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DEVELOPMENT OF OPERATION AND DIAGNOSTIC ALGORITHM COMPLEX FOR TECHNICAL CONDITION ASSESSMENT OF POWER TRANSFORMERS IN PERMISSIBLE RISK CIRCUMSTANCESE

Summary of the Doctoral Thesis

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To be granted the scientific degree of Doctor of Sciences (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on April 30, 2021 at 15:00 online.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Gints Poišs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 6 chapters; Conclusions; 40 figures; 33 tables; the total number of pages is 94. The Bibliography contains 90 titles.

TABLE OF CONTENTS

INTRODUCTION

The Topicality of the Work

Faults of power transformers integrated in the electric transmission system may lead to extensive economic losses caused by unsupplied electricity, repairs of the faulty transformer and additional investment in preventing the damage and restoring power supply.

Data are constantly collected throughout the service life of a transformer, and they serve as a basis or foundation for estimating the condition of the equipment or identifying risks, taking reasoned decisions on further operations or a need for repairs and replacement. Every transformer has to be assessed individually, with due regard to the length of its service and operation history, which includes both diagnostic data and information on previous maintenance works that form a structured data set. At the same time, it is also necessary to collect data on the power system where the respective transformer is installed, such as any changes to the electrical transmission system and the load.

A large volume of obtained data has to be managed efficiently. This could be possible with technical condition index (TCI) method, where condition indexing allows determining a specific number that reflects the general condition or risk level of the equipment. The obtained result represents the general condition of the transformer and in most cases it allows applying a pre-established standard action plan, accelerating the decision-making process after any repairs or upgrades, and planning a specific operation strategy adjusted to the particular power transformer. Although the TCI can be calculated for each transformer individually, determination of risk level for all units contained in a transformer park enables performing a comparative analysis based on pre-set criteria, e. g. among transformers with similar service life, which is a useful contribution to an active management system.

Although the TCI method is based on well-known principles, this method has proved to be timeless in various power transmission systems [30], [57], [52].

It has to be noted, however, that methods for assessing the technical condition of power transformers rely on conventional diagnostic approaches. Nevertheless, the main differences are usually caused by different operational strategies, choice of diagnostic methods, and regularity of measurement data reception. Operational strategies are often based on customized or historically established features, which make every transmission system unique.

The Latvian electric power transmission system is characterized by a high share of aged transformers, low transformer load, large number of reserve (backup) transformers, used diagnostic methods and their periodicity. The existing dataflow of the Latvian electric power transmission system precludes using ready-made assessment methods.

The Goal and the Tasks Solved by the Thesis

The aim: To develop a set of algorithms using technical condition indexing for determining risk levels of power transformers by using result-related data obtained by available diagnostic methods.

Goals

- Analyse technical literature on risk assessment methods and application of the technical condition index.
- Explore the specific features of the existing transformer park, data set of diagnostic results, and periodicity.
- Develop a risk matrix and mathematical description of the TCI indicators (dissolved gas analysis (DGA), oil analysis, and electrical measurements) and their synthesis and using assigned scores develop weight distribution between indicators.
- Verify the developed algorithm complex on power transformers of the Latvian electric power transmission system.

Scientific Novelty of the Thesis

Through efficient use of the existing diagnostic result dataflow, the aim is to develop operation and diagnostic algorithm complex for technical condition assessment of power transformers in permissible risk circumstances of the Latvian electric power transmission system.

The developed methodology includes operation-centered features, such as DGA acetylene concentration, OLTC dynamic resistance, load, and the impact of transformer age. The diagnostic methods, thresholds and concentration limits used in methodology can be easily modified or changed, as well as supplemented with new values.

Practical Significance of the Thesis

The proposed set of algorithms allows:

- to combine in one system the data accumulated during the operation of transformers;
- to calculate the risk level, including information on such transformer parameters as its age, load, upgrades, monitoring system, maintenance history, as well as assessment of individual components – windings and core, bushings, on-load tap changer, and oil parameters, based on diagnostic measurements;
- to visualize the calculated risk level in the risk matrix, make selection among individual transformers or group of transformers based on selected criteria;
- to get an overview of parameters included in the risk-level calculations for a specific transformer and thus detect its “weak points”;
- to modify algorithm by offering a limited scope of user-defined options, for example, editable limits in the case of changes in standards.

This information enables the transmission system operator to analyse the actual situation, plan controls, repairs, and replacement of transformer. Such a TCI algorithm set can be included in the existing data processing procedure and stored in the system, or it can be executed as separate software.

Methodology of the Research

The algorithm set was developed by using the principles of risk management and power transformer operation strategies, the framework of technical condition index method, as well as guidelines of the fuzzy logic theory. Individual proposed algorithms were integrated by synthesis. For calculations, result processing and verification of algorithms, MS Excel and Matlab software was used.

Individual experimental dynamic resistance measurements of transformer's OLTC units were performed. Classification of transformer faults and processing of diagnostic test results were done by data analysis methods, including analysis of factors and correlation analysis for processing the reports of measurements conducted by the transmission system operator "Augstsprieguma tīkls" JSC (AST). The fuzzification rules were supported by means of expert interviews conducted in cooperation with engineers from the accredited Chemical Laboratory of AST.

Approbation of the Thesis

1. Presentation of recent achievements of research in the **7**th International Doctoral School of Electrical Energy Conversion and Saving Technologies (IDS-ECST 2018), "Ronīši", 25–26 May 2018.
2. "Development and Implementation of Risk Indicator for Power Transformers Based on Electrical Measurements", 18th International Scientific Conference on Electric Power Engineering (EPE), Czech Republic, Kouty nad Desnou, 17–19 May 2017.
3. "Development of DGA Indicator for Estimating Risk Level of Power Transformers", 17th International Scientific Conference on Electric Power Engineering (EPE), Czech Republic, Prague, 16–18 May 2016.
4. "Development of a Risk Matrix Considering Specific Features of the Power Transformer Park of Latvia", 12th International Conference of Young Scientists on Energy Issues, Lithuania, Kaunas, 27–28 May 2015.
5. "Overview of the Power Transformer Park and Diagnostic Methods in Latvia", IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), Riga, 11–13 May 2015.

Publications

1. Poišs, G., Vītoliņa, S., Mārks, J. "Development of Indicators for Technical Condition Indexing of Power Transformers", Advances in Science, Technology and Engineering Systems Journal (ASTESJ), Volume 3, Issue 1, pp. 148–154, 2018**.** (Directory of Open Access Journals, Thomson Reuters Researcherid) DOI: 10.25046/aj030118, ISSN:2415-6698.
2. Poišs, G., Vītoliņa, S. "Development and Implementation of Risk Indicator for Power Transformers Based on Electrical Measurements", 18th International Scientific

Conference on Electric Power Engineering (EPE), Czech Republic, Kouty nad Desnou, 17–19 May 2017. (Scopus, IEEE Xplore) DOI: 10.1109/EPE.2017.7967289.

3. Poišs, G., Vītoliņa, S., Mārks, J. "Development of Indicator Based on Oil Analysis for Estimating Risk Level of Power Transformers", RTUCON, Latvia, Riga, 13–14 October 2016, (Scopus, IEEE Xplore). DOI: 10.1109/RTUCON.2015.7343160.
4. Poišs, G. "Development of DGA Indicator for Estimating Risk Level of Power Transformers", 17th International Scientific Conference on Electric Power Engineering (EPE), Czech Republic, Prague, 16–18 May 2016, (Scopus, IEEE Xplore). DOI: 10.1109/EPE.2016.7521813.
5. Poišs, G., Vītoliņa, S. "Overview of the Power Transformer Park and Diagnostic Methods in Latvia", IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), Riga, 11–13 May 2015, (Scopus, IEEE Xplore). DOI: 10.1109/PowerEng.2015.7266301.
6. Žižins-Mališevs, S., Poišs, G. "Power Transformer Mechanical Condition Assessment with a Vibration-based Diagnostic Method", 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2015. (Scopus, IEEE Xplore) DOI: 10.1109/RTUCON.2015.7343160.
7. Poišs, G. "Development of a Risk Matrix Considering Specific Features of the Power Transformer Park of Latvia", 12th International Conference of Young Scientists on Energy Issues, Lithuania, Kaunas, 27–28 May 2015.

1. RISK ASSESSMENT METHODS

1.1. Risk Assessment Methods in Power Transmission System

The risk management guidelines and principles are described in [12]; here, risk management is considered as a structured process that involves risk identification, assessment, analyses, decision-making, as well as risk monitoring.

Risk assessment methods are general and can be used for estimating different risks. The most common risk assessment methods are summarized in Table 1.1. For the risk assessment of electric equipment operated in a power transmission system, including transformers, such methods are used as PATTERN, SEER, MTBF or, for example, online power transformer monitoring system (TPU) Serveron.

Risk assessment method PATTERN (Planning Assistance Through Technical Evaluation of Relevance Numbers) allows determining the amount of financial and material resources necessary for the respective target, whereas the SEER method (System for Event Evaluation and Review) helps determining the probability of specific occurrences (e.g., transformer assembly failure) as well as estimating the time period when this event would become relevant thus determining the degree of risk level.

The MTBT (Mean Time Between Failures) method can be used to determine an appropriate periods for equipment controls. Since failures during the transformer operation may occur in a random order, it is complicated to predict a specific defect. The failure level can be calculated, and this calculation gives an insight in the failure frequency of a specific type of transformers.

Monitoring system (TPU) Serveron is designed for direct data collection and monitoring. The system is intended for in-service, online transformers and it detects the gas concentration in oil and transfers the collected data to the control board for processing [18].

Other risk assessment methods used in power transmission systems include the Markov model [7], [8]. In probability theory, the Markov model is used to model randomly changing systems. It is assumed that future states depend only on the current state, not on the events that occurred before. Such a data set may produce incomplete or misleading results because all the necessary data are not always recorded and stored.

Table 1.1

Risk assessment methods

Failure mode and effects analysis, criticality analysis	FMEA, FMECA
Fault tree analysis	FTA
A hazard and operability study	HAZOP
Mean time between failures	MTBF
A process hazard analysis	PHA
Risk matrix method	Risk matrix

The above-mentioned risk assessment methods fail to provide completely detailed information on a particular transformer. These methods could be useful for experts if they were, for instance, integrated as an additional variable or criterion in a pre-existing methodology based on technical condition evaluation or operation period.

1.2. Technical Condition Index Method and Its Results in the Risk Matrix

Calculated technical condition index (TCI) result allows making fast and justified decisions on the repair needs for an individual transformer or a group of transformers. The TCI is based on transformer operation and diagnostic data. Algorithms for the TCI method are developed to assess individual transformer assemblies and auxiliary component. Weight factors and combinations of algorithms help obtaining the final result that reflects the general condition of a transformer (Fig. 1.2) [16].

TCI focuses on long-term assessment rather than short-term functioning [19]:

- the index should indicate if the equipment is suitable for further operation and show its general technical condition;
- the index should be based on objective and verifiable technical condition parameters instead of subjective observations;
- the index should be comprehensible and easy to interpret.

One of the ways for assessing the TCI results is to develop a risk matrix. The structure, breakdown and application of the risk matrix are described in standard [10] (Fig. 1.1). A summary of basic techniques for developing a TCI and a description of a risk matrix with 6 areas and colour-coded categorization where each area represents a specific severity of damages is provided in Cigre technical brochure [3].

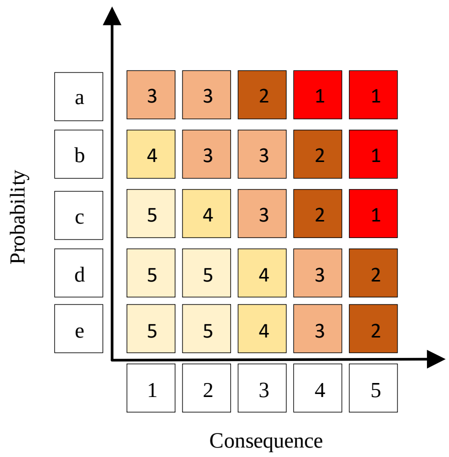


Fig 1.1. Conceptual design of a general risk matrix according to standard *IEC 31010.*

The technical condition index is a way to demonstrate and compare the technical condition of a transformer as part of a large-scale structure, such as a transformer fleet.

Since a transformer consists of several parts: windings, core, oil, auxiliary components such as bushings and OLTC, it is possible to develop an individual degradation algorithm or a module for each of these parts. Therefore, it is also necessary to consider such factors as transformer manufacturing standards and design as well as operational conditions. Other factors might include transformer load and location, age, and the history of upgrades or repairs. When developing the TCI, it is crucial to understand the interaction among transformer parts, as any of the parameters may impact the resulting algorithm of another part [13].

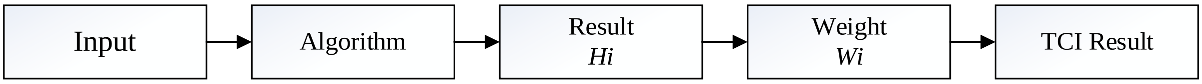


Fig. 1.2. Flowchart of the technical condition index principle.

There is a considerable number of TCI methods developed worldwide, mostly for specific national or individual transmission systems. An example is the TCI risk-assessment method developed in the USA for HPPs or block transformers [4]. The PEA, Thailand’s electric grid operator, [17], [20] offers a method that is applicable only to sub-station transformers. Some methods require large number (up to 20) on input data units, which complicates the task for a user [2], [21]. Various methods often include criteria that do not reflect the technical condition of a transformer directly or occur infrequently. As a result, some defect may go unnoticed. Applicability of several methods depends on the available funding. For instance, the furan analysis on oil is an expensive diagnostic method that is also not available in all power systems.

Just a few globally renowned energy companies offer software for assessing the technical condition of transformers. However, only very limited information on the algorithms of such software is available.

Currently in Latvia, the assessment of individual transformers and a transformer park relies on databases developed within a company. It stores data on all measurements performed. Only a few transformers (<5 %) in the Latvian electric power transmission system are equipped with a continuous monitoring system. Therefore, experts have to perform the assessment and analysis on their own by examining the measurements included in data bases.

2. TCI METHODOLOGY FOR TRANSFORMER PARK IN LATVIAN ELECTRIC POWER TRANSMISSION SYSTEM

2.1. Diagnostic Methods and Periodicity in Lavian Power Transmission System

A. Measurement of insulation resistance.
B. Measurement of tanδ and insulation system capacitance.
C. Measurement of no-load loss.
D. Measurement of winding resistance.
E. Measurement of load loss and short-circuit impedance.
F. Dissolved Gas Analysis (DGA).
G. Insulating oil analysis.

Periodicity of measurements in the Latvian electric power transmission system is reported in Table 2.1 [5].

Table 2.1

Periodicity of diagnostic methods in Lavian Transmission System

Diagnostic method	Device	Periodicity
A, B, C, D, E	110 kV transformers	8 years
	110 kV, 330 kV bushing un 330 kV autotransformers	4 years
F	110 kV transformers un 330 kV autotransformers	6 months
G	110 kV transformers	4 years
	330 kV autotransformers	2 years

2.2. Overview of the Proposed TCI Methodology

The TCI methodology for the Latvian electric power transmission system is developed by using the available continuous dataflow. Its structure is shown in Fig. 2.1. A separate algorithm was developed to obtain results for each block, and they are discussed in the next sections of the Thesis. A1 and A2 are block results that, accordingly, determine the total TCI score and the position of the respective transformer along the abscissa of the risk matrix.

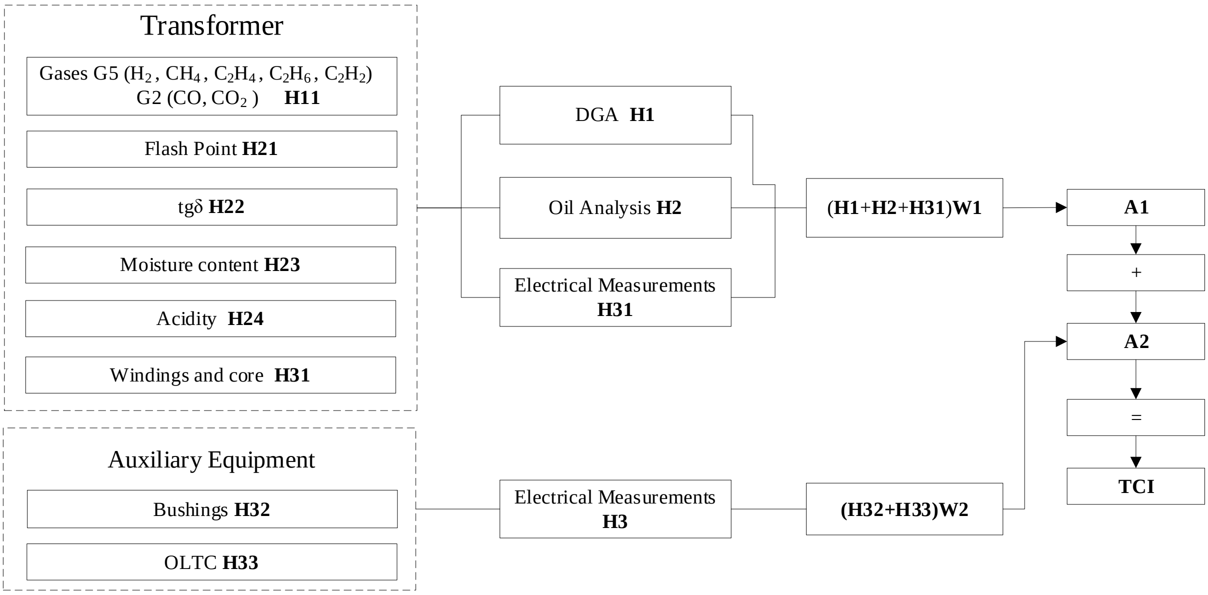


Fig. 2.1. Overview of the technical condition index methodology.

The transformer's vertical positioning on the risk matrix (Fig. 2.2) along the ordinate (*y* axis) is based on continuously available operational data available (Table 2.2). The dataflow is stable and includes the key influence factors F1...F6.

Table 2.2

Data of operation history

Y axis

Factor		**Parameter**	**Influence factor**
F1	Age, years	1..2	+0.25
		3..35	0
		>35	+0.5
F2	Load	In service	+0.5
		Reserve	+0.1
		Backup transformer	–0.25
F3	Upgrade, years	Yes, performed (in 2 years)	–0.1
		No, not performed	0
F4	Monitoring system	Yes	–0.1
		No	0
		System warning	+0.1
F5	Maintenance history	No notes	–0.2
		Repaired	0
		Cannot be Repaired	+0.2
		Gases detected in gas relay	5
F6	Importance in the system	High priority	+0.3
		Medium priority	+0.1
		No priority entered	0

The total influence factor Y for each transformer was obtained as an absolute value by aggregating individual influence factors. In order to focus special attention of the user, the calculated sum of the influence factors can be high but in the matrix it is reduced to value 1, which is the highest risk level in this methodology.

The risk matrix can be developed with all kinds of risk ratios and distribution patterns. In the current methodology developed, the risk matrix is divided differently than in the example in [10], and it includes three risk areas, as proposed in an article by the author of the Thesis [6]. In the matrix shown in Fig. 2.2, green colour represents low risk, blue colour stands for the moderate risk area or acceptable operational condition of the transformer, whereas red indicates a high risk area that requires an immediate action, such as switching-off the transformer, or shows that it is unacceptable to switch on the transformer.

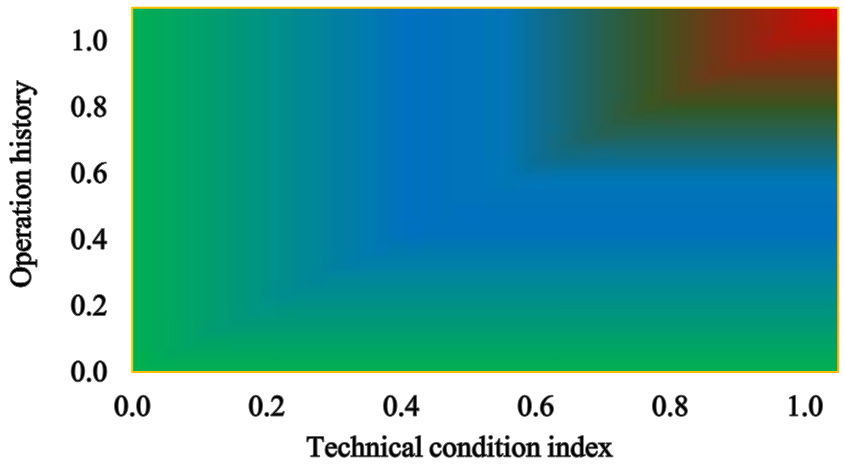


Fig. 2.2. Distribution of risk areas in a risk matrix.

3. DISSOLVED GAS ANALYSIS INDICATOR

3.1. Dissolved Gas Analysis

Gases dissolved in oil of a power transformer in services are often the first indication of a potential malfunction and can eventually lead to a transformer failure. Gases in a transformer are also generated during its normal operation but their concentration is negligible compared to the total amount of oil contained in the transformer. Possible causes for dissolved gas generation in the oil include arcing, partial discharges, low energy electrical discharges, overheating of insulation caused by overloading, and failure or cooling pumps or fans [9].

Most common DGA interpreting methods are based on combustible gases. These methods can be divided into two groups: the first group contains 5 gases (H_2, CH_4, C_2H_4, C_2H_6, C_2H_2) that indicate potential electric or thermal faults in a transformer, and the second group includes 2 gases (CO, CO_2) that indicate deterioration of insulation of a transformer [11].

3.2. Algorithm for DGA Indicator

The DGA indicator (Fig. 3.1) plays an important role in the methodology, and it includes the main characteristics of transformers from the Latvian electric power transmission system such as load, location of OLTC in the transformer tank, and oil processing.

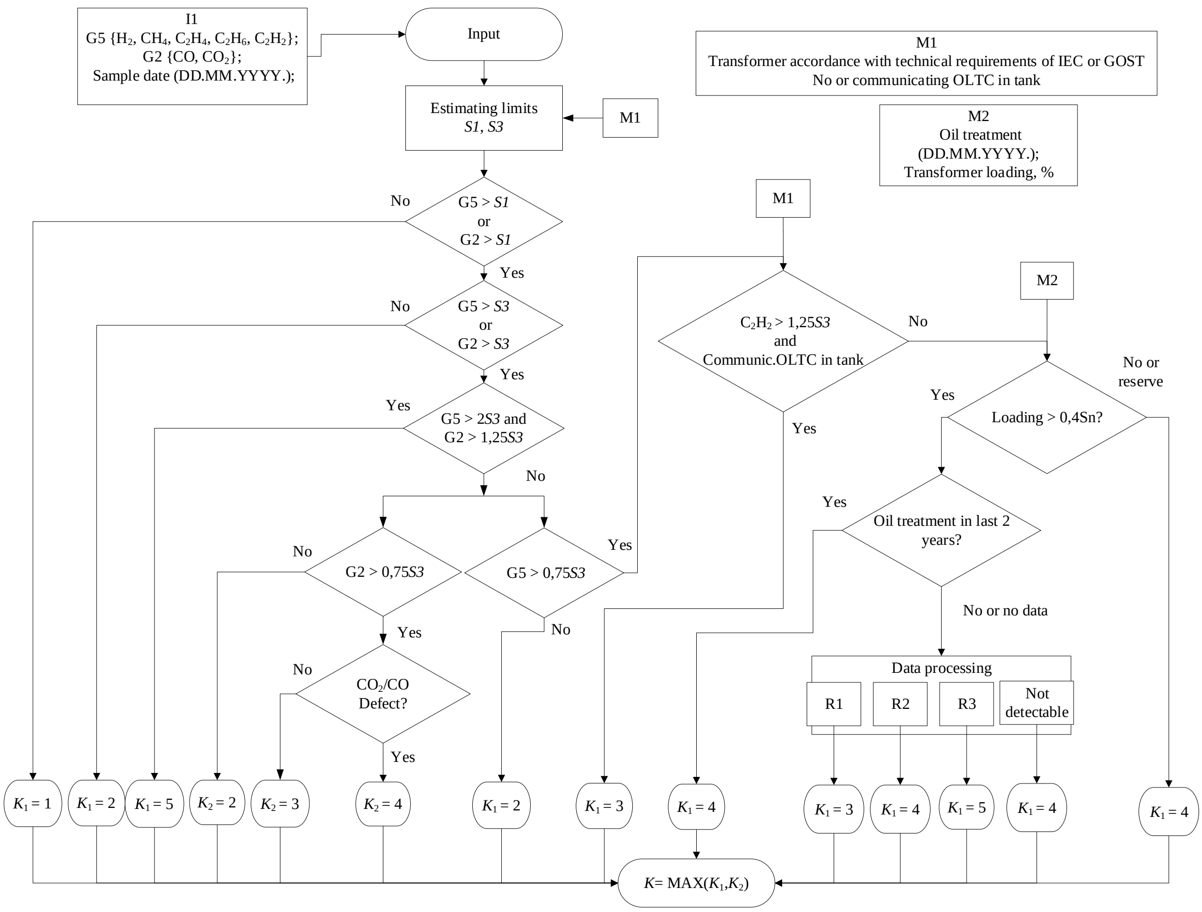


Fig. 3.1. Flowchart of the DGA indicator algorithm.

In the methodology, the DGA indicator is responsible for dynamic changes due to frequent intervals of analysis. The algorithm uses limit *S1* (no fault) and *S3* (high risk) values, as specified in Latvian Energy Standard *LEK 118* [14].

DGA algorithm consists of input data, the comparative part and the final result as a single number (risk level). The path to the result can be short where gas concentrations <*S1*, or it can be complicated for gases above the threshold of >*S3*; in this case the result is obtained by interpreting acetylene concentrations, with regard to the load and oil processing as well.

Increased acetylene concentrations may be caused by a non-sealed OTLC that is located in the transformer tank.

The literature review and applied research leads to a conclusion that it is impermissible to base the assessment only on the present on increased acetylene concentrations. To justify the conclusion, out of 271 transformers included in the Latvian electric power transmission system, 100 transformers were randomly selected for analyses, and in 32 cases acetylene concentrations exceeded 0.75 of *S3* threshold value. Therefore, the DGA algorithm is adjusted for the specific of increased acetylene concentrations to approximate it with real-life conditions. According to the adjustment mechanism, if only the C_2H_2 value exceeds 1.25 from *S3* threshold value and the OLTC is located in the transformer tank, the assigned risk level is $K_1 = 3$. Such criteria as oil processing and loading are necessary for the *IEC* gas ratio method [11] that identifies the type of fault, which then serves as basis for determining the risk level.

3.3. Verification of the Algorithm for DGA Indicator

The DGA algorithm was verified by using 9 real-life cases (Table 3.1) that provide results from different algorithm branches and allows comparison with practical observations.

Table 3.1

Cases for verifying DGA indicator algorithm

No.	**Data block I1**								**Data block M1**		**Data block M2**	
	G5 gases, ppm					**G2 gases, ppm**		**Sampling date**	**Stan-dard**	**OLTC**	**Oil processing**	**Load**
	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2		*IEC/ GOST*	Yes/No	Yes/No	%
1	25.2	118	905	152	10.5	46.1	1406	10.08.2016.	*GOST*	Yes	No	>40
2	96	301.4	661.8	72.1	19.4	711.5	3748.8	20.11.2009.	*GOST*	Yes	No	–
3	4.1	4.2	29.6	1.33	59.5	51.8	1473	02.03.2015.	*GOST*	Yes	No	–
4	1638	253	0.41	58.6	0.4	192	466	16.10.2017.	*IEC*	Yes	No	>40
5	537	1041	1726	295	25	1047	6158	–	–	–	–	–
6	33.7	131	762	127	10.2	30.4	954.0	11.02.2018.	*GOST*	Yes	No	>40
7	6.4	10	29.2	11	4.2	254	1700	12.05.2016.	*GOST*	Yes	No	–
8	2.7	1.2	3.1	0.59	0.62	33.6	899	13.10.2016.	*IEC*	Yes	No	–
9	664.3	192.1	327.1	24.6	352.5	896.6	1302.2	10.06.2009.	*GOST*	Yes	No	–

In verification case No. 1, risk level $K = 4$ was assigned at the end of the algorithm using the *IEC* gas ratio method. In practice, partial discharges have been detected in the measurements performed to the transformer. In case No. 2 the CO_2/CO ratio indicates a defect in the solid insulation – the assigned risk level $K = 4$. In cases No. 5 and No. 9, where the worst-case scenario was examined with the risk level $K = 5$, oil samples were taken immediately after the transformer failure. In case No. 3, the criterion of acetylene concentration is fulfilled and accordingly the risk level K = 3 is assigned. Cases No. 7 and No. 8 correspond to the normal operating condition for transformers with different manufacture standards – *GOST* or *IEC*. The risk level assigned to case No. 6 is K = 4. Here the algorithm fulfilled the criterion of oil treatment due to degassed oil, but after some time repeated significant increase G5 gas concentrations was identified. In case No. 4, the result of the *IEC* gas ratio method could not be determined, and risk level K = 4 was assigned. In practice, H_2 gas was released from the welds inside the power transformer tank.

The assigned risk levels (Fig. 3.2) correspond to the expected and actually observed situation. In total, the DGA algorithm has been verified with 138 transformers with voltage of 110 kV, and mainly, i.e. in 46 cases, risk level K = 3 was assigned because of increased C_2H_2 gas concentrations. The algorithm branches work as expected and the specified conditions have been successfully fulfilled.

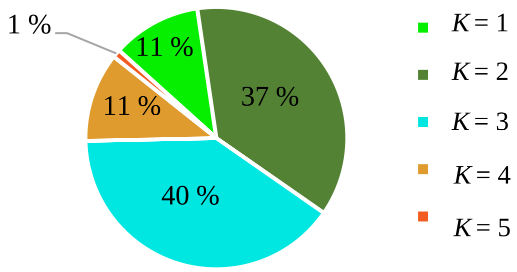


Fig. 3.2. Summary of DGA algorithm verification results.

4. OIL ANALYSIS INDICATOR

4.1. Transformer Oil Analysis

Transformer oil analyses provide data on dielectric and cooling properties as well as the aging level of the oil. Parameters of oil analysis are summarized in Fig. 4.1. In case of a fault in a transformer, oil prevents immediate ignition and thus minimizes environmental pollution and ensures safety of service personnel.

Electrical properties Dielectric strength Dissipation factor Moisture content Specific resistance	**Cooling** Viscosity Freezing point	**Operation time** Antioxidants Acidity
Compatibility of Insulating Oil Sulphur compounds Polycyclic aromatic Hydrocarbon present	**Safety** Flash point	**Others** Interfacial tension and viscosity Sludge content Mechanical particles

Fig. 4.1. Oil properties and parameters.

The main parameters measured for transformers in the Latvian power transmission system include dielectric strength, flash point, acidity, dielectric losses, and moisture content in oil [14]. Other parameters are analysed at the discretion of the person in charge of the equipment.

4.2. Algorithm for Oil Analysis Indicator

The algorithm of oil indicator is based on comparison with limit values. First, binary logic is used to assign risk levels $K_3 = 1$ and $K_3 = 5$. For the rest of risk levels, the principle of fuzzy logic is used (Fig. 4.2) with four input parameters – *H21*, *H22*, *H23*, and *H24* – that are not related, but are sensitive to changes in oil properties.

In order to make the algorithm as close to the actual situation in the Latvian electric power transmission system as possible, typical values of these oil parameters were estimated based on oil analysis results involving 270 transformers. The relative cumulative frequency of the data sample is 90 %. The processed data regarding transformers from the Latvian electric power transmission system over a period of 15 years are summarized in Table 4.1. Typical values of *H21*, *H22*, and *H24* were calculated using the results from 2114 analyses, whereas typical values of parameter *H23* are based on the results frm1568 analyses.

Table 4.1

Typical Values of Oil Parameters from 270 Transformers

H21 Flash point, °C	*H22* tgδ, %	*H23* Moisture content, ppm	*H24* Acidity, mg_{KOH}/g
148	1.8	14	0.05

Limits of oil indicator parameters developed on basis of the identified typical oil parameter values for the Latvian electric power transmission system transformer fleet are shown in Table 4.2. Limits have been divided into 3 levels, where *L1* indicates a good oil condition, *L2* indicates a partially satisfactory condition, and *L3* indicates an unsatisfactory condition.

Table 4.2

Limits for Oil Parameters

Level	***H21*, °C**	***H24*, mg$_{KOH}$/g**	***H23*, ppm**	***H22*, %**
L1	–	0.01	6	0.3
L2	–	0.01–0.05	6–14	0.3–1.8
L3	135	0.05	14	1.8

The flowchart of the oil indicator algorithm and F1 fuzzy logic calculation block with clearly depicted fuzzy logic steps used in this methodology is shown in Fig. 4.2.

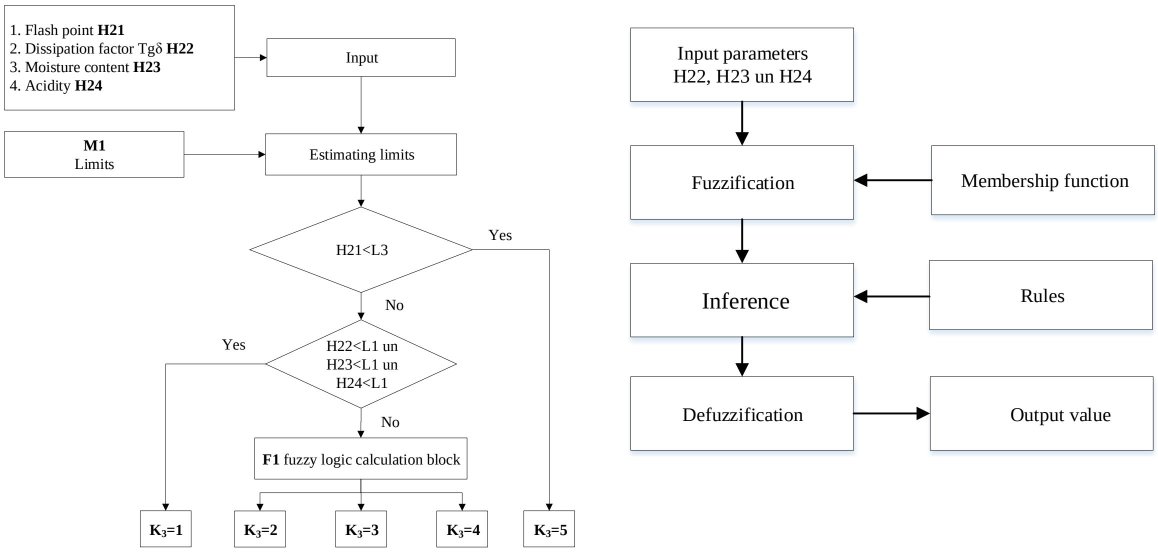


Fig. 4.2. Flowchart for oil analysis indicator and F1 fuzzy logic block.

In this fuzzy logic block system, the membership functions are formed using 10 different transformer oil analysis data and operating history [29]. The inference rules are based on the user experience to obtain the corresponding fuzzy values [28]. A total of 27 combinations are assigned to the membership functions used in the fuzzy logic block. Using inference rules from all membership functions, their minimum values are then used to calculate the centre of gravity. Conversion of fuzzy values to accurate output data or defuzzification is the last step of the fuzzy logic block the result of which is the risk level of the indicator.

4.3. Verification of the Algorithm for Oil Analysis Indicator

A detailed verification of this algorithm was performed with 7 transformers (Table 4.3) but in total with 100 transformers from the Latvian electric power transmission system for verification purposes.

Table 4.3

Oil Indicator Algorithm Verification Cases

Case	Date	Flash point, °C	tgδ, %	Acidity, mg_{HOH}/g	Moisture content, ppm	Performed action	K_3
1	29.11.2017.	143	0.10	0.010	4	New transformer, first connected within last 30 days	1
2	27.03.2007.	143	0.50	0.029	10	Periodic inspection	3
	09.07.2008.	143	0.29	0.015	19	Control sample	3
	11.03.2011.	143	0.40	0.028	9	Inspection after repair	3
3	09.06.2004.	147	0.43	0.016	n/d	Periodic inspection	3
4	21.09.2005.	147	3.14	0.100	12	Periodic inspection	4
	28.07.2006.	147	3.61	0.084	17	After oil processing	4
	25.06.2007.	151	3.55	0.055	13	Control sample	4
	08.08.2008.	153	0.19	0.010	11	After oil replacement	2
5	10.10.2016.	143	2.13	0.024	7	Backup transformer	3
6	01.04.2006.	137	2.62	0.130	13	Periodic inspection	4
	07.05.2009.	139	0.82	0.040	11	After degassing and replacement of silica gel	3
7	30.04.2010.	133	0.09	0.005	54	Periodic inspection	5

Contrary to the risk level of a new transformer $K_3 = 1$ (case No. 1 in Table 4.3), the results of oil parameters in case No. 7 indicate a high moisture content in the oil. As a result, the flash point is <135 °C, and the assigned risk level is $K_3 = 5$. In verification case No. 2, the transformer has been in operation for 45 years. An increased oil acid number after oil treatment indicates on aged paper insulation. The assigned risk level is $K_3 = 3$. In case No. 6, increased dielectric losses indicate oil aging and the assigned risk level is $K_3 = 4$, but after degassing and replacement of silica gel, the risk level is reduced to $K_3 = 3$.

If data on a specific parameter are missing, as it was in case No. 3, it is initially assumed that the value of this parameter corresponds to level *L2*. However, if there are no data also in the next measurement, further approximation is performed on a logarithmic scale.

Risk levels $K_3 = 1$ and $K_3 = 2$ were most commonly assigned (Fig. 4.3) because the transformers are subjected to periodic maintenance and visual inspections to ensure the tightness of a transformer against external environmental conditions.

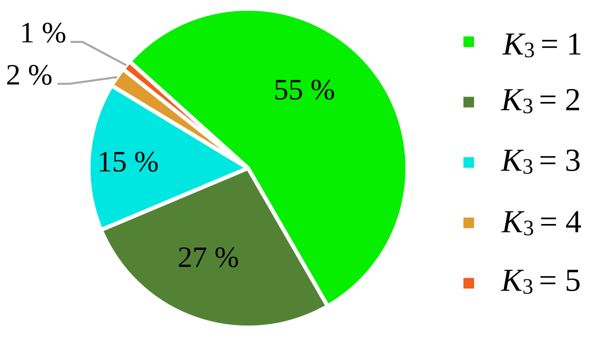


Fig. 4.3. Summary of oil indicator algorithm verification results.

5. ELECTRICAL MEASUREMENT INDICATOR

5.1. The Structure of Electrical Measurement Indicator

All electric measurements (EM) are performed when transformers are offline; therefore the periodicity of such measurements for transformers in the Latvian electric power transmission system is 8 years, and 4 years for autotransformers and bushings [15].

The electric measurement indicator is divided into three parts: the active part (windings and core), bushings, and OLTC (Table 5.1). Each part has its algorithm developed individually, thus the respective algorithms are closer to the actual situation. If an outcome of a separate algorithm changes, it does not alter the whole algorithmic operation.

During data processing the input data are converted into a suitable form for further analysis. For all windings (HV, MV, and LV), dielectric losses and insulation resistance values are recalculated from the test report with the baseline temperature of 20 °C

In the general methodology detailed in Fig. 2.1, the electric measurement indicator impacts both the transformer and the auxiliary component block.

Table 5.1

Parameters of the EM Indicator

Electric measurements		
Windings and core, *H31*	**Bushings, *H32***	**OLTC, *H33***
Dielectric losses tgδ, %	Dielectric losses tgδ, %	Winding resistance $SR_{ph–ph}$, Ω
Insulation resistance R_m, MΩ	Insulation resistance R_m, MΩ	Transition time t_t, ms
No-load losses $P_{0\ ph–ph}$, %	Capacitance *C1*, pF	Current ripple from dynamic resistance measurement (DRM) $I_{N1,2}$, %
Short-circuit impedance $Z_{k\ ph–ph}$, %		

5.2. Indicator Algorithm for Windings and Core

The flowchart of the algorithm for the active part – winding and core – is shown in Fig. 5.1, but all EM indicator parameter limits are shown in Table 5.2.

Coefficient D_t characterizes the minimum insulation resistance for safe operation of electrical equipment, i.e., 1 MΩ per 1000 V [1].

In the research carried out as part of the Thesis, a fleet of 83 transformers from the Latvian electric power transmission system was analysed to determine a typical pattern of no-load losses, 80 % of the analysed fleet correspond to the typical pattern and are used for establishing $P_{0\ ph–ph}$ limits shown in Table 5.2. The input data of the active part algorithm (Fig. 5.1) are values from the reports of electrical measurements. The algorithm starts with the highest risk detection based on the D_t coefficient [1]. Then inequalities are solved, where the assigned risk level could be $T = 4$, $T = 3$ and $T = 1$. At the end of the algorithm, a specific feature – the effect of the transformer age on the measurement is checked. If the insulation resistance value has increased 2-fold compared to the factory measurements, then risk level $T = 3$ is assigned, which indicates a medium risk degree.

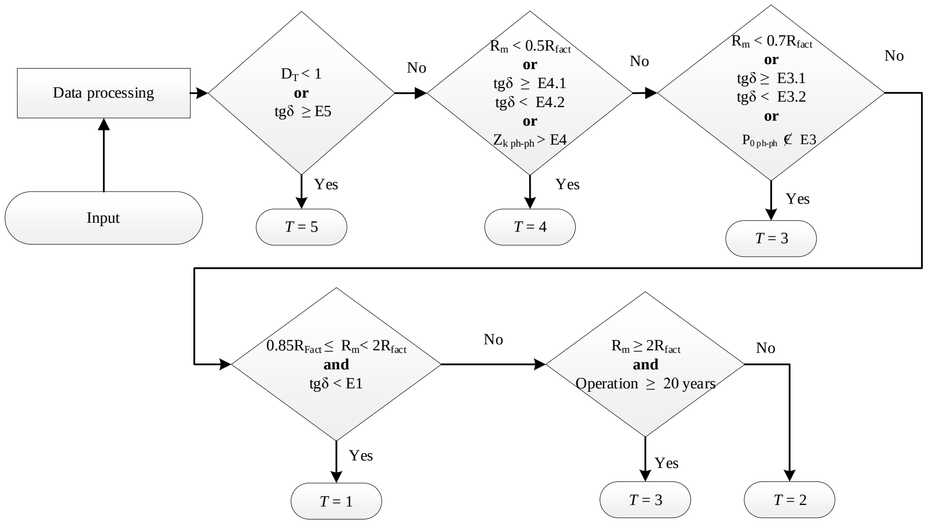


Fig. 5.1. A flowchart of EM indicator for windings and core.

Table 5.2

EM Indicator Parameter Limits

Parameter	Level					
	E1	E3		E4		E5
		Winding and core				
		E3.1	E3.2	E4.1	E4.2	
tgδ (at 20 °C), %	0.5	0.5	1	1	1.5	1.5
D_t						1
$P_{0\ ph\text{–}ph}$, %		$40 \geq P_{0a\text{–}b} \geq 20$ $40 \geq P_{0b\text{–}c} \geq 20$ $10 \geq P_{0a\text{–}c} \geq 0$				
$Z_{k\ ph\text{–}ph}$, %				3		
Bushings						
tgδ (at 20 °C), %	0.5					1
D_c						1
OLTC						
$SR_{ph\text{–}ph}$, %	2			2 (at least in 3 taps)		5
t_t, ms	100					200
$I_{N1,2}$, %				60		

5.3. Indicator Algorithm for Bushings

The indicator algorithm for bushings in Fig. 5.2 is individually applied to each bushing in a power transformer. The algorithm includes electrical measurement parameters as measured insulation resistance R_m, dielectric losses tgδ, main capacitance $C1_m$, and calculated insulation resistance D_c value. To reduce the fragmentation of results, only three risk level values are used.

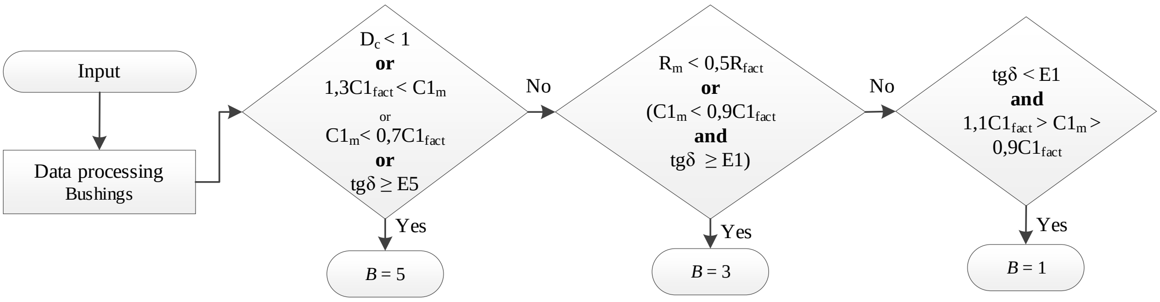


Fig. 5.2. A flowchart of EM indicator for bushings.

5.4. Indicator Algorithm for the OLTC

In transformers that involve voltage adjustments under load conditions, the on-load tap changer performs a large number of switching tasks during the operation. The technical condition of the OLTC device can be verified by determining the static winding resistance in each tap, or such dynamic resistance parameters as the switching time t_t and current ripple $I_{N1.2}$ during switching, which is obtained using current fluctuation values I_r and I_{rA}. The flowchart of the algorithm of the electrical measurement indicator OLTC is shown in Fig. 5.3.

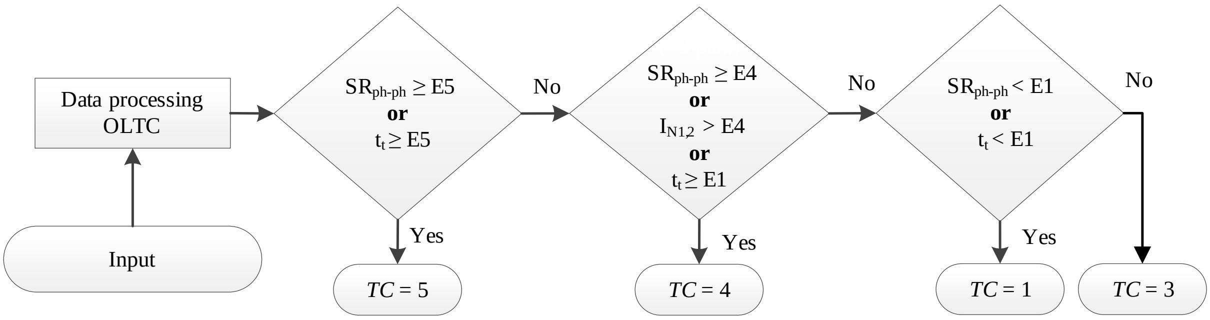


Fig. 5.3. A flowchart of EM indicator for OLTC.

5.5. Verification of Electrical Measurement Algorithm

A detailed verification of EM algorithms was performed with 12 different cases involving 5 transformers, 3 bushings, and 3 OLTCs.

For the transformer winding and core algorithm, five transformer measurement results and input data are provided (Table 5.3), including the assigned risk level T values.

Verification was performed for all branches of the winding and core algorithm. In case No. 1 (Table 5.3), the assigned risk level is T = 3. In practice, the transformer has been in operation for a long time, and the insulation resistance has increased more than 2-fold. In case No. 3, the risk level T = 1 is assigned, which corresponds to the condition of a new transformer. In case No. 4, a sharp increase in dielectric losses indicates the possibility of moisture in windings. Therefore the highest risk degree T = 5 is assigned. The risk level assigned in case No. 5 is $T = 4$ because a difference in Z_k was found, which could indicate on a possible winding deformation.

Table 5.3

Summary of Winding and Core Algorithm Verification Results

No.	Year of manuf.	R_f (20 °C), MΩ	Meas. year	Winding temp., °C	Winding	tgδ, %	R_m, MΩ	Phase / Z_k, Ω		Phase / P_0, W		T
1	1974	1143	2016	14	HV	0.17	4700	A	n/d	a	9.82	3
		1061			MV	0.20	3480	B		b	13.46	
		1225			LV	0.22	3580	C		c	9.81	
2	2005	14 108	2014	10	HV	0.19	79 500	A	n/d	a	5.30	2
		9497			MV	0.18	43 600	B		b	7.00	
		13 370			LV	0.17	40 800	C		c	5.10	
3	2015	5033	2018	16	HV	0.23	22 200	A	n/d	a	34.08	1
		4233			MV	0.34	26 400	B		b	48.00	
		3133			LV	0.26	46 900	C		c	34.02	
4	1967	590	2013	20	HV	1.61	103	A	n/d	a	55.90	5
		885			MV	0.23	11 200	B		b	79.10	
		885			LV	0.45	13 000	C		c	55.80	
5	1971	627	2003	25	HV	795	0.32	A	268.21	a	165	4
		–			MV	–	–	B	286.67	b	239	
		446			LV	540	0.31	C	283.63	c	171	

The algorithm of the winding and core was verified with a total of 50 transformers, and the results are shown in Fig. 5.4.

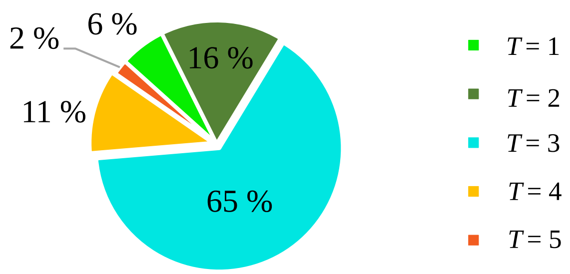


Fig. 5.4. Summary of winding and core algorithm verification results for 50 transformer fleet.

5.6. Verification of Algorithm for Bushings

A detailed verification of the algorithm for transformer bushings involved three 110 kV bushings (Table 5.4), but in general this algorithm was verified with a total of 50 transformer bushings. The results are shown in Fig. 5.5.

As shown in Table 5.4, the bushing for Phase A in case No. 3 fulfills the first-branch (Fig. 5.2) condition, therefore the assigned risk level $B = 5$. Since the algorithm includes individual calculations for bushings, the Phase B and Phase C data were verified in the same way, and the risk level assigned to these bushings was $B = 1$.

Table 5.4

Cases for Verification of the Algorithm for Transformer Bushings

Case	Temperature, °C	Winding	Phase	tgδ, %	R_m, MΩ	R_m, C2, MΩ	*C1*, pF	Assigned *B* value
1	19	HV	A	0.29	252 000	51 000	317.91	1
			B	0.28	252 000	51 000	315.43	1
			C	0.21	252 000	51 000	310.58	1
2	28	HV	A	0.58	132 000	3180	166.84	3
			B	0.42	59 500	4440	171.81	3
			C	1.58	61 000	2260	176.12	3
3	17	HV	A	3.54	252 000	42 700	382.70	5
			B	0.44	252 000	75 500	335.76	1
			C	0.44	252 000	122 000	340.00	1

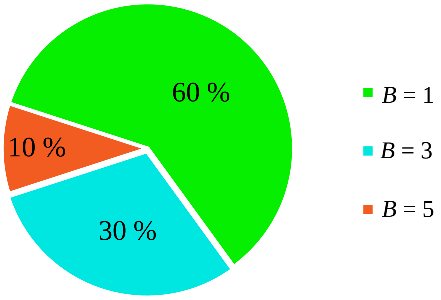
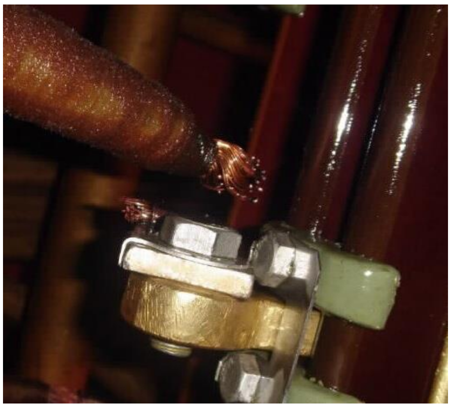


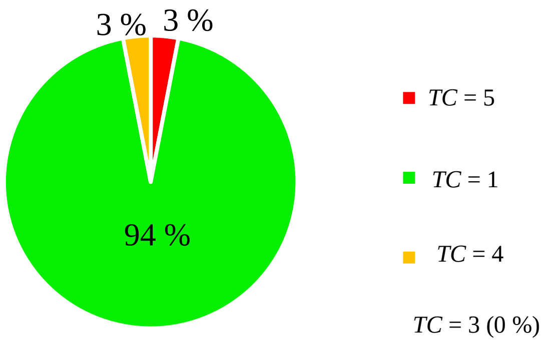
Fig 5.5. Summary of bushing algorithm verification (33 bushings).

5.7. Verification of the OTLC Algorithm

The algorithm for the on-load tap changer was verified in detail with three cases (Table 5.5), but the general verification was performed with a cases consisting of a total of 33 transformers (Fig 5.6).



a)



b)

Fig. 5.6. a) OLTC defect, a broken contact; b) summary of results for OLTC algorithm verification with sample of 33 transformers.

The OLTC algorithm has been developed also for cases when dynamic resistance measurements have not been performed, as in case No. 2 in Table 5.5, where only $SR_{ph\text{–}N}$

values are entered. Thus, the transformer windings, contact connections and their wear condition are checked.

When verified with cases No. 1 and No. 2, the operation of the algorithm corresponds to the results observed in practice.

In case No. 3, the static resistance value of the sixth tap cannot be measured. In the absence of any of the static resistance values in any of the phases, the algorithm fulfills the condition of the first algorithm branch. In this case the division with zero is embedded in the algorithm as exceeding the limit value E5, and risk degree *TC* = 5 is assigned. In practice, this case was taken very seriously, as it was discovered that the contact in the transformer tank of the OLTC device in Phase A was broken (Fig. 5.6 a)).

Table 5.5

Verification Cases of the Algorithm for OLTC

Case	Phase	Level	I, A	$SR_{\text{ph–N}}$, mΩ	I_r, %	I_{rA}, A	t_t, ms	TC
1	A	1	9.93	1462	–	–	–	1
		2	10.0	1444	31.3	3.13	41.6	1
		3	10.2	1426	30.9	3.15	41.1	1
		4	10.3	1408	32.4	3.33	42.0	1
		5	10.4	1390	32.4	3.36	41.3	1
		…	…	…	…	…	…	…
		23	12.4	1158	40.7	5.04	41.4	1
	B	1	9.67	1462	–	–	41.7	1
		2	9.78	1445	30.0	2.93	42.4	1
		3	9.89	1427	31.5	3.11	41.4	1
		4	10.0	1409	31.3	3.13	42.0	1
		5	10.3	1391	32.1	3.30	41.2	1
		…	…	…	…	…	…	…
		23	12	1158	40.5	4.86	42.1	1
	C	1	9.75	1465	–	–	42.3	1
		2	9.86	1447	31.4	3.09	42.1	1
		3	9.98	1429	31.5	3.14	42.2	1
		4	10.1	1412	32.2	3.25	42.4	1
		5	10.2	1393	32.6	3.25	42.3	1
		…	…	…	…	…	…	…
		23	12.1	1161	41.6	5.03	42.4	1
2	A	1	n/d	4.89	n/d	n/d	n/d	1
		2	n/d	4.77	n/d	n/d	n/d	1
		3	n/d	4.66	n/d	n/d	n/d	1
		…	…	…	…	…	…	…
		8	n/d	4.10	n/d	n/d	n/d	1
	B	1	n/d	4.96	n/d	n/d	n/d	1
		2	n/d	4.84	n/d	n/d	n/d	1
		3	n/d	4.73	n/d	n/d	n/d	1
		…	…	…	…	…	…	…
		8	n/d	4.17	n/d	n/d	n/d	1
	C	1	n/d	4.93	n/d	n/d	n/d	1
		2	n/d	4.81	n/d	n/d	n/d	1
		3	n/d	4.70	n/d	n/d	n/d	1
		…	…	…	…	…	…	…
		8	n/d	4.14	n/d	n/d	n/d	1
3	A	5	n/d	2.17	n/d	n/d	n/d	1
		6	n/d	n/d	n/d	n/d	n/d	5
		7	n/d	2.07	n/d	n/d	n/d	1
	B	5	n/d	2.17	n/d	n/d	n/d	1
		6	n/d	2.13	n/d	n/d	n/d	1
		7	n/d	2.07	n/d	n/d	n/d	1
	C	5	n/d	2.16	n/d	n/d	n/d	1
		6	n/d	2.11	n/d	n/d	n/d	1
		7	n/d	2.05	n/d	n/d	n/d	1

6. VERIFICATION OF DEVELOPED METHODOLOGY

6.1. Power Transformer Parameters and Influence Factor Calculation

The verification of the TCI methodology was based on the above-detailed indicator algorithms. The verification process involved the fleet of 38 Latvian electric power transmission system transformers with rated 100 kV and 330 kV voltage, different rated power and manufacturing standard. One detailed case for one randomly selected transformer currently in service in the transmission system was described.

The calculation applies to an *ATDCTN* autotransformer with three windings that was manufactured in 1984, complies with *GOST* standard, rated power 125 MVA, and rated voltage 330 kV.

The total influence factor *Y* for the *ATDCTN* autotransformer is as follows:

$$\begin{gathered} Y = F1 + F2 + F3 + F4 + F5 + F6; \\ Y = 0.5 + 0.5 - 0.1 + 0 + 0 + 0 = 0.9. \end{gathered} \tag{6.1}$$

The operating data of the *ATDCTN* autotransformer used for the verification of the methodology and the value of the influence factor *Y* calculated by expression (6.1) are shown in Table 6.1.

Table 6.1

ATDCTN Autotransformer Operating Data

F1	**F2**	**F3**	**F4**	**F5**	**F6**	**Influence factor *Y***
36	In service	Yes	No	Prevented	None	0.9

6.2. Calculation of DGA Indicator

G5 gas values of a verification case are H_2 14.7 ppm, CH_4 22.79 ppm, C_2H_4 5.87 ppm, C_2H_6 6.07 ppm, C_2H_2 0.73 ppm; for G2 gases: CO 206 ppm and CO_2 2370 ppm. Quantitative limits *S1* and *S3* of a transformer manufactured according to the *GOST* standard are as follows:

$$S1_{\mathrm{G5}} = \begin{pmatrix} 60 \\ 45 \\ 15 \\ 30 \\ 1 \end{pmatrix} \text{ and } S1_{\mathrm{G2}} = \begin{pmatrix} 350 \\ 1500 \end{pmatrix}; \qquad S3_{\mathrm{G5}} = \begin{pmatrix} 100 \\ 100 \\ 100 \\ 50 \\ 10 \end{pmatrix} \text{ and } S3_{\mathrm{G2}} = \begin{pmatrix} 600 \\ 8000 \end{pmatrix}.$$

In the first step, the values of G5 and G2 gases are evaluated against the *S1* limit values, and the inequality condition is fulfilled for the value of CO_2. In the next step, the input data are evaluated against *S3* limit values. The inequality condition is not fulfilled, and risk level $K = 2$ is assigned.

6.3. Calculation of Oil Analysis Indicator

The data required for the oil analysis indicator algorithm are summarized in Table 6.2.

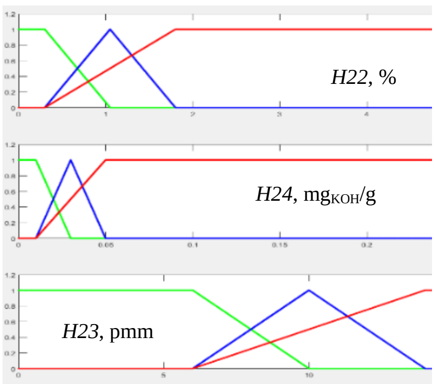
Table 6.2

Autotransformer *ATDCTN* Oil Parameter Values from the Report

***H21*, °C**	***H22*, %**	***H23*, ppm**	***H24*, mg_{KOH}/g**
143	0.04	10	0.01

At first, the algorithm checks for the existence of the most dangerous case scenario. The inequality condition is not fulfilled, the flash point is above 135 °C. In the next step, the opposite or the existence of the best-case scenario is checked, where *H22*, *H23* and $H24 \leq L1$ are used as limits. The moisture content in the oil exceeds the *L1* limit value and a fuzzy logic calculation is performed.

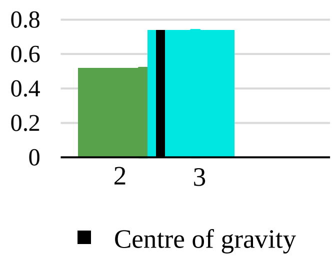
Fuzzy logic system block is calculated:



a)

	Membership function	Membership values
H22	*L*	1
	M	0
	H	0
H24	*L*	1
	M	0
	H	0
H23	*L*	0
	M	0.52
	H	0.74

b)



c)

Fig. 6.1. a) Membership functions for parameters *H22*, *H24* and *H23*; b) membership function values; and c) centre of gravity.

Using inference rules from all membership functions, their minimum values are used to calculate the centre of gravity. The risk level of oil indicator is K_3 = 3, which corresponds to the position of the centre of gravity in Fig. 6.1.

6.4. Calculation of Electrical Measurement Indicator

The calculation of the electrical measurement indicator starts with the algorithm of the winding and core, where the required data from reports are summarized in Table 6.3.

At first, the algorithm checks for the existence of the worst-case scenario. The inequality condition is not fulfilled. Then the measured values of the insulation resistance are evaluated against the factory measurements. The differences of the short-circuit resistance between the phases and typical values of no-load losses are checked. The measured insulation resistance R_m is at least twice as high as the factory measurements, and the transformer has been in operation for 36 years. It reflects the last branch of the flowchart shown in Fig. 5.1, and risk level T = 3 is assigned.

Table 6.3

Autotransformer *ATDCTN* Electrical Measurement Parameter Values from the Report

Winding	R_{fact}, MΩ (34 °C)	R_m, MΩ (32 °C)	tgδ, % (32 °C)	Z_k, %		P_0, W	
HV	580	15400	0.27	H–M	1.07		
				H–L	2.83		
				M–L	0.08		
LV	600	22000	0.22			P_{0a}	169.1
						P_{0b}	240.8
						P_{0c}	168.3

6.5. Calculation of Bushings Algorithm

Data required for calculation of bushing algorithm and measurement results from reports are summarized in Table 6.4. The values of R_m, R_{fact} and tgδ are calculated at the base for each phase bushing. The algorithm (Fig. 5.2) begins with a worst-case scenario check, where the bushing insulation resistance, dielectric losses or capacitance values indicate a defect or dangerous condition of the bushing.

The transformer bushings of the HV winding, as well as Phase A and C bushings of the MV winding are assigned a risk level of B = 1, but Phase B bushing has the highest risk level value of B = 5, which is assigned due to an increased dielectric loss value of 1.66 %.

Table 6.4

Autotransformer *ATDCTN* Electrical Measurement (Bushing) Values from the Report

t, °C	Winding	Phase	tgδ, %	R_m, MΩ	R_m, C2, MΩ	$C1_m$, pF	R_{fact}, MΩ	R_{fact}, C2, MΩ	$C1_{fact}$, pF	t, °C
17	HV	A	0.41	252 000	51 000	1114	252 000	51 000	1113	17
		B	0.41	252 000	51 000	1114	252 000	51 000	1114	
		C	0.41	252 000	51 000	1122	252 000	51 000	1123	
	MV	A	0.23	252 000	51 000	387	252 000	51 000	387	
		B	1.66	70 000	51 000	391	252 000	51 000	391	
		C	0.23	252 000	51 000	387	252 000	51 000	387	

6.6. Calculation of OLTC Indicator Algorithm

Data required for calculation of OLTC indicator algorithm, the calculated static resistance value differences between phases in 330 kV, 110 kV and 11 kV windings and assigned risk level TC values are shown in Table 6.5.

The algorithm (Fig. 5.3) starts with the calculation of static resistance differences and the checking of the worst-case scenario. The next step involves examining the difference between static resistances with the *E4* limit, and then with the *E1* limit. The result of the OLTC indicator is the highest *TC* value assigned. In this case, none of the OLTC values exceed the *E1* limit, and the risk level assigned to the OLTC indicator is *TC* = 1.

Table 6.5

OLTC Values of Autotransformer *ATDCTN* Electrical Measurements from the Report and TC Values of Risk Level

Phase/ tap	Voltage 330 kV			Result SR_{ph-ph}, % Voltage 330 kV			*TC*
	Phase A (A–N)	Phase B (B–N)	Phase C (C–N)	A–B, %	B–C, %	A–C, %	
	1.0960	1.0950	1.0930	0.09	0.18	0.27	1
	Voltage 110 kV						
1	0.1669	0.1681	0.1675	0.72	0.40	0.40	1
2	0.1655	0.1663	0.1656	0.48	0.40	0.10	1
3	0.1641	0.1649	0.1642	0.49	0.40	0.10	1
4	0.1628	0.1636	0.1630	0.49	0.40	0.10	1
5	0.1615	0.1623	0.1616	0.49	0.40	0.10	1
6	0.1602	0.1610	0.1603	0.50	0.40	0.10	1
7	0.1586	0.1590	0.1588	0.25	0.10	0.10	1
8	0.1586	0.1590	0.1588	0.25	0.10	0.10	1
9	0.1587	0.1591	0.1589	0.25	0.10	0.10	1
10	0.1602	0.1609	0.1604	0.44	0.30	0.10	1
11	0.1614	0.1622	0.1616	0.49	0.40	0.10	1
12	0.1628	0.1635	0.1630	0.43	0.30	0.10	1
13	1.0960	0.1647	0.1642	0.43	0.30	0.10	1
Voltage 11 kV							
	Phase A (a–b)	Phase B (b–c)	Phase C (a–c)	a–b, %	b–c, %	a–c, %	
1	0.00413	0.00421	0.00420	1.92	0.20	1.70	1

6.7. Autotransformer *ATDCTN* Results in Risk Matrix

Based on the obtained results, the autotransformer *ATDCTN* is automatically positioned in high risk zone TCI = 1 because of the result from the bushing algorithm *B* = 5, which corresponds to the most dangerous case scenario.

In practice, an expert assessed the situation as dangerous, and an immediate action was taken to minimize dielectric losses. Eight cycles of bushing flushing with oil and vacuum were performed and the ninth cycle involved bushing oil replacement. Control measurements after repairs showed no improvement. The expert took a decision to replace the Phase B bushing during the nearest scheduled shutdown of the transformer. The results of the case used to verify the methodology before the bushing replacement correspond to case No. 1 and after the bushing replacement – case No. 2, as summarized in Table 6.6.

Verification cases are shown in Fig. 6.2, where the TCI value 1 of the autotransformer in case No. 2 decreased to 0.62 after replacement of the bushing in Phase B.

Table 6.6

Verification Results of Autotransformer *ATDCTN*

Case No.	Influence factor *Y*	TCI results				
		DGA	Oil analyses	Winding and core	Bushings	OLTC
1	0.9	$K = 2$	$K_3 = 3$	$T = 3$	$B = 5$	$TC = 1$
2	0.9	$K = 2$	$K_3 = 3$	$T = 3$	$B = 1$	$TC = 1$

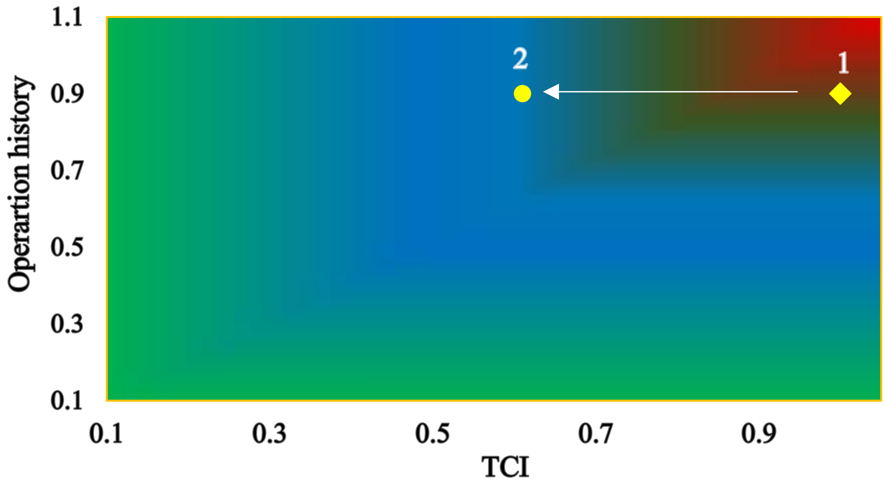


Fig. 6.2. Autotransformer *ATDCTN* positions in the risk matrix.

6.8. Algorithm Verification with Transformer Fleet

Operational parameters of 38 transformers used for the verification of the methodology, as well as the calculated total influence factor *Y* and TCI values are summarized in Table 6.7 and shown in a risk matrix in Fig. 6.3.

Table 6.7

Transformers Used to Verify the Methodology

No.	F1	F2	F3	F4	F5	F6	*Y*	TCI
1	11	In service	No	No	Prevented	None	0.50	0.34
2	41	In service	Yes	No	Prevented	None	0.90	0.62
3	41	In service	Yes	No	Prevented	None	0.90	0.55
4	39	Reserve	No	No	Prevented	None	0.60	0.48
5	36	In service	No	No	No notes	None	0.80	0.41
6	43	In service	No	No	Prevented	None	0.55	0.48
7	45	Reserve	No	No	No notes	None	0.40	0.55
8	29	In service	No	No	No notes	None	0.30	0.55
9	41	In service	No	No	Prevented	None	0.80	0.48
10	34	In service	No	No	No notes	None	0.30	0.48
11	35	Reserve	No	No	Prevented	None	0.10	0.41
12	4	In service	No	No	No notes	None	0.30	0.41
13	4	In service	No	No	No notes	None	0.30	0.55
14	35	In service	No	No	Prevented	None	0.50	0.41

Continuation of Table 6.7

No.	F1	F2	F3	F4	F5	F6	*Y*	TCI
15	44	Reserve	No	No	No notes	None	0.40	0.55
16	43	In service	No	No	Prevented	None	1.00	0.48
17	42	Reserve	No	No	Prevented	None	0.60	0.55
18	41	In service	No	No	Prevented	None	1.00	0.55
19	36	In service	No	No	Prevented	None	1.00	0.62
20	8	In service	No	No	No notes	None	0.30	0.34
21	2	In service	No	No	No notes	None	0.55	0.48
22	37	In service	No	No	Prevented	None	1.00	0.48
23	36	In service	No	No	Prevented	None	1.00	0.48
24	51	In service	No	No	Prevented	None	1.00	0.55
25	57	In service	No	No	Prevented	None	1.00	0.61
26	56	In service	No	No	Prevented	None	1.00	0.48
27	41	In service	No	No	Prevented	None	1.00	0.41
28	36	In service	Yes	No	Prevented	None	0.90	0.55
29	2	In service	No	No	No notes	None	0.55	0.34
30	3	In service	No	No	No notes	None	0.30	0.27
31	3	In service	No	No	No notes	None	0.30	0.27
32	1	In service	No	No	No notes	None	0.55	0.34
33	1	In service	No	No	No notes	None	0.55	0.34
34	4	In service	No	No	No notes	None	0.30	0.41
35	4	In service	No	No	No notes	None	0.30	0.34
36	5	In service	No	No	No notes	None	0.30	0.27
37	42	In service	No	No	No notes	None	0.70	0.55
38	44	Reserve	No	No	No notes	None	0.40	0.62

The transformer fleet consists of 13 transformers that have been in service between 3 and 35 years (Fig. 6.4) and 21 transformers in service over 35 years (Fig. 6.5).

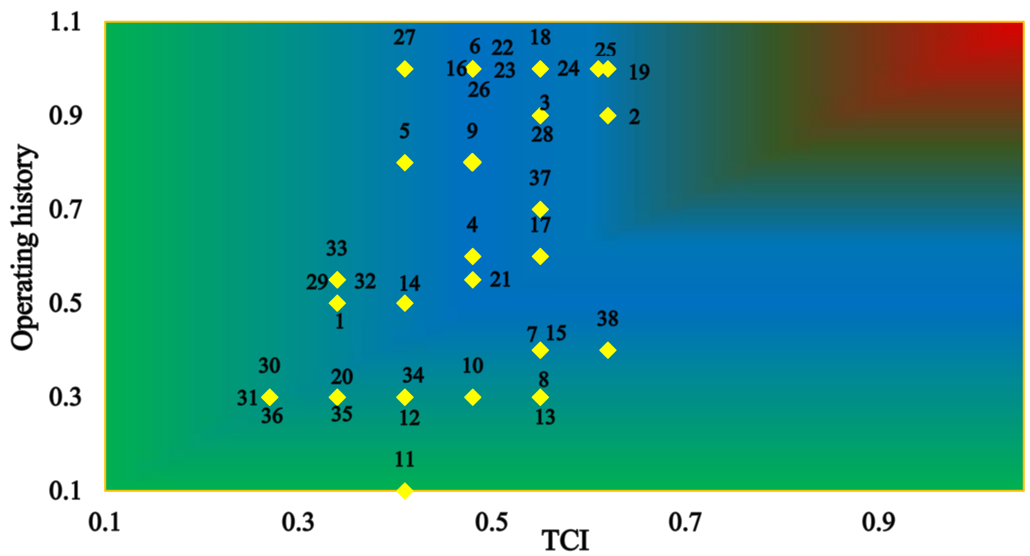


Fig. 6.3. Transformers used for verification of the methodology in a risk matrix.

The positions of all 38 transformers in the risk matrix (Fig. 6.3) give an insight of the actual situation and the risk degree of the respective transformer. As a detailed example the verified case No. 2 from Table 6.7 is chosen. This transformer is 41 years in operation and is still under load. An upgrade has been performed to ensure continued safe operation of the transformer. However, no maintenance repairs have been carried out, as no significant defects have been identified and this transformer is not considered to be highly significant to the system. No monitoring system is installed. By studying the TCI parameters of this transformer, it is possible to establish in detail a justified location of this transformer in the risk matrix.

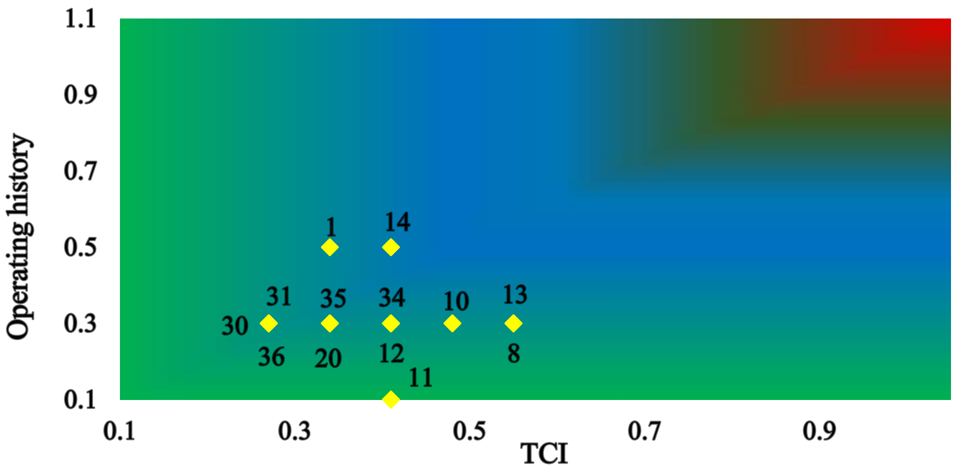


Fig. 6.4. Transformers in service between 3 and 35 years.

Transformers can be grouped according to pre-selected criteria, as it is done in Figs. 6.4 and 6.5. By examining the location of these transformers, it is possible to draw a conclusion on the actual technical condition for transformers of specific operational ages. This allows quickly catching the "weak points". It is important to use pre-selected criteria to distinguish the converged degrees of risk of the transformer.

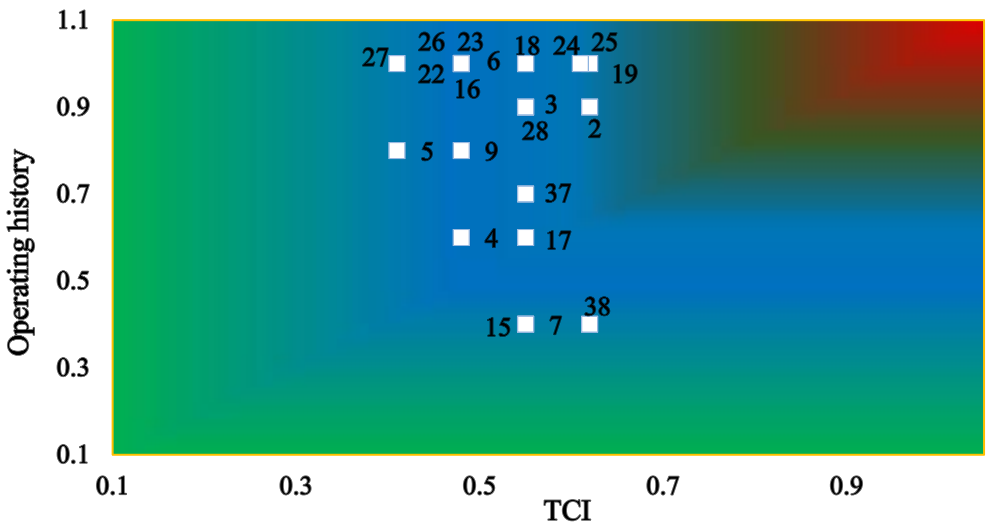


Fig. 6.5. Transformers in service above 35 years.

The operation of the methodology has been verified, it functions in accordance and fully in line with the developed algorithms providing a traceable, unambiguous and visible result.

Thus it facilitates the work the responsible expert does with all transformers of the transmission system. Table 6.8 compares the advantages of the current workflow of expert and the developed TCI methodology.

Table 6.8

The Current Workflow of an Expert vs the Developed TCI Methodology

Activity/process	Expert	TCI methodology
Measurement results are prepared and submitted for review in at least 7 reports both electronically and in a printed form	Examines detailed reports and compares them with factory measurements either manually or by entering them in the MS software	Data has to be entered in the MS Excel environment, and the developed algorithms perform calculations in Matlab
Evaluation of reports with limits and concentration values	Evaluates the operational data to apply relevant limit values	The methodology includes all the current limit values and the expert is given the right to supplement or change them as necessary
Data analysis	Results can be evaluated only for one transformer at a time and there is no graphical representation. The process is time consuming	Results of the reports can be processed for several transformers at the same time, there is a graphical representation and the results can be traced through indicators
Grouping	Grouping shall be performed manually or in the MS environment	Grouping is performed by selecting the required parameters, transformers, or indicators
Data updating	Examines new data and performs analysis, reviews reports and adds them to the data system	Data is updated immediately, thus yielding an up-to-date result

CONCLUSIONS

1. The literarture review leads to a conclusion that there are several different methodologies for the assessment of transformers. The assessment of the technical condition of the power transmission system in some countries mainly relies on conventional diagnostic methods, where the main diferences lie in diverse operational strategies, choice of methods, and periodicity of data reception.
2. Operational strategies are often based on individual or histrorically established features, which make every power transmission system unique. As a result, the general methodology, TCI indicators, their mathematical description and risk matrix development shall be adjusted for each system individually.
3. Based on the evaluation of specific features of the existing transformer fleet and the amount and periodicity of diagnostic results data, the TCI methodology has been developed. It allows combining the data accumulated during transformer operation in a single system and incorporates typical Latvian diagnostic test values and service life criteria.
4. The verification of the methodology and processing of the obtained results clearly shows that a universal solution is not possible. The TCI indicators – gas chromatographic analyses, oil analyses and electrical measurements – cover all parts of a transformer, including accessories, and the different periodicity of diagnostic measurements ensures efficient processing of diagnostic results or the existing continuous data flow.
5. Examination of the TCI indicators, using a large number of measurement results from a fleet of more than 140 transformers in total and an in-depth study of 27 case examples show that the obtained TCI values correspond to the technical condition of the transformers.
6. A risk matrix that combines data on the technical condition and historic operation allows both establishing the operational risk level of an individual transformer and performing a comparative analysis for groups of transformers.
7. The methodology incorporates a rule to first identify the most dangerous cases that require immediate action. It allows effective planning of in-depth inspections, repairs and replacement of auxiliary equipment. The result immediately enters the high-risk area, the upper right-hand red corner of the risk matrix, as demonstrated in the verification of the detailed case example in Chapter 6.

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