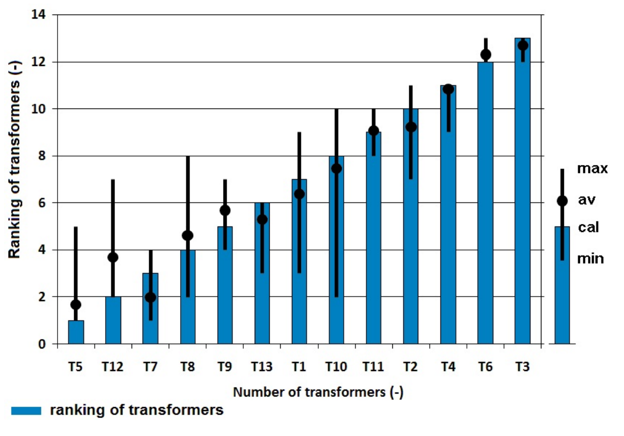

Fig. 4: The results of the sensitivity analysis - ranking of transformers, max, min, av - the highest, lowest, average ranking position obtained in sensitivity test, cal - position corresponding with CI value, better position means better CI valu.

The classification aims to reduce the dimensionality of a data set by finding the similarities between classes

Tab. 3: Four sub-indicatorsand CI values for the 13 transformers.

TR	Sub-indicators				Results of the calculations		
	R_{60}/R_{15}	dU_k[‰]	$\tan\delta$	C [pF]	d^+	d^-	CI
T1	1, 36	0, 47	0, 0217	2881, 4	0, 53	0, 41	0, 43
T2	1, 37	8	0, 0186	4746, 7	0, 51	0, 44	0, 46
T3	1, 58	4, 5	0, 0123	2996, 5	0, 12	0, 81	0, 87
T4	1, 44	7, 9	0, 0075	2731, 5	0, 41	0, 49	0, 54
T5	1, 31	42, 7	0, 0046	1957, 5	0, 74	0, 21	0, 22
T6	1, 55	32, 4	0, 0135	3815, 5	0, 27	0, 76	0, 74
T7	1, 25	0	0, 0424	3940, 0	0, 75	0, 35	0, 32
T8	1, 31	21, 4	0, 0177	4882, 0	0, 66	0, 31	0, 32
T9	1, 30	8, 95	0, 0160	4235, 3	0, 64	0, 39	0, 38
T10	1, 39	2, 41	0, 0122	2236, 0	0, 54	0, 43	0, 44
T11	1, 38	8, 93	0, 0153	3825, 2	0, 51	0, 43	0, 46
T12	1, 32	20, 4	0, 0126	4030, 7	0, 66	0, 31	0, 32
T13	1, 31	3, 64	0, 0187	3775, 0	0, 64	0, 39	0, 38

Tab. 4: Set of weights for sesitivity analysis.

Parameter	$\mathbf{R_{60}/R_{15}}$	$\mathbf{dU_k}$[‰]	tan	C [pF]
Set 1	0, 25	0, 25	0, 25	0, 25
Set 2	0, 5	0, 167	0, 167	0, 0167
Set 3	0, 167	0, 5	0, 167	0, 167
Set 4	0, 167	0, 167	0, 5	0, 167
Set 5	0, 167	0, 167	0, 167	0, 5
Set 6	0, 4	0, 4	0, 1	0, 1
Set 7	0, 1	0, 4	0, 4	0, 1
Set 8	0, 1	0, 1	0, 4	0, 4
Set 9	0, 4	0, 1	0, 1	0, 4
Set 10	0, 1	0, 4	0, 4	0, 1
Set 11	0, 1	0, 4	0, 4	0, 1
Set 12	0, 1	0, 4	0, 4	0, 1
Set 13	0, 24	30, 36	0, 017	0, 22

[2], [5], [6]. A dendogram is the result of method and illustrates the relationships between objects. On Fig. 5 is shown dendogram obtained by the clustering.

It is seen, that the location of the transformers on dendogram corresponds with the values of CI. Transformers with the similar value of CI are located near on the dendogram, e.g. T8 and T12, T9 and T13. The most "separately" located are cases T3, T6, T5 and T7. It may be explained by CI values: T3 and T6 got the best rating, T5 and T7 one of the worst. Thus, the position of points can be used as an indicator of transformer insulation condition.

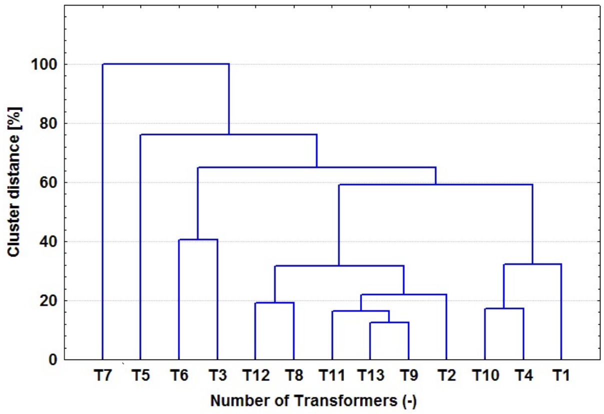

Fig. 5: Dendogram based on hierarchical clustering.

7. Conclusion

On the basis of summary results of the mathematical CI model, there can be set optimized modern techniques for the diagnosis of insulation state chosen oil transformers, thereby a higher quality of trouble-free distribution of heat and electricity will be achieved.

A composed indicator has been accepted as a useful tool in many non-technical areas, such economy, society, and environment [9], [10], [11], [12], [13], [14],[15]. In this paper is presented the application of CI in the field of technical sciences. Beside this, other presented methods of MCDA (e.g. hierarchical clustering) can be used for evaluation the technical condition of electrical equipment.

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