FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 33, N^o 4, December 2020, pp. 571-581
https://doi.org/10.2298/FUEE2004571M

POWER TRANSFORMER HEALTH INDEX ESTIMATION USING EVIDENTIAL REASONING

Srdjan Milosavljević[1], Aleksandar Janjić[2]

[1]Electrotechnical Institute “Nikola Tesla” Belgrade, Serbia
[2]University of Niš, Faculty of Electronic Engineering, Niš, Serbia

Abstract. *Market-oriented power distribution system requires a well-planned budget with scheduled preventive and corrective maintenance during a replacement of units that are in an unsatisfactory condition. In recent years, the concept of the transformer health index as an integral part of resource management was adopted for the condition assessment and ranking of ETs. However, because of the lack of regular measurement and inspections, the confidence in health index value is greatly reduced.*

The paper proposes a novel methodology for the ET condition assessment and the lifetime increase through the establishment of priorities for control and maintenance. The solution is based on the upgraded health index, where the confidence to the measurement results is calculated using Evidential reasoning algorithm based on Dempster – Shafer theory. A novel, two – level hierarchical model of ET health index is proposed, with real weighting factors values. This way, the methodology for ET ranking includes the value of available information to describe ET current state. The proposed methodology is tested on real data of an installed ET and compared with the traditional health index calculation.

Key words: *Dempster Shaffer, Evidential reasoning, Health index, Condition evaluation*

1. INTRODUCTION

Reliability of energy power transformers (ETs) is vital in maintaining the stability of the power system. The market-oriented system and deregulation in the electricity industry requires a well-planned schedule of preventive maintenance and corrective maintenance or replacement of units that are in unsatisfactory condition. However, inspection and testing schedules are predetermined and defined by legislation or internal regulations and company rules for all substations, regardless of their status and importance [1].

In the current practice of most electric utilities, condition diagnostics of each individual ET has been presented descriptively, especially in the field of chemical and electrical tests. In recent years, work has been done on defining a methodology to perform an integral quantification of ET states based on the results of chemical and electrical tests,

---

Received March 5, 2020; received in revised form May 7, 2020

Corresponding author: Aleksandar Janjić
Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: aleksandar.janjic@elfak.ni.ac.rs

maintenance data and work history data, by introducing a state index or so-called "health index" (HI) which would rank ET by its actual condition. Transformer indexing by operating condition, with additional risk analysis, enables a better understanding of the availability and reliability of large transformer populations.

HI is a tool that combines the results of in-service electrical testing, laboratory (chemical) testing of transformer oil, maintenance data and work history data to manage basic resources and build priorities when designing maintenance plans using a numerical ranking of transformer status and capital investment. In [2], a practical HI calculation method is given, combining the impact of all available data and criteria based on the common practices and technical standards. Based on the standard model of twenty-four diagnostic factors, additional three factors (loss factor at very low frequency, conductivity factor and polarization index) are used for the HI calculation in [3]. HI concept can be extended to other equipment, like in [4], where HI was determined for a number of around 2000 secondary substations, each consisting of a MV switchgear, MV/LV transformer and LV rack. A comprehensive study of previous research related to transformer health index by using mathematical models, algorithm or expert judgment is given in [5].

The problem with the traditional HI calculation is the generation of an overall assessment about the transformers condition by aggregating the above judgments in a rational way. Furthermore, very few researches are dealing with the uncertainties, accuracy and confidence of the inspection results. The evidential reasoning (ER) approach is suitable method for dealing with the aggregation problem, turning a transformer condition assessment problem into an multi-criteria decision solution. The process can model various types of qualitative and quantitative uncertainties and is developed on the basis of Dempster- Shafer evidence theory [6] and evaluation analysis model [7].With the introduction of the concepts of belief structure [8, 9] and the belief decision matrix, it became possible to model various types of uncertainties in a unified format.

In recent period, the usage of ER methodology has been applied for the ET condition assessment. In [10], various dissolved gas analysis (DGA) methods have been given different subjective judgment grades. Then, the concept of a preference degree was introduced to quantify these evaluation grades and subjective judgments with uncertainty. ER approach is used in [11] to transformer winding assessment based on frequency response analysis (FRA), but the degree of uncertainty, like in the previous study, relies only on the expert’s judgement. The integrated fuzzy and evidential reasoning model is presented in [12], with previous operation history, results of the latest inspection and states of the onload tap changer taken as evidence to assess the working state of the transformer. The fuzzy model is proposed for generating the original basic probability assignments for the second-level model. The testing data of indices are normalized according to the attention value on transformer tests and operation standards, but the practical grade assessment of different ET components has not been analysed.

This paper presents the new methodology for the ET condition assessment and prioritization, solving three main problems of previous condition assessment approaches:

- rational aggregation of different ET components,
- uncertainties, accuracy and confidence of the inspection results
- consistent grade assessment and weighting of different ET components.

The novel methodology is based on the upgraded HI where the ER methodology has been used for the quantification of uncertain data, as a general, multi-level evaluation process for dealing with multi-criteria decision problems. A basic tree structure necessary for ER assessment is developed based on the modified two-level transformer model and individual HI of every component. The importance of different components and different inspection methods are both evaluated by the real and practical weighting factors used in ET maintenance practice. The ET condition is represented as a belief distribution over all possible health states. The comparison with the traditional HI calculation method shows that the novel methodology gives more accurate results in the presence of obsolete and inaccurate measuring data.

The rest of the paper is organized as follows. After the introductory section, section 2 presents the methodology: briefly outlines the HI approach and how it works as prioritization method, and explains the evidence reasoning algorithm. Section 3 provides an illustrative example of the proposed methodology, data analysis and a discussion, while section 4 gives a conclusion and further research activities.

2. HEALTH INDEX ASSESSMENT

2.1. Health index definition

In recent years, the numerical assessment (indexing) of the current state of ET and other high-voltage equipment in plants assigning a HI emerges as a tool that could effectively provide a transition to condition based maintenance. HI is a numerical value that can be used to estimate the overall condition of an ET. By individually evaluating the most representative key factors that are vital to the reliable operation of transformers and mathematically aggregating them into a quantitative index, this value provides information on the "health" of the ET.

With this index, it is possible to evaluate the state of a large population of distribution transformers and group them according to the state. Introducing this concept, the availability and reliability will increase while reducing maintenance costs.

The assessment of the condition of an ET is based on [13]:

- results of electrical and chemical tests
- maintenance information
- transformer work history (previous loading)
- condition of equipment: isolators, cooling system, transformer tank, expansion tank and auxiliary equipment
- the estimated condition of the paper insulation
- expert opinion.

HI represents the sum of these estimates. It is very important to view the health index as a variable parameter because, by performing a multi-parameter analysis of the condition, it changes over the life of the ET [14]

The assessment of the condition of the ET should include an assessment of the condition of the key parts: magnetic core and coil, solid insulation and insulating oil, bushings and voltage regulators, cooling system, transformer tank, expansion tank and auxiliary equipment. The assessment is based on the results obtained by applying appropriate test methods in the field of chemical and electrical testing and visual inspection as well as evaluation of load histories [15, 16]. The health indices for each of these parts, as well as the ET HI must be determined.

2.2. Weighting factors of examination methods

The transformer health index should include an assessment of the condition of its key parts (Table 1). Each part of the ET is assigned a weight factor W_d based on the impact it has on the overall condition of the ET. The impact of part of ET is also estimated according to the current statistics of the place of occurrence of failure in ET [11]. Weighting factors are given based on experience, and can take the integer value from 1 to 5, as shown in Table 1. The source of weighting factors values is the industry practice. The condition monitoring and assessment is performed for the long time period in Serbian power industry and the factors are the result of accumulated practice and experience. The more detailed explanation is given in [17].

Table 1 Weighting factors for different ET components

No	ET component	Weighting factor (W_d)
1	Magnetic core	3
2	Geometry end electric contacts of windings	4
3	Insulation	4
4	Bushings	5
5	On line tap changer	5
6	Dissolved Gas Analysis (DGA) for the active part	5
7	Transformer oil	4
8	Transformer tank and auxiliary equipment	2
9	Work history	3

Different test methods are used to evaluate the condition of each of the above parts of the ET. Some parts are joined by a group of appropriate test methods, each corresponding to a weight factor W_m = (1–5), depending on how accurately the results of that method can describe the state of ET component (Table 2).

Table 2 Weighting factors of different inspection methods

ET component	No	Inspection method	Weighting factor (W_m)
Magnetic core	1	Open circuit test/ SFRA	5
Geometry end electric contacts of windings	2	Resistance testing	5
	3	Leakage inductance test /SFRA	5
Insulation	4	Insulation resistivity/tgδ and capacitance test	5
	5	PDC/RVM/FDS/Water content in oil	4
	6	Furan derivatives analysis	3
Bushings	7	tgδ and capacitance	4
On line tap changer	8	Static/dynamic resistance testing	5
DGA analysis for the active part	9	Dissolved gas analysis (DGA)	4
Transformer oil	10	Physical and chemical oil characteristics	5
	11	Content of water in oil	4
Transformer tank and auxiliary equipment	12	Testing of cooling system and auxiliary equipment	2
	13	Visual inspection-/Leakage control	2
Work history	14	Loading and operation history	3

Since the dissolved gas analysis (DGA) of the transformer oil sample may indicate a problem of overheating or the occurrence of particles, but it cannot reliably define the location of the resulting fault, it is singled out as special category. This limited its impact on the value of total HI, but not on specific components, such as windings or cores.

2.3. Overall Health Index

The overall health index of a transformer can be calculated using:

$$HI = \frac{\sum_{i}^{n} O_{di} \cdot W_{di}}{\sum_{i}^{n} W_{di}} \tag{1}$$

O_d is a grade for each individual ET part in the range $0 \leq O_d \leq 3$:

$$O_d = \frac{\sum_{i=1}^{k} O_{mi} \cdot W_{mi}}{\sum_{1}^{n} W_{mi}} \tag{2}$$

In Equation (2), n corresponds to the number of components, while k corresponds to the number of test methods for which there are applicable results and which assess the state of a given system. The estimation of the O_m method is given by an expert on the basis of the results of the last and previous tests, experience and specificity of individual ETs, and using the criteria given in the applicable standards and technical recommendations. The possible range is $0 \leq O_m \leq 3$. The state estimates for electrical measurements are given in descriptive terms:” good”, “moderately good”, “moderately bad”, and “bad. The numerical range of each corresponding estimates for the health index calculation is shown in Table 3.

Table 3 Comparison of electrical and chemical test scores with appropriate numerical estimates for HI calculations

Test results	HI
Good	3
Moderately good	$2 \leq$ HI < 3
Moderately bad	$1 \leq$ HI < 2
Bad	< 1

Given that three-stage grading is usually used to diagnose the condition: "good", "doubtful" and "poor", the second grade in the methodology is divided into two grades: "moderately good" and "moderately bad". The criteria for the two grades is the same - the difference is that the “moderately good” rating indicates dubious results, but without major changes over time, e.g. comparing the last two to three trials and continuing the follow-up with more frequent testing. On the other hand, the rating "moderately bad" indicates a growing trend of deterioration of the transformer state, and it tightens control by more frequent testing, recommends additional testing, or emphasizes the need to plan for a specific intervention in the coming period.

Because of irregular inspection period, it is hard to perform accurate yearly ET condition assessment. Some data may be old several years and the main problem in interpretation is the lack of confidence of testing results. In this paper, evidential reasoning is used for the quantification of different parameters and the algorithm is presented in the following section.

2.4. Evidential reasoning algorithm

In a two level hierarchy of attributes with a general attribute at the top level and L basic attributes at the lower level e_i (i = 1, ..., L) it is possible to define a set of low level attributes as follows:

$$E = \{e_1, ...e_i, ... e_L\}. \tag{3}$$

The weights of the attributes are presented by $\omega = \{\omega_1, ...\omega_i, ...\omega_L\}$ where ω_i is the relative weight of the ith lower level attribute (e_i) with value between 0 and 1 ($0 \le \omega_i \le 1$). The evaluation grades are represented by

$$H = \{H_1, ...H_n, ...H_N\}, \tag{4}$$

(it is assumed that H_{n+1} is preferred to H_n) An assessment for *ith* basic attribute e_i may be represented by the following distribution:

$$S(e_i) = \{(H_n, \beta_{n,i}), n = 1, ...N\} \quad i = 1,\dots, L; \tag{5}$$

where $\beta_{n,i}$ denotes degree of belief and $\beta_{n,i} \ge 0$, $\sum_{n=1}^{N} \beta_{n,i} \le 1$. If $\sum_{n=1}^{N} \beta_{n,i} = 1$ then assessment $S(e_i)$ is complete. In opposite case, assessment $S(e_i)$ is incomplete. Eq. (6) denotes a complete lack of information on e_i

$$\sum_{n=1}^{N} \beta_{n,i} = 0 \tag{6}$$

Let H_n be a grade to which the general attribute is assessed with certain degree of belief β_n. The problem is to generate β_n by aggregating the assessments for all associated basic attributes e_i. For this purpose, following algorithm is used.

Let $m_{n,i}$ be a basic probability mass representing the degree to which basic ith attribute e_i supports judgment that the general attribute y is assessed to the grade H_n. Respectively, let $m_{H,i}$ be a remaining probability mass unsigned to any individual grade after all the N grades, concerning the e_i attribute, are considered. The basic probability mass is calculated in (7):

$$m_{n,i} = \omega_i \beta_{n,i} \quad n = 1,\dots, N. \tag{7}$$

The weight normalization is given by the following expression:

$$\sum_{n=1}^{N} \omega_n = 1 \tag{8}$$

Remaining probability mass is calculated as:

$$m_{H.i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i} \tag{9}$$

Suppose that $E_{I(i)}$ is a subset of the first i attributes $E_{I(i)} = \{e_1, e_2, \dots, e_i\}$ and according to that $m_{n,I(i)}$ can be probability mass defined as the degree to which all the i attributes support the judgment that y is assessed to the grade H_n. Also $m_{H,I(i)}$ is remaining probability mass unassigned to individual grades after all the basic attributes in $E_{I(i)}$ have been assessed. Probability masses $m_{n,I(i)}$, $m_{H,I(i)}$ for $E_{I(i)}$ can be calculated from basic probability masses $m_{n,j}$ and $m_{H,j}$ for all $n=1,\dots, N$, $j=1,\dots, i$. Concerning all above statements, the recursive evidential reasoning algorithm can be summarized by the following expressions:

$$m_{n,I(i+1)} = K_{I(i+1)}(m_{n,I(i)}m_{n,i+1} + m_{n,I(i)}m_{H,i+1} + m_{H,I(i)}m_{n,i+1}) \quad n = 1,\dots,N \tag{10}$$

$$m_{H,I(i+1)} = K_{I(i+1)}m_{H,I(i)}m_{H,i+1} \tag{11}$$

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N}\sum_{\substack{j=1\\ j\neq t}}^{N} m_{t,I(i)}m_{j,i+1}\right]^{-1} \quad i = 1,\dots,L-1 \tag{12}$$

where $K_{I(I+1)}$ is a normalizing factor so that $\sum_{n=1}^{N} m_{n,I(i+1)} + m_{H,I(i+1)} = 1$ is ensured. It is important to note that basic attributes in $E_{I(i)}$ are numbered arbitrarily and that initial values are $m_{n,I(1)}=m_{n,1}$ and $m_{H,I(1)}=m_{H,1}$. And finally, in original evidential reasoning algorithm combined degree of belief for a general attribute β_n is given by:

$$\beta_n = m_{n,I(L)}, n = 1,\dots,N \tag{13}$$

$$\beta_H = m_{H,I(L)} = 1 - \sum_{n=1}^{N}\beta_n \tag{14}$$

while β_H denotes degree of incompleteness of the assessment.

The algorithm for the ET assessment can be presented in following five steps:

Step 1. Define a set of L inspection methods (basic attributes) influencing the assessment of the ET component state (M is the number of components - upper level attributes). Determine the importance weighting of every inspection method W_d and each component W_m.

Step 2. For each attribute ε_i and evaluation grade H_n a degree of belief β_n is assigned. $m_{n,i}$ - a basic probability mass, representing the degree to which the ith inspection method ε_i supports a hypothesis that the Health index is assessed to the nth evaluation grade H_n is calculated (Eq. 7–9).

Step 3. The combined probability masses are generated by aggregating all the basic probability assignments using the recursive ER algorithm (12–14). This step is repeated for each basic attributes for one component.

Step 4. Calculate the combined degrees of belief for a higher level property. The combined probability masses are generated by aggregating all the probability assignments from previous step using the recursive ER algorithm (12–14). This step is repeated for each ET component.

Step 5. The procedure is terminated and the utility can be calculated.

The flowchart is presented graphically on Figure 1.

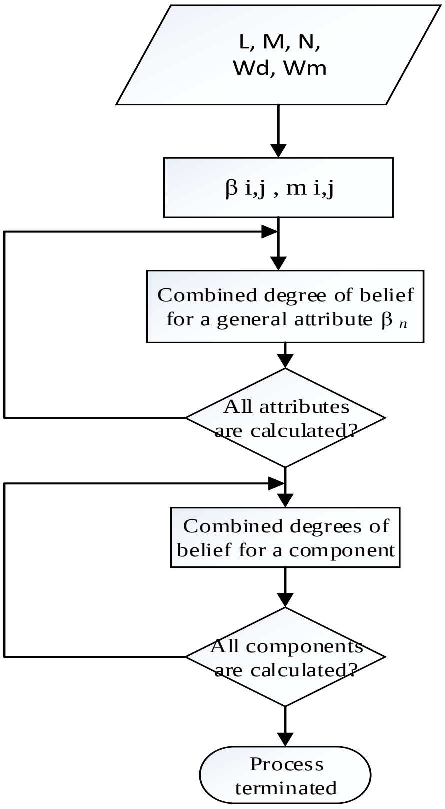

Fig. 1 Flowchart for the ET condition assessment

The methodology is illustrated on a real data from an ET operating in Serbian distribution utility and compared with the traditional HI calculation.

3. CASE STUDY

The methodology for the condition assessment will be applied to the existing transformer 110/35/10 kV, 20/20/10MVA operating in EPS (Electric Power Industry of Serbia). Starting from a complete model presented in Tables 2 and 3, a reduced model concerning only the main transformer parts without the on- line tap changer is presented on Figure 1. Because of different dates of inspection methods, different degrees of belief are presented in the table. The degree of belief denotes the source's level of confidence when assessing the level of fulfilment of a certain property. For instance, due to the lack of Frequency Domain Spectroscopy (FDS) test, all belief values equal to zero.

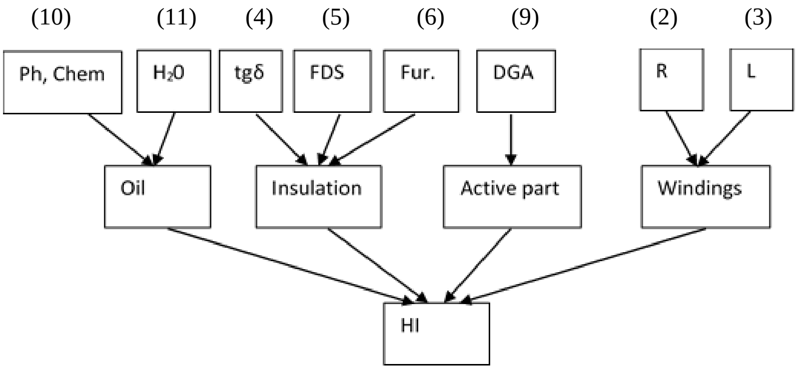

Fig. 2 Hierarchical scheme for transformer HI assessment

Numbers above the inspection methods in Figure 2 represent the ordinal number of inspection method listed in Table 2. Actual gradings for the transformer 110/35/10 kV were effectuated during regular inspection and maintenance activities and they are presented in Table 4. Results for Physical and Chemical measurements, active resistance and leakage resistance are two years old.

Table 4. Transformer assessment using traditional HI

	Oil		Insulation			Active part	Windings	
W_d	4		4			5	4	
W_m	5	4	5	4	3		5	5
	Phys, Chem	$H_2 0$	*tgδ*	*FDS*	*Furan*	*DGA*	*R*	*L*
O_m	3	2	1	-	3	2	3	3

Using the traditional HI calculation method (Equations 2), the grade O_d for oil, insulation, active part and windings equals 2.56, 1.75, 2 and 3, respectively. Using Equation (3), the value of HI is given in (15).

$$HI = \frac{\sum_{i}^{n} O_{di} \cdot W_{di}}{\sum_{i}^{n} W_{di}} = \frac{4 \cdot 2,56 + 4 \cdot 1,75 + 5 \cdot 2 + 4 \cdot 3}{17} = 2,3 \tag{15}$$

As stated before, some measurements are not actual (two years old) and some inspection methods are not absolutely accurate. The new methodology require the initial degrees of belief listed in Table 5. Weighting factors for ET component (W_d) and for testing method (W_m) are also presented in the table. Starting from values in tables 2 and 3, factors are normalized to fulfil the condition (8).

Table 5 Initial data for the degrees of belief calculation

	Oil		Insulation			Active part	Windings	
W_d	0,24		0,24			0,28	0,24	
W_m	0,55	0,45	0,41	0,34	0,25		0,5	0,5
H_i	*Phys, Chem*	H_20	$tg\delta$	*FDS*	*Furan*	*DGA*	*R*	*L*
	$(\beta_{i,1})$	$(\beta_{i,2})$	$(\beta_{i,1})$	$(\beta_{i,2})$	$(\beta_{i,3})$	(β_i)	$(\beta_{i,1})$	$(\beta_{i,2})$
3	0,5	0	0	0	0,8	0	0,5	0,5
2	0,5	0,8	0	0	0	0,9	0,3	0,3
1	0	0,2	0,8	0	0	0	0	0
0	0	0	0	0	0	0	0	0

Recursively using Equations (12) - (14) for the aggregation of probability masses for individual inspection methods, probability masses for individual ET components are obtained and represented in Table 6. For instance, assessment of the transformer oil (Oil) for the grade H_3 = "good", H_2 = "moderately good", H_1 = "moderately bad" and H_0 = "bad", equal to 0.17, 0.44, 0.045 and 0 respectively. The remaining probability mass (m_{hi}) equals 0.34.

Table 6 Degrees of belief for main transformer components

	$\beta_{i,3}$	$\beta_{i,2}$	$\beta_{i,1}$	$\beta_{i,0}$	$m_{h\ i}$
Oil	0,17	0,44	0,045	0	0,34
Insulation	0,062	0	0,14	0	0,8
DGA	0	0,252	0	0	0,748
Windings	0,153	0,07	0	0	0,777

By using equations (12 - 14) and with the values calculated in step 3, we get the combined degrees of belief for the H3 = "good", H2 = "moderately good", H1 = "moderately bad" equal to 0.32, 0.175, and 0.08 respectively.

Using the traditional HI calculation method, the transformer is graded as "moderately good" (Table 3). The ER methodology, however, gives the distribution of belief states, with 0.44 degree of belief that the transformer is in moderately good state, and the significant value that the transformer could be in the better state (0.17). According to current practice in EPS, grading the transformer in category 2, means that inspection should be carried out more often, resulting in increased expenses and non-supplied energy. Further research will be focused on the estimation of financial losses resulting from the interruption of electricity supply that can be caused by an ET failure.

4. CONCLUSIONS

Calculating the transformer health index produces an extremely useful tool for quality resource management, analysis of the current state of transformers in the network and planning preventative maintenance. This index provides an assessment of the status of the power transformer, which makes it possible to perform a comparative analysis between individual transformers, parts of the distribution system, and to set priorities and adequately channel financial resources and plan corrective measures to improve the HI that is, to ensure transformer operational readiness.

The methodology presented in the paper is using ER approach which is one of the latest developments in multi-criteria decision-making, applied for the prioritization of ET according to their condition. The methodology proved to be very useful in the field of reliability and stability of the distribution system. Unlike the traditional HI calculation method, the ER methodology gives the distribution of belief states that the transformer could be in better condition. According to current practice in EPS, grading the transformer in lower categories means that inspection should be carried out more often, resulting in increased expenses and non-supplied energy. Currently, the methodology doesn't address the precise economic model for the estimation of financial losses resulting from unnecessary interruption of electricity supply caused by inspections or on the other hand, interruptions that can be caused by failure. Therefore, further research will be focused on the more precise estimation of financial losses resulting from the interruption of electricity supply that can be caused by an ET failure or unnecessary inspections.

REFERENCES

[1] D Stevanović, A Janjić, "Influence of circuit breaker replacement on power station reliability", *Facta Universitatis, Series: Electronics and Energetics*, vol. 32, no. 3, pp. 331–344, 2019.

[2] A. N. Jahromi, R. Piercy, S. Cress, J. R. R. Service, W. Fan, "An Approach to Power Transformer Asset Management Using Health Index", *IEEE Electrical Insulation Magazine*, vol. 25, no. 2, pp. 20–34, 2009.

[3] B. Gorgan, P.V. Notingher, V.L. Badicu, G. Tanasescu, "Calculation of power transformers health indexes", Annals of the University of Craiova, Electrical Engineering Series, 2010 no. 34, pp. 13–18,

[4] M. Vermeer, J. M. Wetzer, P.C.J.M. van der Wielen, E. de Haan, E. de Meulemeester, Asset-management decision-support modeling, using a health and risk model. 2015 *IEEE Eindhoven PowerTech* 1–6.

[5] A. Azmi, J. Jasni, N. Azis, M.Z.A .Ab. Kadir, "Evolution of transformer health index in the form of mathematical equation", *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 687–700, 2017.

[6] G.A. Shafer, "Mathematical theory of evidence". Princeton University Press, Princeton, 1976.

[7] Z.J. Zhang, J.B. Yang, D.L. Xu, "A hierarchical analysis model for multi-objective decision making. Analysis, Design and Evaluation of Man–Machine System", Oxford, UK, pp. 13–18, 1990.

[8] J.B. Yang, M.G. Singh, "An evidential reasoning approach for multiple attribute decision making with uncertainty", *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 24, no. 1, pp. 1–18, 1994.

[9] J.B. Yang, D.L. Xu, "On the evidential reasoning algorithm for multi-attribute decision analysis under uncertainty", *IEEE Transactions on Systems, Man and Cybernetics Part A Systems and Humans*, vol. 32, no. 3, pp. 289–304, 2002.

[10] W. H. Tang, K. Spurgeon, Q. H. Wu, Z. J. Richardson, "An Evidential Reasoning Approach to Transformer Condition Assessments", *IEEE Transactions on Power Delivery*, vol. 19, no. 4, 2004.

[11] A. Shintemirov, W.H. Tang, Q.H. Wu, "Transformer winding condition assessment using frequency response analysis and evidential reasoning", *IET Electr. Power Appl.*, vol. 4, no. 3, pp. 198–212, 2010.

[12] R. Liao, H. Zheng, S. Grzybowski, L. Yang, Y. Zhang, and Y. Liao, "An Integrated Decision-Making Model for Condition Assessment of Power Transformers Using Fuzzy Approach and Evidential Reasoning", *IEEE Transactions on Power Delivery*, vol. 26, no. 2, 2011.

[13] E. Duarte, D. Falla, J. Gavin, M. Lawrence, T. McGrail, D. Miller, P. Prout, B. Rogan, "A Practical Approach to Condition and Risk Based Power Transformer Asset Replacement", In Proceedings of the IEEE International Symposium on Electrical Insulation IEEE, 2010.

[14] F. Scatiggio, A. Fraioli, V. Iuliani, M. Pompili, "Health Index: the TERNA's Practical Approach for Transformers Fleet Management", CIGRE, Paris, 2014.

[15] N. Dominelli, "Equipment Health Rating of Power Transformers" In Proceedings of the IEEE International Symposium on Electrical Insulation Indianapolis, USA, September, 2004, pp. 163–168.

[16] Life Management Techiques for Power Transformers", Cigre Working Group 12.18, Brochure 227, 2003

[17] J. Ponocko et all. "Health index as the part of asset management in the area of power transformers" (in Serbian), CIGRE conference, Zlatibor, 2015.