ABSTRACT

This paper presents the TrafoGrade system, developed by Energo-Complex Ltd. The main purpose of this tool is to aid a decision-making process regarding the operation of power transformers. The system consists of four modules, the most important being a multi-parameter evaluation of the technical condition of a transformer. The second is an assessment of importance of the unit, which concerns things such as energy security, technical possibilities of a transformer renovation or replacement, as well as reliability of the power supply and costs of its absence. The third module aims to determine prospects for operation of each unit, with an emphasis on technical and economic factors. Lastly, the data is processed by a computer system to support the decision-making process for transformer population management. The article presents an example of implementation of this system in a power distribution company in Poland.

KEYWORDS

asset management, diagnostics, TrafoGrade, transformer

Transformer management system - TrafoGrade

1. Introduction

The power distribution and industrial companies operate several thousands of medium and high-power transformers. Rationalisation of investment costs leads to optimization of the operation period of individual elements in the power system, while maintaining a low risk of failure. This is particularly important for transformers, which are a crucial part of power grids [6, 7, 8].

According to statistics in many countries, more than 50 % of transformers have already been in operation for over 25-30 years [1, 3, 9]. Therefore, it is necessary to have in place an approach for optimizing transformers' operation based on a comprehensive assessment of their technical condition and their importance in the power system. Combining those two factors indicates prospects for the further reliable operation of the unit and an eco-

TrafoGrade is a tool for a comprehensive transformer management system that allows for an optimal decision-making process in terms of renovation economy and the investment policy

nomic assessment of profitability of renovation works or replacement [2, 3, 4, 7].

Based on these considerations, Energo-Complex has developed a comprehensive transformer management system known as the TrafoGrade. The idea of a system that introduces a scoring scale for assessments of technical condition of a transformer and its importance in the power grid is to link the technical aspects of diagnostics with economic and financial factors for optimisation of decisions in the scope of the current operation, maintenance management, and investment strategy. The TrafoGrade system has been developed in cooperation with researchers from West Pomeranian University of Technology, Szczecin. They have developed unique combined methods of winding deformation diagnostics, assessment of moisture content in the insulation, and evaluation of the bushing condition based on dynamic measurement of various physical processes.

This article presents basic information about the TrafoGrade system and gives examples of evaluation results for 44 transformers operated by a Polish distribution company. An economic analysis of the system implementation was also compared with the costs of transformer failure.

2. The TrafoGrade structure

The TrafoGrade transformer management system consists of four modules, which are depicted in Fig. 1.

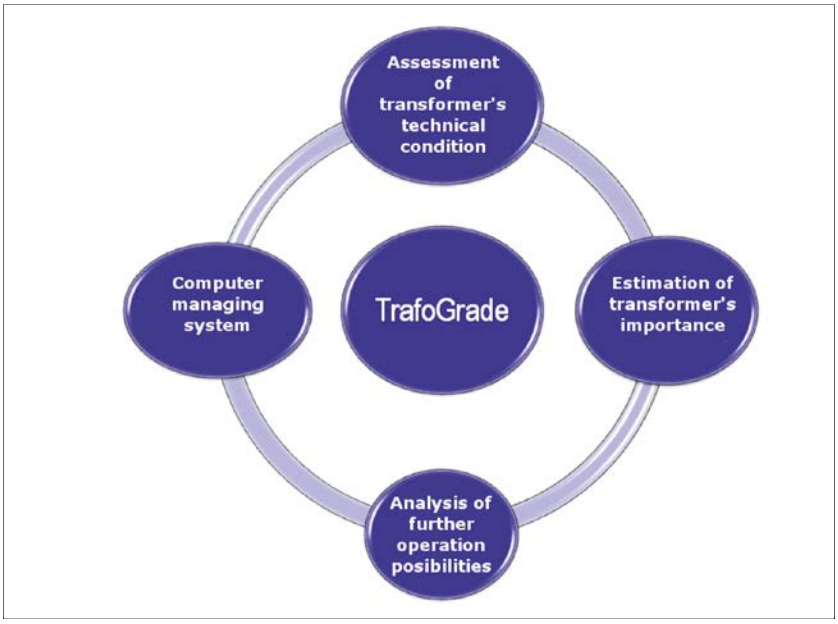

Figure 1. The TrafoGrade scheme

It is necessary to have in place an approach for optimization of transformers' operation based on a comprehensive assessment of their technical condition and their importance in the power system

In the presented system, a point-based valuation (from 1 to 3) method was adopted for each transformer parameter or property included in the technical assessment and significance. A three-stage judgment scale was used: good, fair, and poor. A simple, point-based description of the transformer's technical condition allows for an analysis of test results both by the engineering staff and economic departments possessing no technical knowledge.

3. Transformer condition assessment

The main task of the TrafoGrade system is a reliable assessment of technical condition of the transformer carried out using state-of-the-art diagnostic methods. The multi-parameter evaluation of the technical condition includes a number of diagnostic criteria.

The key elements of condition assessment

An assessment of the active part and insulation system of a transformer

The fitness of the active part and insulation system of a transformer is considered when the operation period of a transformer must be extended or a scope of renovation works needs to be determined. The evaluation consists of the following factors:

- condition of electrical and magnetic circuits,
- existence of partial discharges (PD), their location and intensity,
- existence of local points of an excessive temperature-rise in the insulation system,
- state of the structure and winding deformation,
- water content in solid insulation and aging of cellulose.

Condition of electrical and magnetic circuits is assessed based on periodical test results and dissolved gas analysis (DGA) in the transformer oil.

In operating units, a common problem is loosening of the clamps on the active part of a transformer and winding deformation or displacement. They mostly result from dynamic forces generated during short circuits when mechanical properties of the cellulose are significantly lower than nominal. A displacement or deformation of coils does not always lead to immediate damage to the insulation but substantially increases the risk of a catastrophic failure in subsequent events.

The Sweep Frequency Response Analysis (SFRA) method is used to identify deformation in windings. The evaluation is carried out by comparing recorded characteristics to the model waveforms. This requires detailed knowledge of methodology for determining SFRA characteristics, including:

- the type of device was used to determine the reference waveforms,
- the type and method of connection of measurement cables and screens [10, 11, 12].

Adequate diagnostic experience is also necessary, as well as a large library of reference measurements and comparative data from transformers of identical construction and similar age.

The degradation rate of the transformer insulation also depends on the degree of moisture in the cellulose solid insulation. The rate of depolymerization process, which consists in chain shortening of cellulose fibre and results in a loss of mechanical strength, is several times higher in a moist cellulose than in a dry one. For example, in a pressboard with 3 % water content, this process is five times faster than in a pressboard with approximately 1 % moisture.

Therefore, an important consideration when deciding to extend the life of transformers is to distinguish between the units in terms of kinetics of this process and the degree of cellulose degradation. Generally, it is assumed that transformers with a moisture content above 2.5 % are at risk of accelerated and excessive insulation degradation [13, 14, 15].

A practical and effective way to determine the degree of polymerization (degradation) of the cellulose is to measure the content of furan compounds in the oil, mainly 2-furfural (2-FAL), which is a long-lasting product of thermal degradation of paper and it accumulates in the oil. However, interpretation of the measurement result is a complex issue and requires qualified personnel.

Another unfavourable phenomenon associated with a presence of large quantities of water in the insulation is a possibility of a so-called "bubble effect," which consists in rapid evaporation of water when the critical temperature is exceeded. As a consequence, in transformers with excessive water content, it is necessary to lower the permissible operating temperature, which requires load reduction. For example, the rated power of a transformer with 3.5 % moisture content is decreased by half, and the unit should not operate above 60 ^{0}C. This is due to reduced heat transfer between the winding and oil and the possibility of a "bubble effect" occurrence. This fact should also be taken into account in the management of a medium and high-power transformer population.

Bushing diagnostics

Statistics from various sources [11, 14] indicate that bushings account for 20 to 40 % of catastrophic failures in transformers. A typical cost of a repair procedure after bushing malfunction is much higher than the value of the device. For example, the total cost of repairing damage caused by a 400 kV bushing explosion in the Polish transmission system was about €400,000, while the isolator itself was worth about €35,000. Dielectric loss within the bushing insulation may lead to a significant temperature increase, especially in layers close to the conductor. Simulations of temperature distribution within the 220 kV bushing showed that the insulation temperature in this area might be higher than 120 ^{0}C on hot summer days [16]. This value exceeds the thermal strength of the insulating paper leading to its deterioration. Development of this process may lead to generation of PD in individual layers of the insulation, and consequently to its breakdown.

The analysis of bushings dielectric breakdown mechanisms leads to a conclusion that standard measurements of the loss factor at 50 Hz are not a comprehensive method to assess the insulation system. At most, they allow identifying a very advanced state of the aging processes. Much better results are obtained by dynamic measurements of the polarization phenomena using the Frequency Domain Spectroscopy (FDS), which provides frequency-based capacitance and loss factor characteristics [16].

In case of oil-impregnated paper (OIP) bushings, an oil sample is taken for a DGA analysis.

On-load tap changer (OLTC) diagnostics

An assessment of OLTC is generally a part of basic diagnostics of the transformers' technical condition. The evaluation needs to include a thorough visual inspection, switchover oscillography, and dynamic contact resistance measurements [17]. On their basis, a scope of possible renovation or modernization of OLTC can be estimated [19, 20].

4. Parametric evaluation of a transformer's technical condition

All diagnostic parameters are assigned into three groups:

- Group I – basic transformer assessment,
- Group II – condition of the active part,
- Group III – degree of the aging processes.

Group I includes the most basic features of the transformer. Poor technical condition of any of the parameters does not significantly affect their performance. However, in some extreme cases, it is advised to withdraw the unit from further operation. For example, some of the features listed in this category are visual inspection, auxiliary equipment condition check, and evaluation of OLTC.

Group II is made of those elements which play an important role in performance of the transformer. Poor technical condition of most of them eliminates the transformer from further operation and restoring to acceptable technical condition usually requires significant financial and organizational expenses. For example, a negative result of DGA may require switching off the transformer to perform an internal revision.

The main task of the TrafoGrade system is a reliable assessment of technical condition of the transformer carried out using state-of-the-art diagnostic methods

Group III properties do not concern problems related to the current operation of a transformer but are rather oriented on the expected "lifespan" and planning of repairs and upgrades. Therefore, even a negative assessment of any of them does not exclude the individual from the operation but requires proper planning of renovation. To this group, such features as the age of a transformer, condition of paper insulation and transformer oil are assigned.

Detailed instructions have been developed for the TrafoGrade system and they include the way of defining and differentiating values of individual parameters, as well as a methodology for group and final scoring. Limit values of individual parameters have been determined based on international standards and operating instructions, taking into account many years of expert practice of Energo-Complex. They are the know-how of the TrafoGrade system.

5. Assessment of transformer importance in the power grid

In a decision-making process concerning the investment and renovation policy, apart from the transformer assessment, its importance in the power network should

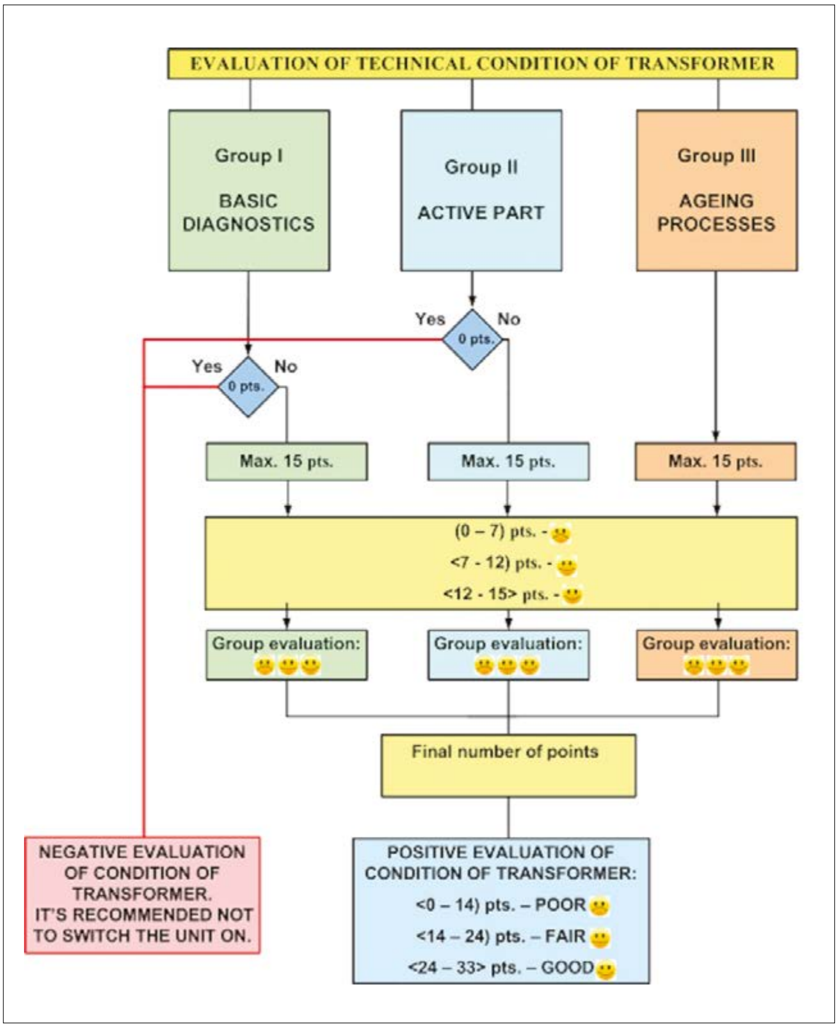

Figure 2. The algorithm of the TrafoGrade system

Adequate diagnostic experience is also necessary, as well as a large library of reference measurements and comparative data from transformers of identical construction and similar age

also be taken into account. This issue is of particular importance in terms of increasing the reliability of energy supply to consumers, as well as improving the energy security of the area. In the TrafoGrade system, evaluation of the transformer's importance is expressed in a point scale and it is implemented through an analysis of:

- power network configuration at the place of transformer operation, with particular emphasis on reliability parameters,
- the consumer profile,
- a possibility of supply redundancy, etc.

A combination of those attributes allows for assigning the transformer to an appropriate operating group.

The final result of a comprehensive assessment of the transformer's technical condition is development of operational perspectives for each unit. This information is particularly important for those who manage the operation of transformers, as it enables the execution of a reliable diagnostic and repair plan for the following years. An exemplary transformer TDR 63000/110 received a score of 16,3/33 points after 33 years of operation, which classified it as being in fair technical condition. A 5–7-year plan recommended for this unit included oil change and insulation drying.

6. Computer management system

The main part of the TrafoGrade system is a computer-based decision support system in which all the aforementioned modules have been implemented. The system consists of many extensive database functions, as well as elements indicating the current assessment of technical condition of a transformer and importance of the transformer within the network. Apart from the basic characteristics of a specific unit for each transformer, the following are entered: incident and disturbance records, reports with measurement results, and other files that can be useful in the process of a transformer fitness evaluation. An exemplary technical condition assessment report is shown in Fig. 3.

The system provides recommendations formulated based on input data, together with a cost estimation for carrying out repair procedures. The measurement results are analysed in detail and individually archived. Fig. 4 shows a graphic window of a detailed DGA assessment.

The TrafoGrade Inspection application for mobile devices uses documentation processing and data archiving on a database server. Implementation of such digital assistance allows for introduction of a uniform standard on visual examination of the transformer's most important elements and accessories. During an inspection, all collected data (pictures, answers to questions, and other detailed information) is automatically saved in a database. In addition, all photographic records are simultaneously stored in the memory of a mobile device.

The mobile application is compatible with the TrafoGrade system. It enables viewing and processing of photographic material and automatically generates a transformer inspection card in form of a PDF file. The editing window of the transformer inspection card is shown in Fig. 5.

TrafoGrade has a detailed instruction system inbuilt based on transformer assessment, thanks to the many years of expert practice and know-how

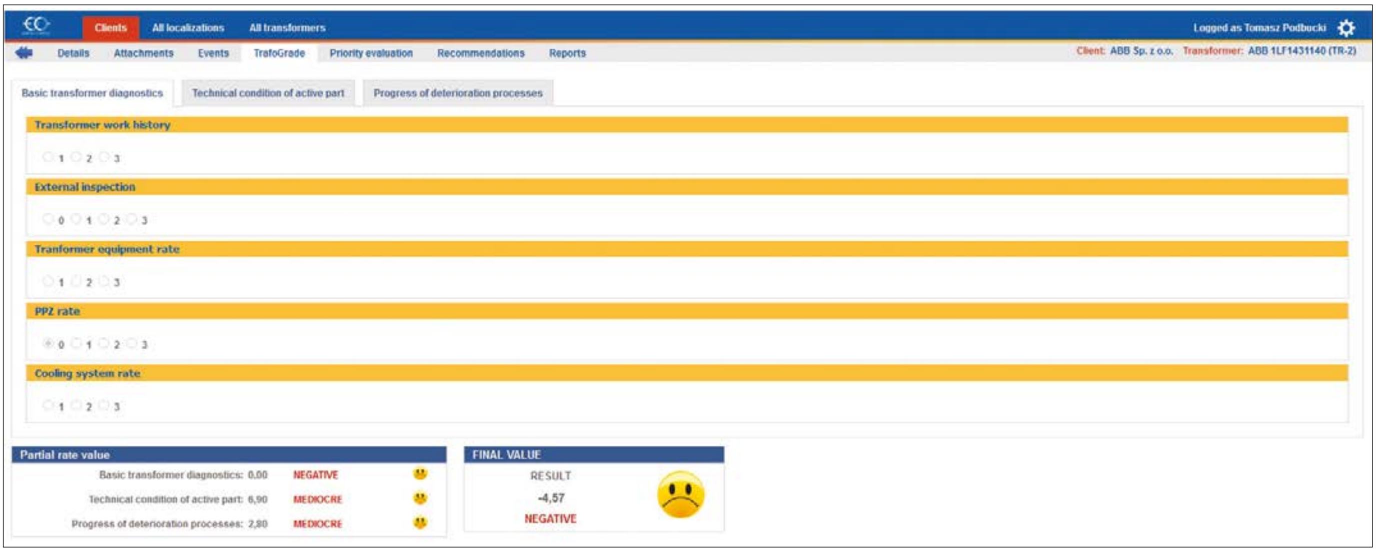

Figure 3. The TrafoGrade system – A screen of the tab with results of a technical condition assessment

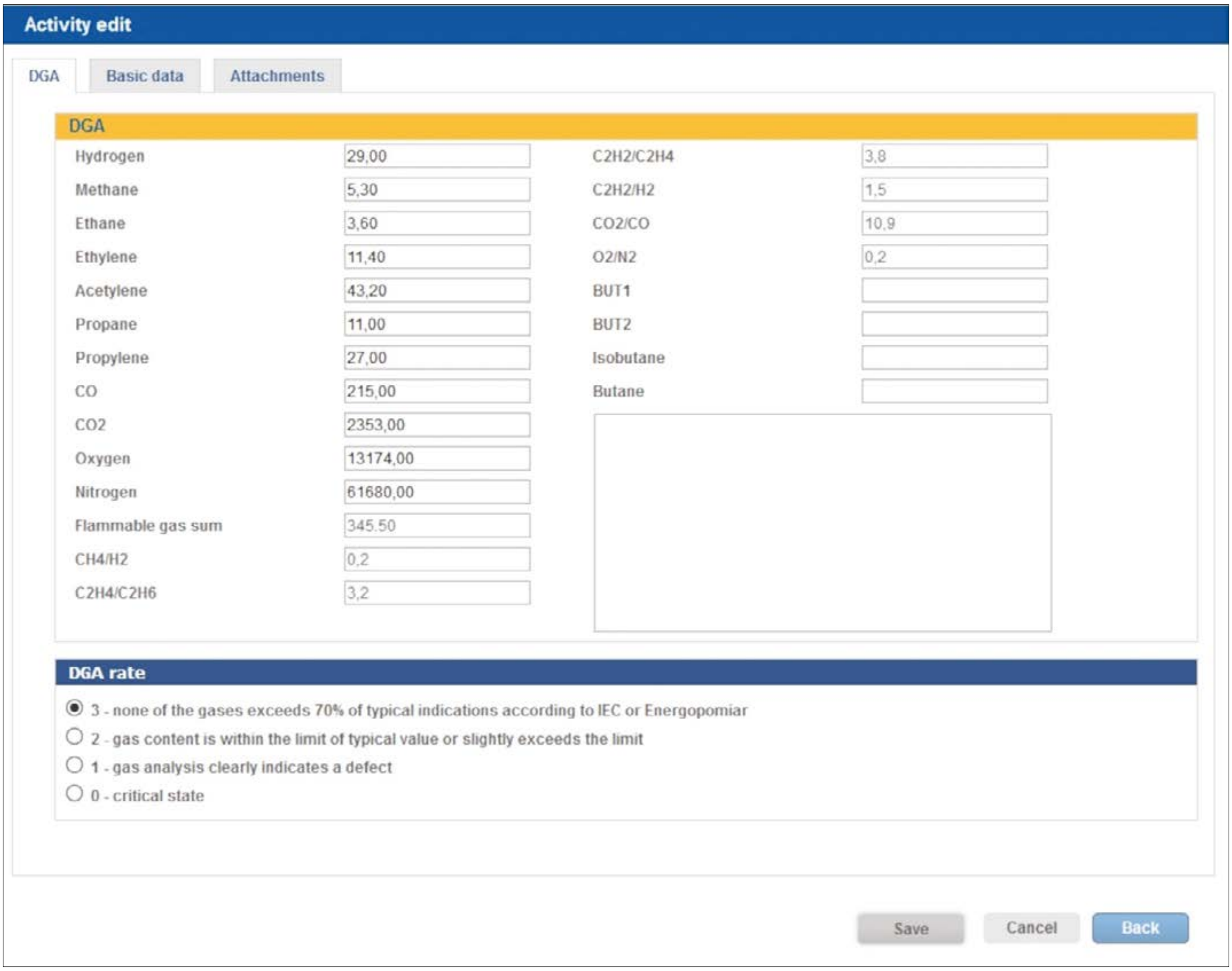

Figure 4. The TrafoGrade system – A screen of the tab with detailed results of a dissolved gas analysis

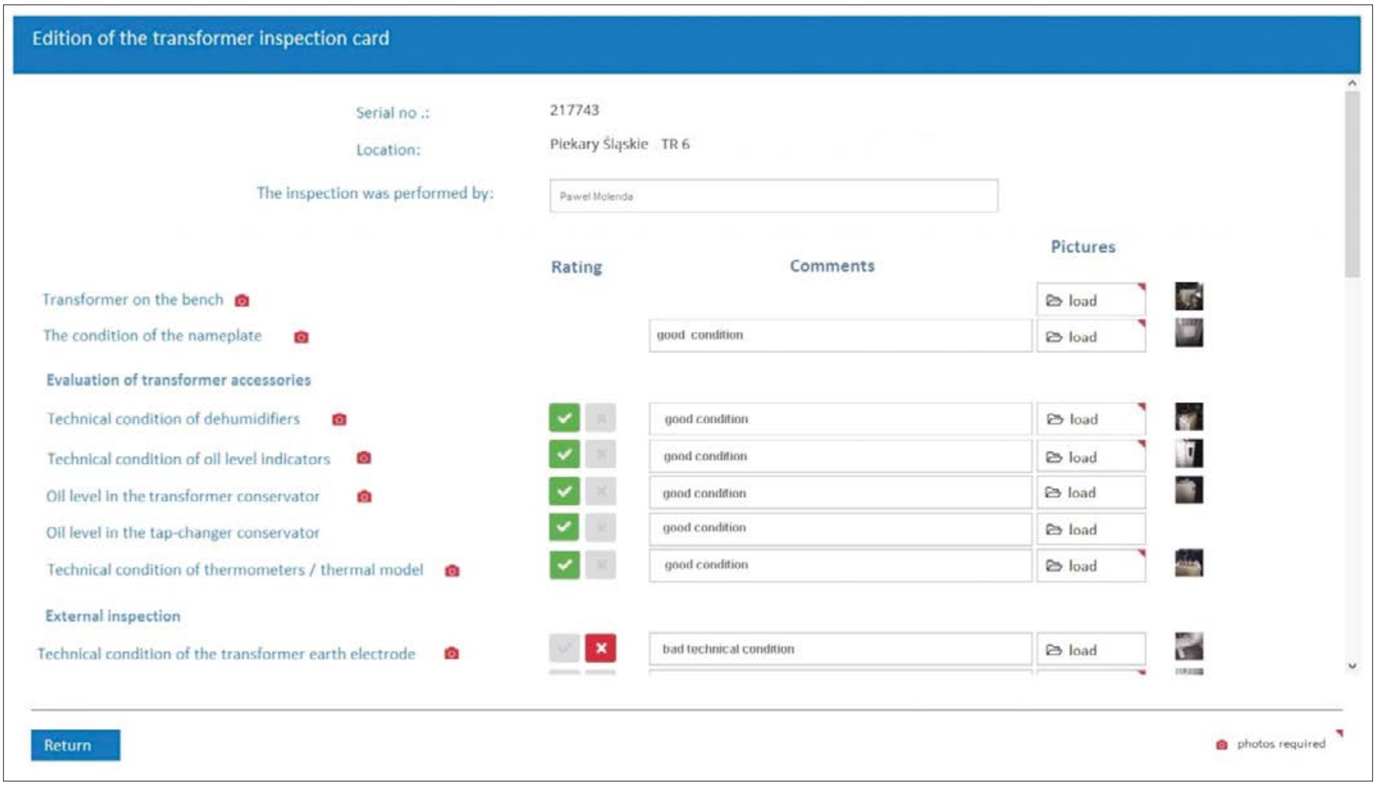

Figure 5. The TrafoGrade system window – edition of the transformer inspection card

The TrafoGrade Inspection application for mobile devices uses documentation processing and data archiving on a database server

The layout of the mobile application TrafoGrade Inspection is presented in Fig. 6.

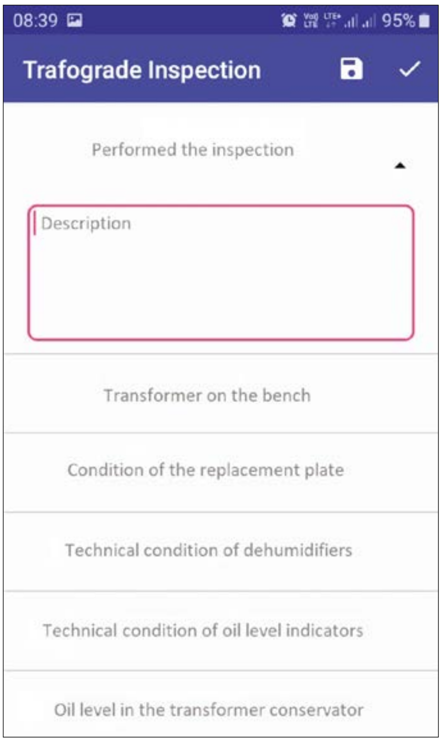

Figure 6. Examination form on the TrafoGrade Inspection for mobile devices

7. Implementation of the TrafoGrade system

The TrafoGrade system was implemented in a power distribution company where a comprehensive assessment of 44 transformers was carried out. Fig. 7 presents the age distribution of the tested transformers population.

The age dependencies presented in Fig. 7 are a typical representation of the medium power transformer population. Therefore, it is assumed that characteristics of technical condition, operational prospects, and main technical problems obtained by the TrafoGrade method will also apply to transformers used by other energy distribution companies.

Out of the 44 tested transformers, 4 units were in poor technical condition, 33 in fair condition, and 7 in good condition. The main elements of a reliable assessment of transformers' technical condition are state-of-the-art diagnostic methods. Fig. 8 shows the population examples of results from the DGA test, measurement of moisture content in solid insulation, and evaluation of mechanical deformations of windings by the Frequency Response Analysis (FRA) method.

The DGA, FRA, and moisture content criteria were adopted on the basis of international standards and long-term operating experience.

According to Fig. 8, only a small percentage of the examined transformer population has major technical problems that may require significant financial resources. Fig. 9 presents operational prospects determined for the analysed population of 44 transformers with the use of the TrafoGrade system.

The operational perspective determined based on technical condition parameters is a baseline for an economic analysis.

8. Economic aspects of the TrafoGrade system implementation

The classical approach requires the unit owner to perform a detailed analysis of data most often collected in several protocols and, on this basis, draw appropriate conclusions. Integration of all measurement data in a computer system, as well as introduction of a scoring scale of technical condition assess-

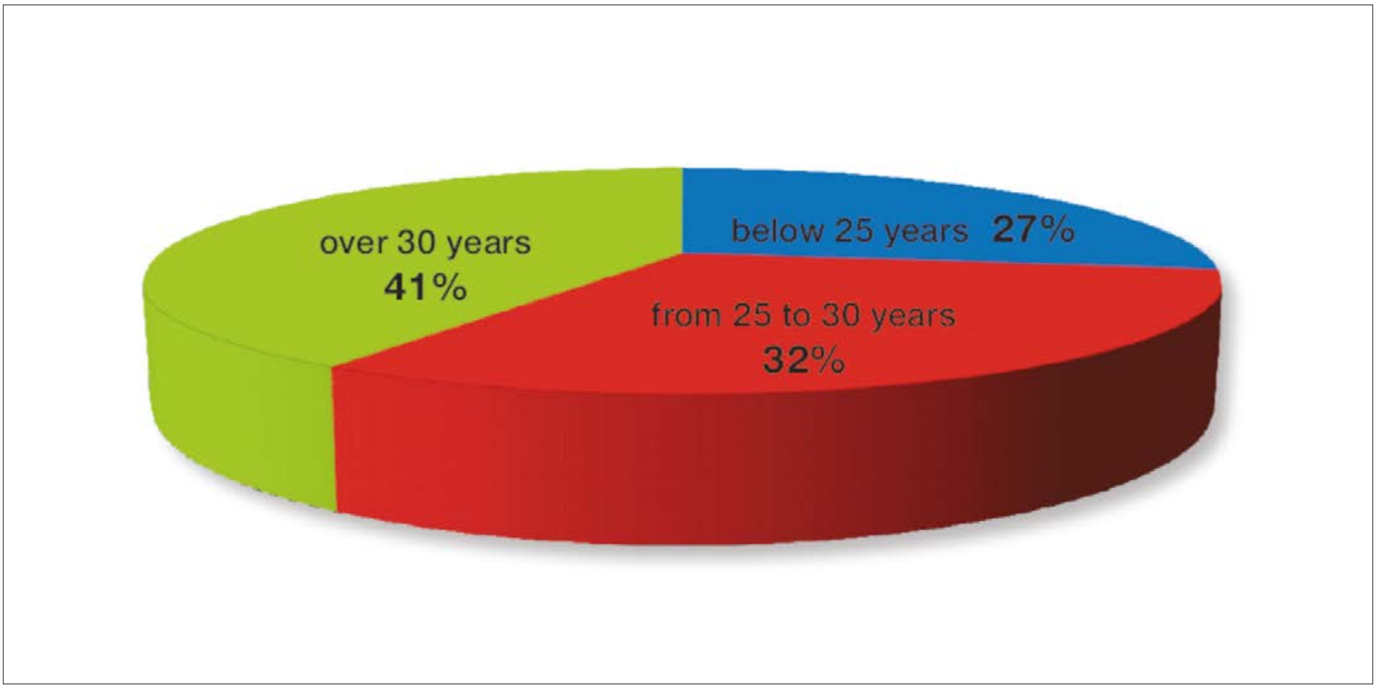

Figure 7. The age distribution of tested transformers

ments, facilitates the analysis of results and allows managers with no detailed knowledge of transformer diagnostics to make decisions. Introduction of a comprehensive management system based on a multi-parametric assessment of the transformer fitness allows for optimization of investment expenses.

This approach to transformer population management makes it easy to capture the right moment when technical condition of a given unit can be significantly improved with a relatively low financial expenditure. An example can be a transformer with a substantial moisture content in solid insulation, with poor oil parameters but with windings in good mechanical condition. Renovation of such a unit involves the following activities:

- drying and cleaning of the windings,
- re-applying compressive force on the core and windings,
- oil treatment or refilling,
- replacement of radiators,
- renovation of the OLTC,
- auxiliary equipment upgrade.

The cost of such overhaul is currently estimated at 15–20 % of a new transformer. The unit's renovation allows the transformer to continue performing its duty for another 10–15 years.

The TrafoGrade system was implemented in a power distribution company where a comprehensive assessment was carried out on 44 transformers

In case of poor technical condition of a transformer, repair or replacement of the unit should be considered. This decision should take into account the following factors:

- an analysis of no-load losses, in case of a transformer core manufactured from hot-rolled steel the excessive no-load losses are economically unacceptable,
- evaluating the probability of electricity demand increase at the place of transformer installation,
- the vector group of the transformer.

The main goal of advanced transformer diagnostics is to avoid catastrophic failures. Occurrence of such incident results not only in damage of the transformer itself but it may also impact other substation equipment. An example is a failure of a 25 MVA transformer in a distribution company, which destroyed medium and high voltage bays as a result of a fire. The total cost of removing the effects of this failure amounted to approximately €1,500,000, which was about 10 times higher than the cost of a major overhaul for this type of unit.

For a typical distribution company, the cost of implementing the TrafoGrade system is amortized when failure of only a single transformer is prevented.

With the introduction of a scoring scale in evaluations and adapting transformer operating instructions to the TrafoGrade method standards, it is possible to reduce costs associated with periodic diagnostics. An individual approach to a certain unit makes it possible to limit the scope of tests for the least important transformers and to rationalize the scope of necessary measurements for devices of particular significance.

Conclusion

The approach to the transformer population management proposed in the

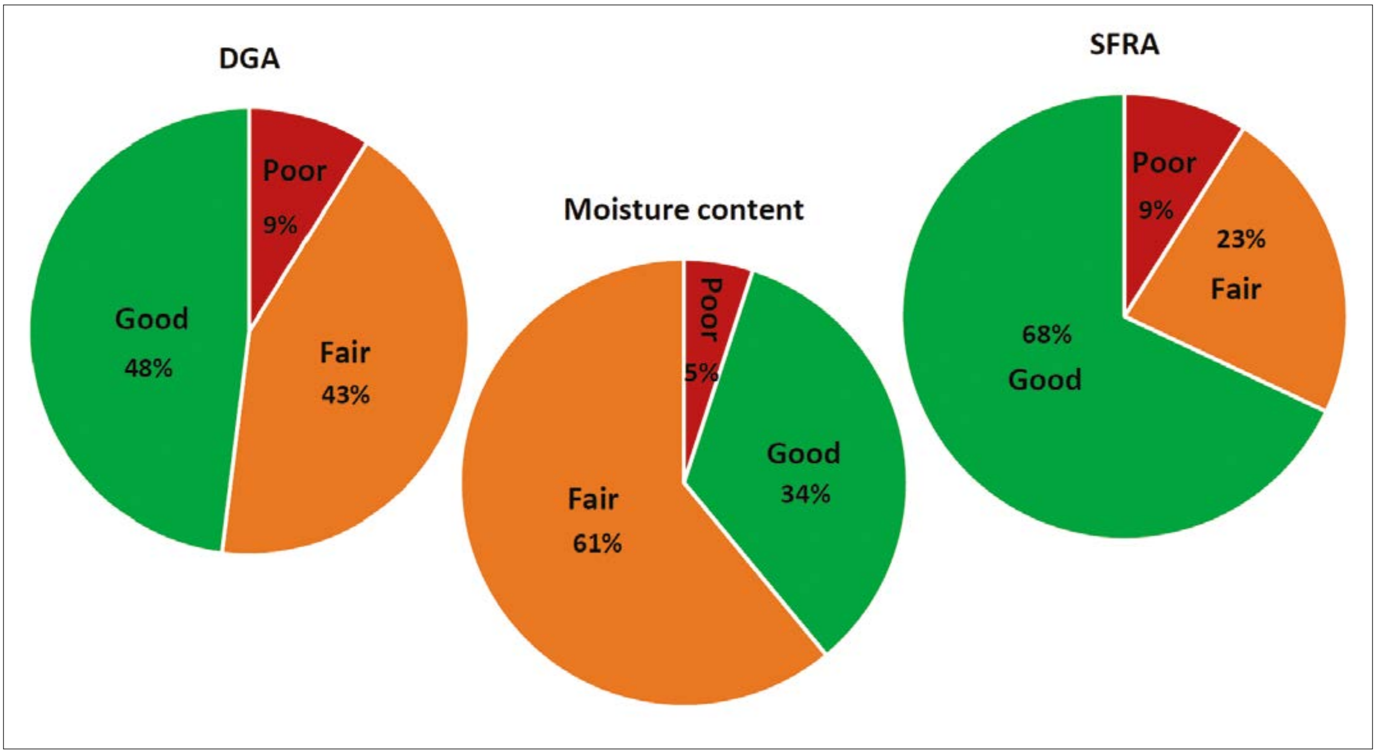

Figure 8. Transformer population analysis with the use of: DGA method (a), moisture content in cellulose insulation (b), and the FRA (c)

Integration of measurement data in the application with a scoring system based on technical condition assessments allows managers with limited technical knowledge to make the decisions

publication allows to improve quality and reliability of units in operation and significantly reduce the risk of catastrophic failures. The assessment of importance of a transformer in the power system facilitates taking actions aimed at increasing energy security of the network. These data, in combination with the technical condition assessment, allow for a real assessment of failure consequences, including costs associated with undelivered energy.

From distribution companies' point of view, preventing interruptions in the electricity supply is important not only for economic but also for marketing reasons, taking into account the company's reputation. A comprehensive condition assessment provides a lot of valuable information for the logistics and financial policy of companies operating power transformers.

Bibliography

[1] M. Krüger, *Transformer diagnosis – practical experience using simple methods like winding resistance measurement, dynamic tap changer testing, ratio, leakage reactance capacitance and dissipation factor measurement*, Omicron Electronics Gmbh Austria, 2005

[2] CIGRE-WG 12-05: Technical Brochure *An international survey on failures in large power transformers in service,* Electra No. 88 1983, s. 21-48

[3] CIGRE Technical Brochure No. 227, *Life management techniques for power transformer,* 2003

[4] CIGRE Technical Brochure No. 445, *Guide for Transformer Maintenance*, 2011

[5] IEEE Power and Energy Society, IEEE Std C57.152-2013. *Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors*, 2013

[6] Sparling, B., Transformer monitoring and diagnostics, *Power Engineering Society 1999 Winter Meeting*, IEEE, 1999

[7] C. L. Kwong, L. C. Kit, and K. Y. Yan, *Remarkable Life Cycle Management by Effective Condition Monitoring and Assessment System of Power Transformer in CLP Power System*, IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2014

[8] Z. Poniran, Z. A. Malek, *Life assessment of power transformers via paper ageing analysis*, in POWERENG 2007 - International Conference on Power Engineering - Energy and Electrical Drives Proceedings, 2007

[9] N. Hashemnia, S. Islam, *Improved Power Transformer Winding Fault Detection using FRA Diagnostics – Part 1: Axial Displacement Simulation*, IEEE Trans. Dielectrics and Electrical Insulation, Vol. 22, (1), (Feb. 2015), pp. 556–563

[10] E. Kornatowski, S. Banaszak, *Diagnostics of a transformer's active part with complementary FRA and VM*

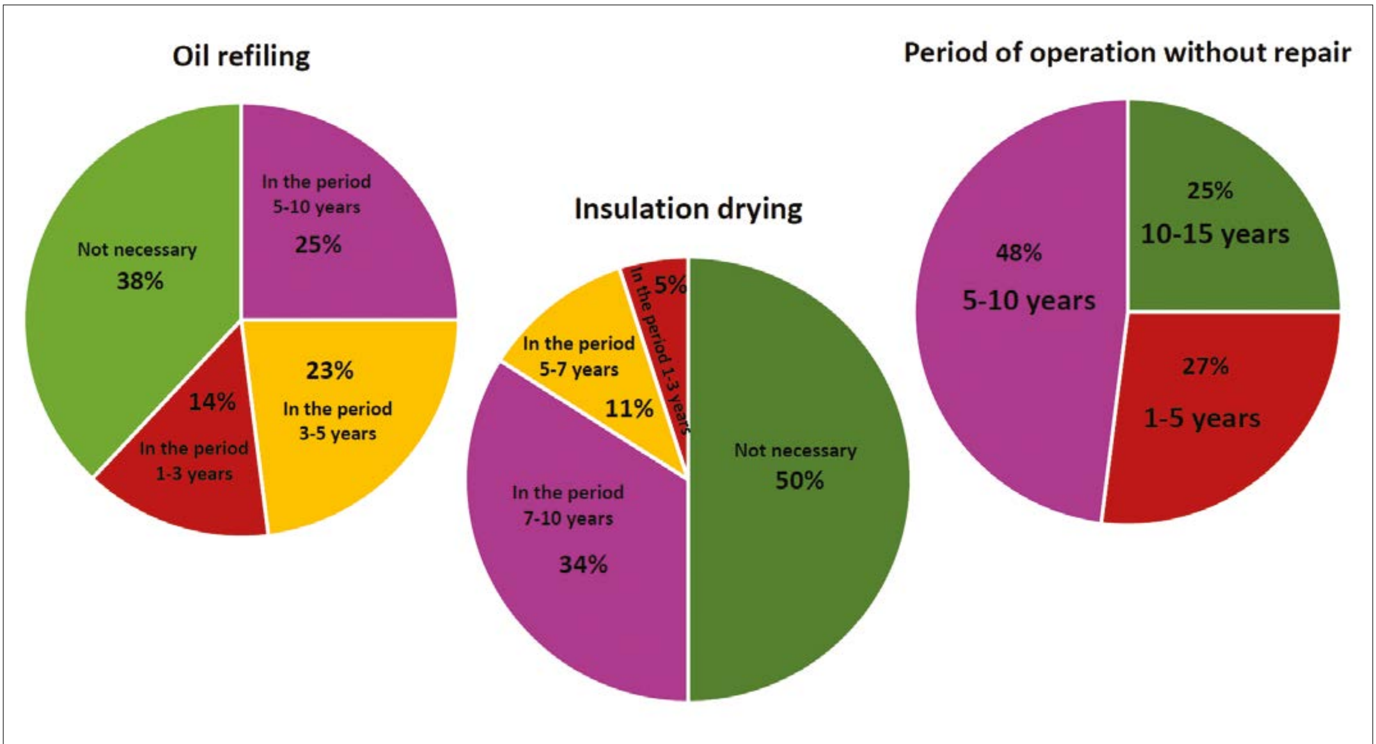

Figure 9. The operational prospects: oil refilling (a), insulation drying (b), repair-free operation period (c)

measurements, IEEE Trans. on Power Delivery, vol. 29, No. 3, (2014), pp. 1398–1406

[11] A. A. Reykherdt, V. Davydov, *Case studies of factors influencing frequency response analysis measurements and power transformer diagnostics*, IEEE Electrical Insulation Magazine, Vol. 27, (1), (January–February 2011), pp. 22–30

[12] J. Gao, et al., *Condition diagnosis of transformer oil-paper insulation using dielectric response fingerprint characteristics*, IEEE Trans. Dielectrics and Electrical Insulation, vol. 23, No. 2, 2016, pp. 1207–1218

[13] J. Subocz, *Transformatory w eksploatacji,* Chorzów: Wyd. Energo-Complex, 2007

[14] M. F. M. Yousof, C. Ekanayake, T. K. Saha, *Examining the ageing of transformer insulation using FRA and FDS techniques*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, No. 2, 2015, pp. 1258–1265

[15] J. Subocz, Z. Emirsajłow: *Modelowanie rozkładu temperatury w przepuście WN* (Modelling of the temperature distribution in the HV bushings), Przegląd Elektrotechniczny, 11 b, (2010), p. 154 (in Polish)

[16] J. Subocz, et al. *Condition Assessment of HV Bushings with Solid Insulation based on the SVM and the FDS Methods*, Energies (13), 4, (2020), pp. 1-13 https://doi.org/10.3390/en13040853

[17] J. J. Erbrink et al., *Condition assessment of on load tap changers using dynamic resistance measurements*, 2010 Inter. Conf. on High Voltage Engineering and Application, DOI: 10.1109/ICHVE.2010.5640735

[18] M. A. A. Aziz, M. A. Talib, R. Arumugam, *Diagnosis of On-Load Tap Changer (OLTC) using dynamic resistance measurement*, in Proceedings of the 2014 IEEE 8th International Power Engineering and Optimization Conference, PEOCO 2014, 2014

[19] F. Poza et al., *OLTC measurements in electrical power grids*, Midwest Symposium on Circuits and Systems, 2006

[20] I. G. N Satriyadi Hernanda et al., *Application of Health Index Method for Transformer Condition Assessment Conference Paper*, DOI: 10.1109/TENCON.2014.7022433

[21] M. Wang and K. D. Srivastava, *Review of condition assessment of power transformers in service*, IEEE Electr. Insul. Mag., vol. 18, No. 6, pp. 12–25 Nov./Dec. 2002

[22] I. Höhlein et al., *Transformer life management German experience with condition assessment*, Contribution for CIGRE SC12 / A2, Jun 2003

[23] P. Bohatyrewicz 1, 2, *, J. Płowucha 3, J. Subocz 1, *Condition Assessment of Power Transformers Basedon Health Index Value*, Appl. Sci. 2019, 9, 4877

[24] S. Tenbohlen et al., *Development and Results of a Worldwide Transformer Reliability Survey*, in Proceedings of the CIGRE SC A2 Colloquium, Shanghai, China, 20–25 September 2015

[25] Cigre WG, *Mechanical Condition Assessment of Transformer Windings using Frequency Response Analysis (FRA)*; Brochure 342; CIGRE: Paris, France, 2008

[26] A. W. Darwin et al., *Interpretation of Frequency Response Analysis (FRA) Results for Diagnosing Transformer Winding Deformation*, in Proceedings of the CIGRE 2009 6th Southern Africa Regional Conference, Cape Town, South Africa, August 2009

[27] L. E. Lundgaard et al., *Aging of oil-impregnated paper in power transformers*, IEEE Trans. Power Deliv. 2004, 19, 230–239

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