

Article

The Analysis of Power Transformer Population Working in Different Operating Conditions with the Use of Health Index

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Abstract: The management of the power transformer population is a complex process, as the grid companies operate thousands of devices. For this issue, the health index method can be applied to facilitate asset management. The algorithm can be used not only in the technical assessment of the individual units, but also to determine the relationships within the whole population. In this paper, the presented health index method consists of periodic oil diagnostics, including the physicochemical properties, dissolved gas analysis, and furfural content, and further assessment in terms of the criticality of the device to determine the technical condition. The algorithm was specifically designed to reflect even the smallest changes of the input parameters in the final score. The performance of the health index was tested on 620 oil analyses from 220 transformers divided into four subpopulations based on the service conditions. The results have proven to be largely dependent on the criticality level and the operating conditions of the device. The analysis of the study group has shown the influence of corrective maintenance on the mean value of the health index score.

Keywords: power transformer; health index; condition assessment; population management



Citation: Bohatyrewicz, P.; Mrozik, A. The Analysis of Power Transformer Population Working in Different Operating Conditions with the Use of Health Index. *Energies* **2021**, *14*, 5213. <https://doi.org/10.3390/en14165213>

Academic Editor: Inmaculada Fernandez

Received: 6 July 2021

Accepted: 19 August 2021

Published: 23 August 2021

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1. Introduction

Power transformers are a key component of the electric distribution system. They enable the transmission of electricity from power plants to consumers by linking the systems of different voltage levels. The electricity distribution operators strive to keep the availability rate as high as possible to ensure minimal negative impact on commercial activities. Transformer reliability has been the subject of research by the CIGRE Working Group A2.37 in recent years, the results of which have been presented in [1,2].

The periodic maintenance and technical diagnostics of transformers are widely described in the literature and updated periodically based on recently developed methods. The publications, in the form of standards or technical guides, can be divided into those that are global [3,4] and those that are national [5,6]. The aforementioned publications may be a source for the development of transformer operating instructions for power system operators.

The knowledge of methods for transformer technical condition evaluation by maintenance personnel is of great importance in the management of network assets. The expertise in this area facilitates the decision-making process. The paper [7] describes various operation strategies in the context of asset management. Based on national experience, an expert system [8] was created in Poland to manage the population of transformers based on their technical condition and importance in the system.

The power grid companies aim to operate cost-effectively, resulting mainly from the desire to reduce operating costs. As a consequence, the initial evaluation of the technical condition is carried out based on the diagnostics of the insulating oil and the visual assessment of transformer elements. These tests can be performed on a live transformer without causing downtime of some part of the power station, which means that they do not impair the commercial activities of the network operators. The advanced diagnostics are

usually performed only as indicated by the oil tests, during planned maintenance outages or after an emergency shutdown.

The power transmission companies operate transformer populations of up to several thousand units. Such large groups are a collection of individual units and tracking the technical condition of the entire population becomes a difficult task. It can be facilitated with the use of the health index method, which, depending on the used criterion parameters, presents the technical condition of the unit in a form of a single indicator, typically a numerical one.

The health index (HI) has found applications in transformer diagnostics in the previous decade. The existing algorithms vary in complexity—they may consist of a large number of inspection points [9] or be a simplified method consisting of oil diagnostics and operating conditions [10]. The application of the aforementioned methods was evaluated in [11] on a population of 52 transformers examined over a five-year period. The technical assessment based on the health index method may also be based on expert analysis [12], mathematical models [13], and intelligent algorithms, such as neuro-fuzzy networks [14] and combined artificial neural networks and adaptive neuro-fuzzy inference systems [15].

In this paper, the authors introduce a health index algorithm based on the guidelines provided by the technical committees and the experience in the area of transformer operation in the Polish power system. The presented health index uses linear functions to reflect any changes in the input parameters on the final score, which cannot be achieved with similar methods based on step functions. With the diagnostics based on periodic examinations, it is possible to determine the health index much more frequently than in the case of much more complex algorithms due to lower cost and less man-hour demands. Thus, a typical transformer will receive a technical assessment every year, which will add up to several dozen evaluations during its lifetime to significantly improve the health condition monitoring of the unit. The algorithm was tested on a large population of devices working in the Polish power system, which were characterized by various ages and different operating conditions.

2. Materials and Methods

2.1. Subject of the Research

The research was based on 620 individual analyses from 220 power transformers operating in Poland. The devices ranged from 15 to 220 kV in the rated voltage of the high voltage side and from 5 to 270 MVA in rated power. It must also be mentioned that all transformers were filled with mineral oil. The composition of the study group was characterized by the different operation philosophies, which allowed us to classify the following four groups of devices:

- Generator step-up (GSU)—transformers working in power generation plants as the step-up units or the devices supplying the auxiliary power directly from the generator;
- Electric arc furnace (EAF)—transformers working in the steel or ferroalloy plants as the power supply for industrial furnaces;
- Distribution—widely used in the power transmission grids;
- Industrial—transformers used to supply power to factories and process lines.

This was intended to make the study group diverse to ensure that it represents most types of power transformers in service. The analyzed population had to consist of devices of various average load levels, ranging from low, in the case of distribution transformers, to high for GSU units. Additionally, the EAF transformers were included in the study group as they face the most extreme operating conditions, such as frequent short circuits, harmonics, and thermal stress. The type distribution of the transformer population is presented in Figure 1.

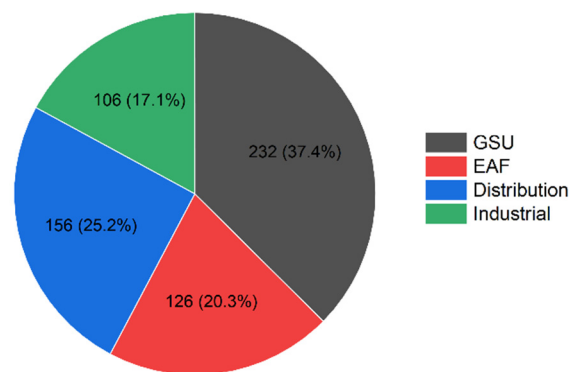


Figure 1. The distribution of operation type of the devices in the study group.

In the terms of age distribution, transformers ranged from less than one year to 50 years in operation. For the purpose of this study, the authors assumed that the average service life of a power transformer is 40 years. Although it is possible to extend this period when the units are in good condition, the authors chose not to include the results of transformers over 50 years old as their results tend to be misleading in the analysis of the whole spectrum of the population, which is later discussed in Section 4. The age distribution of the study group is presented in Figure 2.

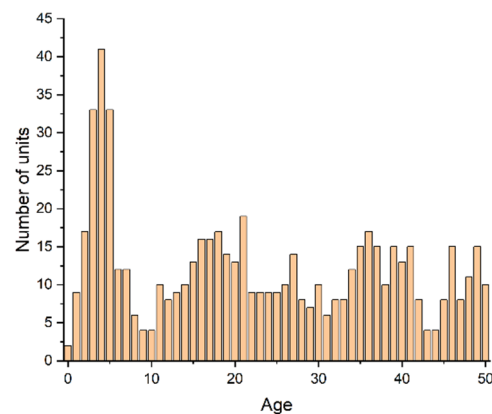


Figure 2. The distribution of age of the devices in the study group.

2.2. The Health Index Model

The main objective was to determine the health index frequently and in regular intervals to facilitate the condition monitoring. For this purpose, the insulating oil diagnostics are excellent, due to the fact that they are carried out periodically on almost all power transformers. The incorporation of additional complex diagnostic methods into this health index would result in the decrease of the frequency of checks, as some tests require de-energization of the transformer and also the increase of the total cost of a single assessment.

The algorithm was divided into three parts—the diagnostics of the physicochemical properties of the insulating oil, the assessment of dissolved gases in the oil (DGA), and the evaluation of the transformer's solid insulation. Each part (later referred to as a subindex) was considered both individually and as a component of the overall transformer health index. The design of the algorithm is similar to one described in [16], but the authors decided to exclude the operating parameters and the age from the evaluation in order to improve the effectiveness of the monitoring of the technical condition. The full list of parameters that were included in the algorithm is presented in Table 1.

Table 1. The diagnostic parameters included in the presented health index with the division into respective subindexes.

Physicochemical Properties HI _{OIL}	Dissolved Gas Analysis HI _{DGA}	Solid Insulation Evaluation HI _{ISO}
Breakdown voltage (BDV)	Hydrogen (H ₂)	Furfural (2-FAL)
Water content	Methane (CH ₄)	Carbon monoxide (CO)
Acidity	Ethane (C ₂ H ₆)	Carbon dioxide (CO ₂)
Loss factor (Tan δ)	Ethylene (C ₂ H ₄)	
	Acetylene (C ₂ H ₂)	

The subindexes are a weighted sum of the individual functions of the defined parameters. For this purpose, the minimum and maximum values had to be adopted to determine the observation spectrum for the condition monitoring. Due to the difference in the acceptable values of the parameters, it was necessary to determine individual formulas of the $F(j)$ functions based on standards [17–19] and recognized world recommendations [20–22], which were additionally confronted with the results (e.g., 90th and 95th percentile values) in the analyzed population. Unlike most health indexes, which use the step functions, the F_{OIL} , F_{DGA} , and F_{ISO} were adopted as linear functions to ensure that even the smallest changes in the input values would result in the change of the overall value. The scores of the individual functions ranged from 0, in the case of good condition, to 10 for the significant values exceeding the typical observable within transformer populations. The criteria for determining the weighting parameters are described in detail in the following paragraphs. The calculation formulas of the respective subindexes are shown in the equations below:

$$HI_{OIL} = \sum_{j=1}^n F_{OIL}(j) \cdot W(j) \quad (1)$$

$$HI_{DGA} = \sum_{j=1}^n F_{DGA}(j) \cdot W(j) \quad (2)$$

$$HI_{ISO} = \sum_{j=1}^n F_{ISO}(j) \cdot W(j) \quad (3)$$

The HI_{OIL} subindex consists of four oil parameters—breakdown voltage, water content, acidity, and dielectric loss factor. These properties directly indicate whether the oil can fulfill its role as the electrical insulating medium. For this subindex, priority is given to the slow-changing properties—the acidity and the loss factor, which indicate the degree of aging of the oil. The BDV and water content are generally assessed individually, as preventive shutdown decisions are made on their basis. Additionally, it should be mentioned that according to global [18,20] or national [6] guidelines, the requirements for physicochemical parameters are differentiated based on the voltage level, which is also reflected in the construction of the algorithm. Tables 2–4 contain the F_{OIL} formulas for each parameter and the respective weighting $W(j)$ values.

The HI_{DGA} subindex includes the so-called key gases, which are hydrogen, methane, ethane, ethylene, and acetylene. The ratios of these gases allow for identification of the defect type within the transformer, while their weekly increments indicate the fault severity. Greater importance is given to hydrogen and acetylene, as they are commonly present in the case of partial discharges and arcing inside the transformer, which are the electrical defects. The remaining parameters—methane, ethane, and ethylene are mainly present in the case of thermal faults, such as local low-temperature and high-temperature overheating. Table 5 contains the F_{DGA} formulas for each parameter and the respective weighting $W(j)$ values.

Table 2. The individual formulas and weighting factors used to evaluate the physicochemical properties of oil for transformers with the upper voltage of $U \leq 69$ kV.

Parameter	Value	F _{OIL(j)} Formula	W(j) Factor
BDV (kV)	$x > 55$	$y = 0$	0.14
	$55 \geq x \geq 40$	$y = -0.6666667 \cdot (x - 55)$	
	$x < 40$	$y = 10$	
Water content (ppm)	$x < 15$	$y = 0$	0.13
	$15 \leq x \leq 35$	$y = 0.5 \cdot (x - 15)$	
	$x > 35$	$y = 10$	
Acidity (mgKOH/g)	$x < 0.02$	$y = 0$	0.42
	$0.02 \leq x \leq 0.25$	$y = 43.4782609 \cdot (x - 0.02)$	
	$x > 0.25$	$y = 10$	
Tan δ	$x < 0.1$	$y = 0$	0.31
	$0.1 \leq x \leq 1$	$y = 11.11111111 \cdot (x - 0.1)$	
	$x > 1$	$y = 10$	

Table 3. The individual formulas and weighting factors used to evaluate the physicochemical properties of oil for transformers with the upper voltage of $69 \text{ kV} < U \leq 230$ kV.

Parameter	Value	F _{OIL(j)} Formula	W(j) Factor
BDV (kV)	$x > 60$	$y = 0$	0.14
	$60 \geq x \geq 45$	$y = -0.6666667 \cdot (x - 60)$	
	$x < 45$	$y = 10$	
Water content (ppm)	$x < 10$	$y = 0$	0.13
	$10 \leq x \leq 25$	$y = 0.6666667 \cdot (x - 10)$	
	$x > 25$	$y = 10$	
Acidity (mgKOH/g)	$x < 0.02$	$y = 0$	0.42
	$0.02 \leq x \leq 0.20$	$y = 55.5555556 \cdot (x - 0.02)$	
	$x > 0.20$	$y = 10$	
Tan δ	$x < 0.1$	$y = 0$	0.31
	$0.1 \leq x \leq 1$	$y = 11.11111111 \cdot (x - 0.1)$	
	$x > 1$	$y = 10$	

Table 4. The individual formulas and weighting factors used to evaluate the physicochemical properties of oil for transformers with the upper voltage of $U > 230$ kV.

Parameter	Value	F _{OIL(j)} Formula	W(j) Factor
BDV (kV)	$x > 60$	$y = 0$	0.14
	$60 \geq x \geq 50$	$y = -(x - 60)$	
	$x < 50$	$y = 10$	
Water content (ppm)	$x < 8$	$y = 0$	0.13
	$8 \leq x \leq 15$	$y = 1.428571429 \cdot (x - 8)$	
	$x > 15$	$y = 10$	
Acidity (mgKOH/g)	$x < 0.02$	$y = 0$	0.42
	$0.02 \leq x \leq 0.15$	$y = 76.9230769 \cdot (x - 0.02)$	
	$x > 0.15$	$y = 10$	
Tan δ	$x < 0.1$	$y = 0$	0.31
	$0.1 \leq x \leq 1$	$y = 11.11111111 \cdot (x - 0.1)$	
	$x > 1$	$y = 10$	

Table 5. The individual formulas and weighting factors used to evaluate the dissolved gas content in oil.

Parameter	Value	F _{DGA(j)} Formula	W(j) Factor
H ₂ (ppm)	x < 30 30 ≤ x ≤ 350 x < 350	y = 0 y = 0.03125 · (x − 30) y = 10	0.32
CH ₄ (ppm)	x < 30 30 ≤ x ≤ 150 x > 150	y = 0 y = 0.083333333 · (x − 30) y = 10	0.15
C ₂ H ₆ (ppm)	x < 30 30 ≤ x ≤ 400 x > 400	y = 0 y = 0.027027027 · (x − 30) y = 10	0.05
C ₂ H ₄ (ppm)	x < 25 25 ≤ x ≤ 200 x > 200	y = 0 y = 0.057142857 · (x − 25) y = 10	0.15
C ₂ H ₂ (ppm)	x < 3 3 ≤ x ≤ 70 x > 70	y = 0 y = 0.149253731 · (x − 3) y = 10	0.33

The HI_{ISO} subindex consists of three parameters—carbon monoxide and carbon dioxide determined during the DGA test and furfural obtained during the analysis of furan compounds in the oil. The concentrations of carbon monoxide and carbon dioxide indicate the overheating within the solid insulation. In the case of furfural, the content of this compound is associated with the degree of aging of the solid insulation of the windings [23], as its level allows for the estimation of the degree of polymerization (DP) of cellulose with the use of different equations [24]. The low DP value further indicates the significantly deteriorated mechanical properties of cellulose, which affects its strength under short-circuit conditions. The power transformers in Poland are characterized by high 2-FAL concentrations [22] compared to the rest of the world due to the low share of thermally upgraded paper as solid insulation of windings. Table 6 contains the F_{ISO} formulas for each parameter and the respective weighting W(j) values.

Table 6. The individual formulas and weighting factors used to evaluate the aging of the solid insulation.

Parameter	Value	F _{ISO(j)} Formula	W(j) Factor
CO (ppm)	x < 250 250 ≤ x ≤ 1000 x < 1000	y = 0 y = 0.013333 · (x − 250) y = 10	0.15
CO ₂ (ppm)	x < 3000 3000 ≤ x ≤ 10,000 x > 10,000	y = 0 y = 0.001428571 · (x − 3000) y = 10	0.15
2-FAL (ppm)	x < 0.1 0.1 ≤ x ≤ 4 x > 4	y = 0 y = 2.564103 · (x − 0.1) y = 10	0.70

The total health index score is the weighted sum of the previously calculated subindexes. It can be calculated as shown in Equation (4) below with the group weighting factor W_(g) presented in Table 7:

$$HI = HI_{OIL} \cdot W_{OIL} + HI_{DGA} \cdot W_{DGA} + HI_{ISO} \cdot W_{ISO} \quad (4)$$

Table 7. The weighting factors of the subindexes used to calculate the total health index value.

Subindex	Weighting Factor $W_{(g)}$
HI _{OIL}	0.224
HI _{DGA}	0.395
HI _{ISO}	0.381

The ultimate health index value ranges from 0 to 10 points, with 0 being the minimum value typically attributed to new transformers and 10 being the maximum obtainable score exhibiting the end-of-life unit condition. The score assessment criteria are discussed in detail in the next section of this paper.

2.3. Assessment Criteria

Since every health index algorithm is unique, so will be the criteria for the evaluation of its score. Proper selection can significantly improve the efficiency of the analysis [16], which is required to draw correct conclusions from the statistical analysis of power transformers.

For the sake of the presented algorithm, the criterion of transformer criticality was used. This is due to the fact that the operation of certain transformers is much more important than others, which occurs, for example, in the case of GSUs, when the fault may cause an outage of the entire power unit. This affects the level of maintenance and the frequency of inspections, since it is in the owner's interest to keep the transformers in adequate condition. Such a classification method has already been proposed in [25]. The criticality division, which was adopted for the presented algorithm, is shown in Table 8.

Table 8. The criticality levels used in the evaluation of the proposed health index.

Level "0"	Level "1"	Level "2"	Level "3"
Group I as per [6]	Group I as per [6]	Group II as per [6]	Groups III&IV as per [6]
Crucial importance	Significant importance	Standard importance	Minor importance

According to the classification presented above, it should be considered that level "0" devices are of key importance due to their direct impact on the operation of the entire power system, level "1" units are important due to the power supply safety and financial aspect, the fitness of level "2" transformers determines the correct operation of small network sections, and the level "3" devices may only be considered as important for small individual consumers. The specification of typical applications is as follows:

- Level "0"—GSU in power plants and autotransformers interconnecting the high voltage grids;
- Level "1"—auxiliary transformers in power plants, large distribution devices, and units supplying complex and costly process lines;
- Level "2"—typical high voltage network distribution equipment and smaller transformers of significant importance;
- Level "3"—medium voltage pole-mounted transformers and small units supplying non-complex technological processes.

However, it should be mentioned that the above groups are not a fixed classification of transformers. The criticality of a unit can be increased after considering the following conditions:

- Customer type (the importance, cost of downtime);
- The average load factor;
- The redundancy and power backup possibilities;
- The possibility of transformer renovation or replacement;
- Potential increase in the load in the future.

Therefore, each transformer in the study group had to be individually analyzed with regard to its importance. This procedure is usually performed once for each device—at the time of the first calculation of the health index—and the same value is adopted throughout its lifetime (unless, of course, the operating conditions change). The criticality distribution within the study population is shown in Figure 3.

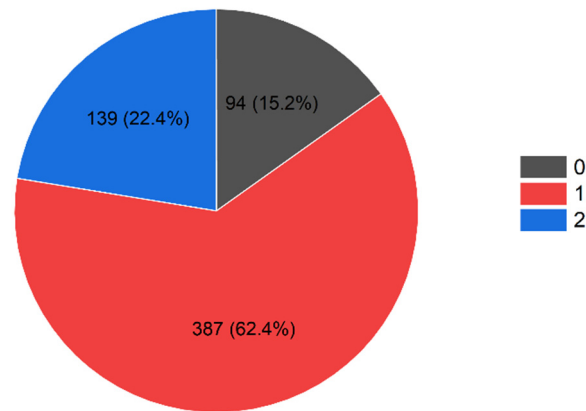


Figure 3. The distribution of device criticality in the study group.

Each of the criticality levels has individual score assessment criteria. The thresholds were set as the percentage value of the obtainable score, which for a score of 0 points corresponds to 0% while 10 points is 100% of the achievable value. The evaluation scale used in the presented algorithm is a four-grade type (good, fair, poor, risky) and the detailed thresholds are presented in Table 9.

Table 9. The condition rating based on the percentage value of the health index score and the device criticality.

Condition	Level "0"	Level "1"	Level "2"	Level "3"
Good	0–5%	0–10%	0–15%	0–15%
Fair	5–15%	10–20%	15–25%	15–30%
Poor	15–30%	20–40%	25–50%	30–55%
Risky	30–100%	40–100%	50–100%	55–100%

To further explain the meaning of the condition rating, it is necessary to understand their context. A transformer rated as good will not cause problems in further operation. A unit considered as fair still exhibits adequate health, but the test results indicate the first signs of aging or an early stage of internal defect. The results of a device rated as poor reflect the existing problems within the unit or picture the past issues. Transformers considered risky pose a threat in the continuous operation of the local power grid, which often qualifies them as unsuitable for further operation, with a recommendation for an overhaul or removal from service. It should, therefore, be in the interest of the grid operators to keep the transformers in good or fair condition, undertake extensive diagnostics when they are considered as poor, and take action when there is excessive operational risk.

3. Results

The results obtained using the presented algorithm for the specified groups are presented graphically in Figure 4 and in detail in Table 10. The main conclusion is the noticeable impact of operating and environmental conditions on the overall health of the unit, which is reflected in the scores of GSUs (Figure 4a) and distribution transformers (Figure 4c). Additionally, some nuances in the age spectrum are also visible—in the case of EAFs, significant expenditures on replacement and modernization of equipment have taken place in the last decade. The same applies to the group of industrial transformers, where almost no units were older than 40 years, which was caused by two factors—historical

(private industrialization in Poland took place mainly in the post-communist period) and business approaches to their operation.

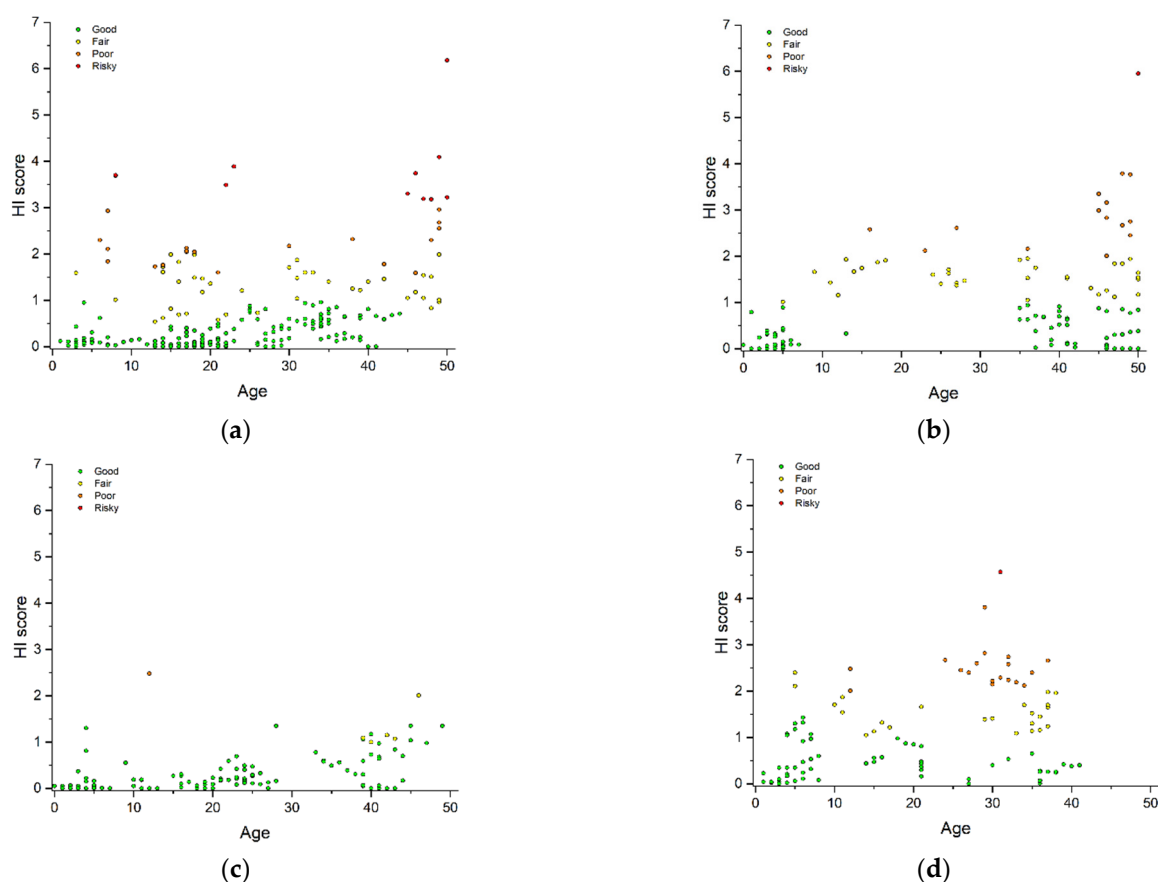


Figure 4. The results of the analysis of the power transformer technical condition with the use of a presented health index for selected populations: (a) generator step-up; (b) electric arc furnace; (c) distribution; (d) industrial.

Table 10. The results of technical condition assessment within the specified transformer populations.

Condition	GSU	EAF	Distribution	Industrial	Overall
Good	160	76	150	63	449
Fair	42	34	5	24	105
Poor	19	15	1	18	53
Risky	11	1	0	1	13

The distribution of results for the entire population presented in Table 10 is typical for power transformers and the variations in individual groups are due to differences in their operation. It should be noted, however, that the scores of different populations are highly dependent on the criticality of the units included in them. This is reflected, for example, in the case of the GSU group, where about a half of the devices were ranked with the highest criticality level “0” and the remainder being level “1”, which resulted in the largest share of transformers with increased operation discipline. The opposite was observed for distribution units, where a mix of criticality level “1” and “2” and good service conditions resulted in a small share of transformers that would be potentially problematic in operation.

The main objective of this paper was a population-based analysis of the study group, so it was necessary to merge the data from all analyzed subgroups as a starting point for further consideration of population trends. The results from the entire study group are shown in Figure 5.

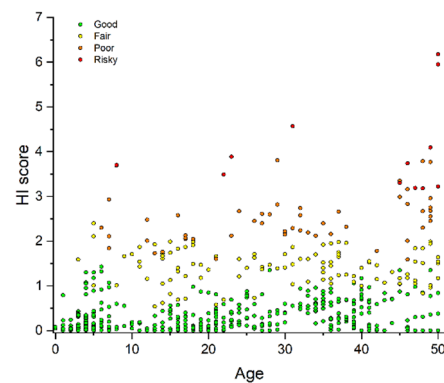


Figure 5. The results of the analysis of the power transformer technical condition for the whole study group using the presented health index method.

Due to insufficient sample size in individual subgroups, the analysis of the health index changes was performed on the entire population. For this purpose, two calculations were performed. The first used all the available data to obtain information on the estimated mean health index score across the entire age span. This was intended to reflect the actual nature of transformer aging. The second calculation was carried out with the exclusion of data with a large deviation from the mean HI value, which was the case for the aged units after oil treatment or workshop repair, where the results were significantly underestimated. This procedure was intended to check how the corrective maintenance (CM) influences the estimated mean value of the health index. These two functions are plotted together in Figure 6.

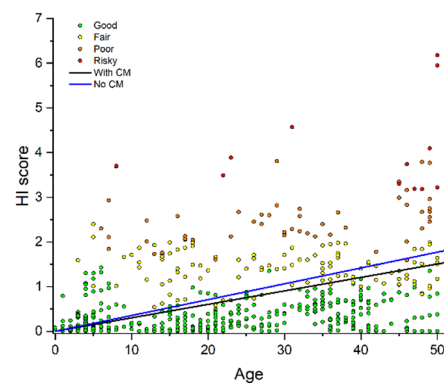


Figure 6. The results of the analysis for the power transformer population for two scenarios: actual aging (“no CM”) and with operational efforts to improve device health (“with CM”).

The difference between the two trend lines is clearly visible. The estimated actual aging line exhibited a larger gradient, which resulted in a 17.5% higher value at the upper age limit of the analyzed population. The estimations indicate that power transformers are still mostly in good or fair condition at the end of their life depending on their criticality. Thanks to good operating conditions and adequate maintenance, the observable health index score reached lower values than the actual aging score, which statistically translates into an extension of the service life of the transformer from the assumed 40 years by up to 7 years.

4. Discussion

In the model presented in Section 2, the selection of parameters and weighting factors was based on operating experience and technical guidelines, however, it would be appropriate to refer to the available literature references. In [26], the presented weights indicated the condition of the solid insulation as the most important group of parameters

in assessing the technical condition of a transformer. The paper [27] suggested physico-chemical parameters of oil and 2-FAL concentration as important in effective assessment with the health index method. In [28], the authors proposed an additional reduction in the number of parameters without significantly affecting the effectiveness of the analysis. The abovementioned references highlight the need for individual selection of criteria for the population analysis. In the case of the presented health index, the weighting factors were chosen to produce a greater impact on the overall score for the parameters that indicate long-term condition changes within the transformer.

The results presented in Section 3 show that the technical conditions of the vast majority of analyzed power transformers do not pose any operational problems and their further operation should be carried out according to the operator's guidelines. About 8.5% of the test group consisted of transformers with recommendations for further diagnostics, which could be scheduled at the nearest convenient time for the owner, such as the periodic maintenance of the substation. The devices classified as risky accounted for about 2% of the study group and their condition did not guarantee trouble-free operation in the foreseeable future. However, it should be mentioned that despite such indications, the operators rarely decided to take immediate action and consciously agreed to the increased risk by delaying the required repair works until the nearest convenient date due to business activities.

The transformers classified as risky were usually characterized by an inflated score of more than one subindex. In the case of relatively young transformers (less than 20 years old), they were mainly characterized by high dissolved gas content in oil and poor physicochemical values, which indicated the presence or development of an internal defect limiting the trouble-free operation of these units. In contrast, the group of older devices marked as risky was characterized by high levels of 2-FAL and an elevated score of some other subindex. Excessive levels of furan compounds in the oil indicate a low degree of polymerization of cellulose, the main component of solid winding insulation, which consequently affects its mechanical strength [29]. Once the level of DP below 200 is reached, the cellulose insulation is particularly prone to breakdown, which can initiate the development of further internal defects that have a destructive effect on the overall health of the individual.

The technical assessment of the power transformer's condition is mainly based on inspections and maintenance at regular time intervals. The use of the health index as a complementary method can bring advantages for devices with an abnormal condition—the observable change in the HI score will be much higher than with conventional aging. In a case study [30], it was found that despite the effectiveness of the DGA method in detecting and determining the nature of the damage, the localization of damage is impossible without the use of additional tests. The aforementioned result is consistent with the assumption of analysis using the health index method, which is intended to provide recommendations for more extensive diagnostics based on the dynamics of changes in the score.

The individual case analysis may be particularly useful if an extensive record of historic assessments of the unit is available. It is also applicable in the case of long-term ongoing monitoring of the device's technical condition. It should be mentioned, however, that it is important to have a large reference database, which will allow users to catch anomalies and also for comparison to the determined population characteristics. This is intended to facilitate the service by improving the efficiency of the maintenance teams. If appropriate corrective actions are taken to restore the unit to the desired condition, the life of the transformer can be extended by 10 to 15 years [31].

In the preparation of the paper, the units with an age well beyond the expected lifetime were also taken into account (the oldest transformer analyzed was 67 years in operation). The analysis of their results revealed that their operability beyond 50 years is due to either being in extraordinary technical condition in relation to their peers or to the fact that they underwent a major overhaul in due time. The performance of units older than 50 years deviated significantly from the characteristics presented in this paper in both ways. In order not to base the analysis on such individual cases, the authors decided not to include

these results in the study, as the purpose of this work was to determine the population characteristics within the expected operating horizon.

The paper does not cover the comparison of the presented health index to the traditional methods due to lack of research data for the majority of the study group. However, the authors have performed such a comparison in [16] for a large portion of the distribution transformers (96) included in this study, which has shown consistency between the results from the health index evaluation and the assessment with the use of an expert system based on the comprehensive transformer diagnostics.

The development of the health index method requires working on large amounts of data to determine accurate population characteristics for different groups of transformers. In its final form, an algorithm of this type should predict the residual life of a unit based on the available data, population analysis, and reliability data [32]. Such a prediction, due to the limited nature of the input data, will of course be subject to some error. In order to make significant progress in this area, machine learning can be utilized to improve on the current expert knowledge.

5. Conclusions

The health index described in this paper is applicable to the analysis of the transformer population and was specifically designed to facilitate the condition monitoring in the long run. The selection of parameters and their respective weights was based on the guidelines of the technical committees and the experience in operation and diagnostics of power transformers in Polish power grids. Due to differences in the approach to operation, the application of the presented health index in other countries may vary in the effectiveness of the analysis. However, the simplicity of the solution allows for unrestricted modifications, which, combined with expert knowledge, allows users to adapt it to one's needs.

The presented results of the whole population indicated the positive effect of corrective maintenance on the mean value of the health index. For different groups of transformers, only illustrative population diagrams were presented. The authors did not attempt to determine their characteristics due to insufficient data. Future research on larger groups will allow observation of the population aging trends in transformers operating in various operating conditions.

Author Contributions: Conceptualization, P.B.; methodology, P.B. and A.M.; investigation, P.B. and A.M.; resources, P.B.; writing—original draft preparation, P.B. and A.M.; writing—review and editing, P.B. and A.M.; visualization, P.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Restrictions apply to the availability of these data. Data was obtained from Energo-Complex Ltd. and are available from the corresponding author with the permission of Energo-Complex Ltd.

Acknowledgments: Authors would like to thank Energo-Complex Ltd. for providing the research data for this study.

Conflicts of Interest: The authors declare no conflict of interest.

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