The reliability of power transformers is crucial in the context of power system operation; the unplanned long-term shutdown of a single unit may result in both technical and economic consequences

ABSTRACT

The article presents a health index calculation method based on easily obtainable periodical oil condition data. The algorithm is tested on a population of 96 transformers working in the Polish power grid. The outcomes are compared with the expert analysis conducted with the use of much more advanced methods. The results show that an effective simplification of the initial assessment criteria can achieve satisfactory efficiency if the choice of weighting criteria for the selected parameters is appropriate.

KEYWORDS

health index, management, population, transformer

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Preliminary assessment of the technical condition of the power transformer based on regular oil testing

Condition monitoring of power transformers with the use of online measurement methods

1. Introduction

The reliability of power transformers is crucial in the context of power system operation. The distribution companies usually manage the fleets of hundreds of power transformers which is the reason why worldwide research is being regularly carried out addressing their reliability [1]. The unplanned long-term shutdown of a single unit may result in both technical and economic consequences.

The condition assessment of the transformer is mainly based on periodical tests [2, 3]. The advanced methods are used only in the case of emergency events, monitoring defect development or when determining the unit's operating prospects. The unavailability of regular comprehensive diagnostic data means that the assessment of the general condition of the transformer is mainly based on the results of oil tests.

The introduction of online monitoring systems has created a new quality in the assessment of the transformer's technical state. The data gathered during periodical tests and acquired in the process of continuous online measurements can be synthetically presented in the form of a single numerical indicator, also known as the health index. This form is much more understandable at the level of company asset management and simplifies the comparison of transformers with different parameters. The application of the health index has been the subject of several different studies in recent years [4, 5].

The scientific-industrial consortium between Energo-Complex Ltd. and West Pomeranian University of Technology has established projects concerning the creation of new methods of transformer assessment and the prediction of future exploitation prospects [6]. One such project is the development of a health index algorithm based on the national operational and service experience, which aims to simplify the assessment by aggregating the most common measurement data.

The data gathered during periodical tests and acquired in the process of continuous online measurements can be presented in the form of a single numerical indicator - the health index

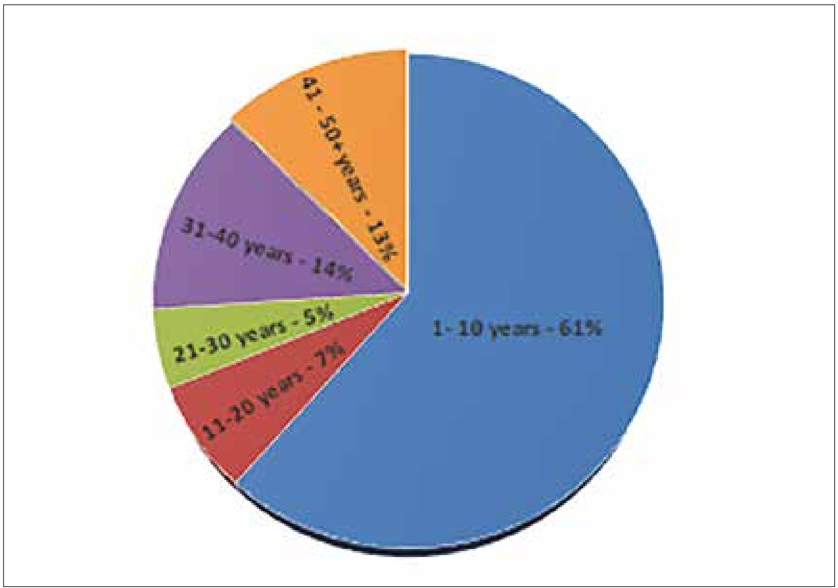

Figure 1. Distribution of tested transformers by the time of operation

A presented new algorithm for health index estimation was developed and tested on a fleet of 96 transformers with different operating settings to assess their general condition

This paper presents the health index based on the results of periodically performed advanced oil diagnostics. The non-complex acquisition of the oil samples and the relatively low cost of performing such procedures creates a condition for a frequent calculation of the transformer's overall health state. The presented algorithm was tested on a fleet of 96 transformers with different operating settings to primarily assess their general condition. The results were then compared to the expert reports regarding the technical condition carried out with the application of much more advanced measurement methods.

2. Materials and methods

2.1 The subject of the experiment

The subject of the research was a population of 96 transformers working in the Polish 110 kV distribution network. The principles for choosing the control group was the selection of units as similar to each other as possible. Therefore, the whole population is characterised by the same voltage level, similar rated power (10 – 25 MVA), equipped with an on-load tap changer (OLTC), filled with the same type of mineral oil and operated by a single distribution company in the same region to ensure the same quality of operation and service.

The exact age distribution of the transformers is shown in Fig. 1. The transformers in the control group vary from new to units that have been in operation for 50 years. Such a deliberate selection allows evaluating this population thoroughly.

2.2 The health index algorithm based on regular oil diagnostics

To build a health index (HI) it is necessary to properly select the parameters and consider the impact of each test results on the transformer's technical condition. The presented algorithm contains four categories of parameters including the physicochemical properties of the oil (HI_{OIL}), the content of gases dissolved in oil (HI_{DGA}), the condition of solid insulation of the windings (HI_{ISO}) and the coefficient taking into account the age and environmental conditions (HI_{AGE}).

The first category HI_{OIL} takes into account the breakdown voltage, water content in oil, acid value and dielectric dissipation factor. The HI_{DGA} subindex consists of the results of dissolved gas analysis (DGA) and includes the content of 5 key gases such as hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4) and acetylene (C_2H_2). The third category HI_{ISO} takes into account the parameters such as the concentration of carbon monoxide (CO), carbon dioxide (CO_2) and content of furfural (2-FAL) compounds. The final coefficient HI_{AGE} is constructed from the components such as the transformer's age, work history, and its overall importance in the power system.

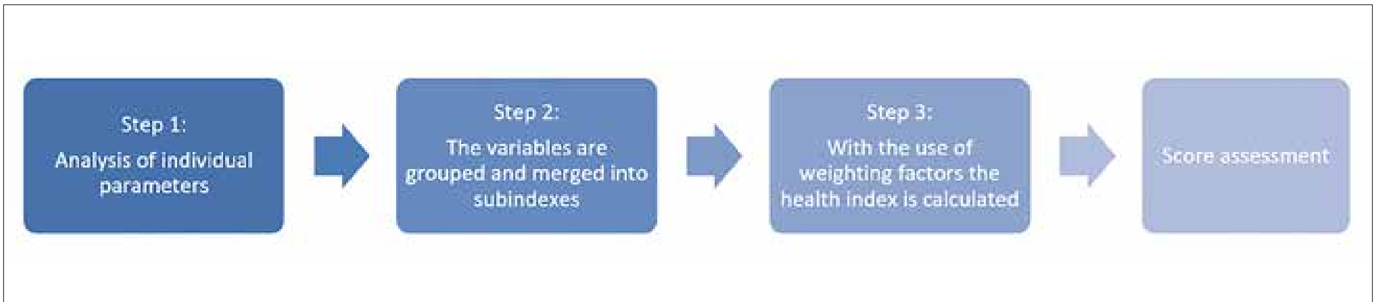

Figure 2. The flow chart of the calculation process of the proposed health index

The mathematical model used for the construction of the presented algorithm consists of three stages. Firstly, the numerical scores of individual parameters are calculated according to their measured values. Further on, the calculated scores are merged into the designated subindexes using specific weights. In the end, the four categories are added together to form the final score. The construction of this model was described in detail in [7]. To illustrate the dependencies more clearly, the impact of weighting factors of all parameters on the final health index are shown in Table 1.

The mathematical model for HI estimation uses numerical scores calculated on the basis of measurements which are then processed and are subject to different quality criteria evaluation

The values presented in Table 1 were adopted as a combination of guidelines from the operating instructions in the Polish power system [8] and the practical experience resulting from many years of transformer operation and service. For this reason, some parameters have been given higher weight as they have a more significant impact on the overall health of the transformer.

In this case, much more importance is attributed to the acidity value of the oil, the presence of gases such as hydrogen and acetylene, and the concentration of 2-FAL compounds. The critical levels of the aforementioned parameters indicate the poor condition of the insulating oil and the development of electrical and thermal faults within the transformer. In addition, the parameters included in the age coefficient subindex are important supplementary information to the oil test results due to giving additional information on the unit's operation.

The algorithm for determining the health index contains numerical values, mainly in the range of 0 to 10 points. The range of possible values was divided into zones marked as good, average, and risky. To increase the efficiency of the assessment, the criteria are based on the percentage values of the possible range of solutions, instead of using rigid boundaries. Used percentage values are shown in Table 2.

Table 1. The components and weighting factors used to calculate the HI based on regular oil examination

Category	Parameter	Weight
Physiochemical properties	Acidity	0.0776
	Loss factor	0.0573
	Water content	0.0241
	Breakdown voltage	0.0258
Dissolved gas analysis	Hydrogen (H_2)	0.1042
	Methane (CH_4)	0.0488
	Ethane (C_2H_6)	0.0163
	Ethylene (C_2H_4)	0.0488
	Acetylene (C_2H_2)	0.1074
Cellulose ageing	Carbon monoxide (CO)	0.0471
	Carbon dioxide (CO_2)	0.0471
	Furfural (2-FAL)	0.2199
Age coefficient	Age	0.1756
	Transformer load	
	Operation history	
	Importance of the unit	

The purpose of the experiment was to examine the effectiveness of the proposed health index algorithm on a considerable group of transformers; results were compared to the proven conventional methods

Table 2. The criteria for the technical condition assessment based on the values of the health index

Health index value	Technical state
0 – 27 %	Good
27 – 57 %	Average
57 – 100 %	Risky

2.3 The experimental setup

The purpose of the experiment was to examine the effectiveness of the proposed health index algorithm on a considerable group of transformers. To achieve that, the proposed method had to be compared to a proven conventional method. The experimental population has been carefully selected to minimise the parameter and operation discrepancies. These criteria have resulted in the selection of the group of units described in section 2.1.

The population of transformers was first subjected to technical expertise to determine their technical condition and operational prospects. The measurements used for this purpose were the excitation current test, dielectric dissipation factor and capacitance of the windings and bushings, sweep frequency response analysis (SFRA), frequency dielectric spectroscopy (FDS), turns ratio test, insulation's resistance, an oscillographic inspection of the OLTC, and comprehensive diagnostics of transformer oil including physicochemical properties, dissolved gas analysis, and the content of furan compounds. Such a wide selection of state-of-the-art tests allows for an accurate assessment of the transformer technical state.

The analysis of the population with the health index is based on the same oil properties dataset as the aforementioned technical expertise. This experimental setup compares the results of the comprehensive analysis, which is performed occasionally with the proposed algorithm outcomes based on periodically (mostly annually) collected data. In this situation, it can be determined whether it is possible to effectively monitor the health of the transformer-based only on the easily accessible oil and operational data.

To maximise the accuracy of the experiment, the technical expertise was conducted by a small group of experienced professionals. The oil analysis was conducted in the OBRE laboratory (Fig. 3), which is a part of the

Figure 3. The laboratory tests of electrical insulating oil

Energo-Complex group. High testing standards and repeatability due to the analysis taking place in the same facility has created an excellent environment to examine the assumptions and effectiveness of the health index.

3. Results

The representation of the HI values of a group of 96 transformers is presented in Fig. 4. The results show that the whole population is free of excessive operational risk. However, significant differences in the health index values can be observed in particular age groups. For example, the scores achieved by some transformers after 5 - 15 years of operation are comparable with the values achieved by devices that have already been working for 30 - 40 years. This effect is most visible in individual cases, which are subjected to increased average load and large momentary overloads.

The proper selection and adequate weighting of diagnostic parameters are crucial for effective health monitoring of the transformers. The presence of gases, such as hydrogen, acetylene, and 2-FAL compounds, mainly occurs during the development of the defects, thermal ageing of insulation, and the ageing changes in the active part of the transformers. Furthermore, with the age factor being taken to a moderate extent, the observation of changes in HI values over time is facilitated.

In the next step, the results obtained with the health index algorithm were compared with the conclusions of the technical expertise based on plenty of sophisticated diagnostic methods. For the expert analysis, the good state indicated that there are no significant problems with the transformer's health, and the average score meant that the unit required corrective maintenance. If the transformer was unable for further operation or it required a major renovation, it was marked as risky. To summarise the outcomes, a matrix was built containing all technical condition assessments obtained with both methods (Table 3).

The conclusions of the two studies were found to be convergent. All of the units in the control group were found to be able to continue their operation for several years, and the only difference in the evaluation of the two algorithms was due to the bushing malfunction discovered in the expert analysis. Such an event is undetectable in the case of the presented health index, but in general, it has proven to be a suitable method for the indication of the overall health of the transformer.

In both methods, the transformers that have reached the "average" condition state are mostly still able to continue the operation for the next few years. The operational and internal revision experiences [9] show that, depending on the quality of service, the technical condition of the active part of the transformer is satisfactory considering their age. To ensure a proper degree of reliability, some minor renovation works

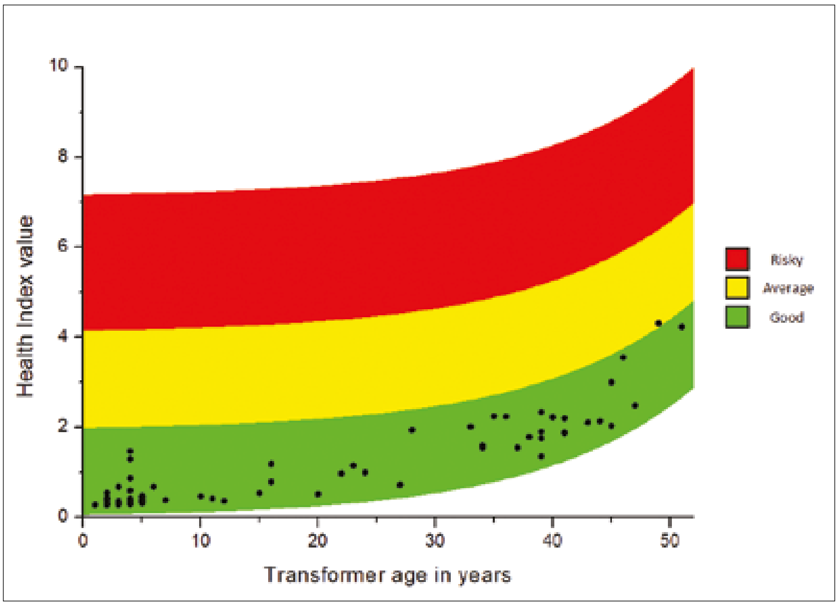

Figure 4. The values of health indexes of 96 transformers calculated with the regular oil diagnostics algorithm

The proposed algorithm has satisfactory effectiveness for the assessment of the health index, which was evaluated on a population of 96 transformers

Table 3. The results of transformer population analysis using two different algorithms

Technical state	Health index	Expert analysis
Good	95	94
Average	1	2
Risky	0	0

can be performed in order to extend the operation period by another 10 - 15 years [10].

Conclusion

The presented algorithm has shown satisfactory effectiveness in the assessment of a population of 96 transformers. This effect is mainly attributed to a proper selection of parameters and the determination of their individual impact on the overall technical state. The proposed method has been designed to facilitate detection and continuous observation of the development of the most common faults occurring in transformers. The further development of the health index based on regular oil testing will be carried out in the future on the additional groups of devices in different operating environments.

Effective simplification of transformer health evaluation is promising in terms of cost optimisation of transformer fleet management. This allows earlier fault detection and, if handled properly, the operation period of the unit can be extended. Since the transformers are the most expensive devices in the power substations, the development of new algorithms, such as health index, is necessary to maximise the economic efficiency of the grid operators in the future.

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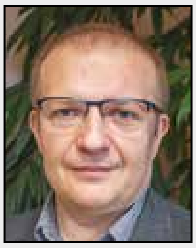

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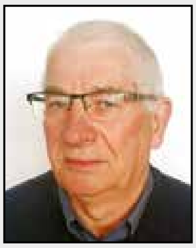

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