New Trends in Power Transformer Surveillance and Diagnostics in the Function of Power System Maintenance

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Abstract. The restructuring of the electricity market that occurred in the previous years has led to a change in the approach to the maintenance of equipment, stations and grid elements. With the liberalization of the market, profit becomes the most important aspect in power system exploitation, hence, in order to avoid costs, there is a reduction in preventive maintenance procedures for both transformers and other equipment. This inherently reduces the safety and reliability of the system. In order to maintain the level of safety and reliability of operation at a sufficient level, they are replaced by systems of occasional or continuous monitoring and periodic thermal imaging. The most effected grid elements are energy transformers which are coherently the most important and most expensive elements of the grid. Determining the availability of power transformers is important for the safe operation of the power system. Transformer monitoring and diagnostic systems are particularly interesting for more efficient resource management, increasing system reliability and safety while preventing unwanted consequences or grid faults. Monitoring systems have poor diagnostic properties and are, therefore, combined or supplemented with other methods or procedures. Additionally, new diagnostic methods and techniques are being investigated that could continuously monitor and diagnose the condition of transformers. Thereby, different thermal imaging procedures present an unavoidable factor in proper transformer diagnosis.

Keywords: Monitoring · Thermovision · Power transformer

1 Introduction

The market approach has forced transmission and distribution system operators to choose appropriate maintenance procedures for their equipment, stations and grid elements. Otherwise, unplanned breakdowns and power outages would cause unacceptable costs or other economic losses. The fault reclamation time consists of the time required to diagnose the fault and the time to repair the fault. The goal of all methods of preventive maintenance, various diagnostic methods and various periodic inspections, monitoring and thermal imaging procedures is to reduce the number and duration of faults, reduce the duration of troubleshooting and reduce overall economic costs and its consequences.

With preventive maintenance, certain pieces of equipment are replaced at set intervals. Today, preventive maintenance is the most common principle of maintenance. The

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issue is that it usually requires a planned decommissioning, but since this decommissioning can be planned at the optimal moment, this method minimizes the costs of decommissioning. Preventive weather maintenance is expensive because the elements are changed according to a predetermined schedule, although these elements may still be in good enough condition. On the other hand, some elements may need to be changed before the time set by the maintenance schedule.

Increased pressure on costs and new technological possibilities of diagnostics have led to the improvement of preventive maintenance. Additionally, maintenance is no longer time based but also based on the element to the condition. The concept of predictive maintenance—maintenance according to the condition was introduced. A good example of condition-based maintenance is transformer oil analysis. Previously, the oil was changed, regardless of its condition after each predetermined period of time. Testing and analyzing the oil can increase its service life, reduce costs due to its expensive nature. The transformer is in overhaul less often and environmental problems are avoided as old oil needs to be disposed of properly.

The principle of condition-based maintenance is professional equipment based diagnosis to which a subjective, experiential diagnosis is added for achieving better results i.e. maintenance costs and the number of downtimes are reduced. Therefore, in addition to objectify measurement results and computational procedures, it is extremely important to model the experience of diagnostic experts from their daily practice. This method will be increasingly used in the future as it can significantly reduce losses for plant owners and increase availability.

The concept of proactive maintenance involves acting on the cause of the problem. The concepts of predictive and proactive maintenance, which are superior to traditional reactive and preventive maintenance, especially in terms of cost reduction and avoidance of sudden station faults are inconceivable without the organization and implementation of quality technical station diagnostics. For these reasons, a department of technical diagnostics is organized within the maintenance sector.

By applying reliability-based maintenance, each element of the station has its own minimum safety scheduled maintenance, which contributes to the overall increase in safety, reliability, as well as maintenance costs reduction. This method also takes into account the consequences of faults and outages, on the environment, drive and safety of people [1].

Figure 1 shows a holistic approach to developing a successful maintenance strategy based on operational reliability.

Diagnostics in maintenance should determine the condition of individual parts of the system without dismantling them, and preferably without their downtime. The basis of these diagnostics is the measurement of the selected parameter and the given value. By comparing diagnostic parameters or quantities, with predefined permissible values of these quantities, a decision is made on the availability of an individual grid element and the possible need of repair or replacement of a distinct component.

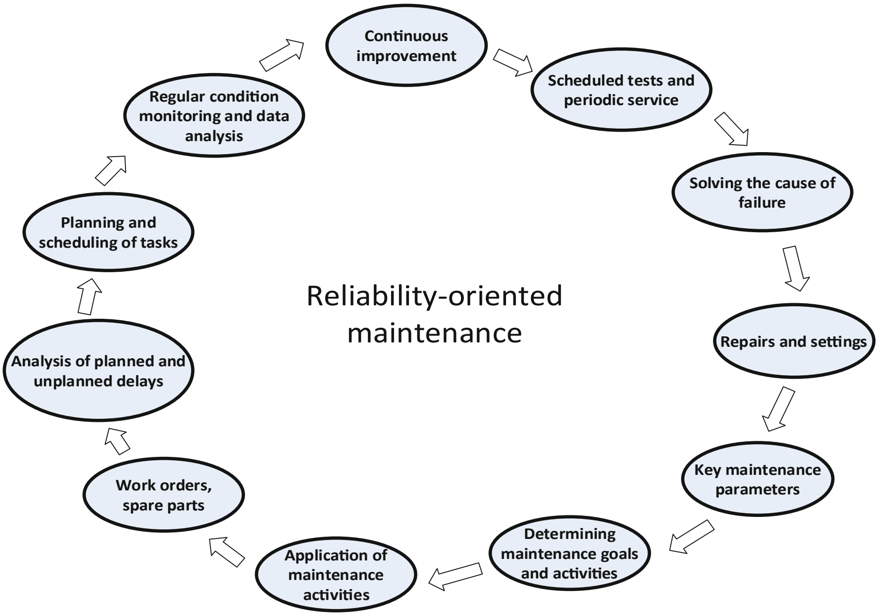

Fig. 1. Reliability-oriented maintenance.

2 Significance and Characteristics of Diagnostic Methods and Monitoring of Power Transformers

Diagnostic tests can be performed continuously or periodically at set times, and there is also the possibility of installing diagnostic devices in the station, which provide continuous diagnostic monitoring. Continuous monitoring is done constantly and is performed by an external device. Periodic inspection is performed at regular intervals, and can be performed by a device or a human [2–6].

The organization and implementation of diagnostic monitoring achieves the following beneficial effects:

- reduction of total costs,
- increasing the reliability of work,
- increase safety at work.

The cost reductions are manifested through:

- better planning of maintenance activities,
- reduction of consumption of spare parts,
- reduction of required spare parts stocks,
- lower energy consumption,
- avoiding accidents at the station.

It should be noted that the organization and implementation of diagnostic monitoring allows for better maintenance planning, as it provides a good insight into the condition of equipment. Therefore, before the overhaul of the transformer, its diagnostic inspection can be performed, which reveals its defects that need to be sorted out during the overhaul. According to some research, the application of technical diagnostic methods reduces the consumption of spare parts. The reason for reducing their consumption lies in the fact that the application of these methods provides insight into the true condition of the elements parts, which allows them to be replaced only when they are completely worn out without the threat that no suitable spare parts will be available in the critical moment.

2.1 Power Transformer Monitoring

As transformers are key assets in the power grid and industrial processes need to be constantly monitored to prevent an unexpected transformer failure that can be catastrophic. A major failure on a transformer is defined as an incident that takes the transformer out of service for seven or more days. To determine the risk of unexpected failure, it's important to consider the consequences and the probability of failure occurring. According to [6] about one out of every 200 transformers fails each year with major failures cost about $14,000 per MVA in property damage. Figure 2 shows major failure locations on power transformers.

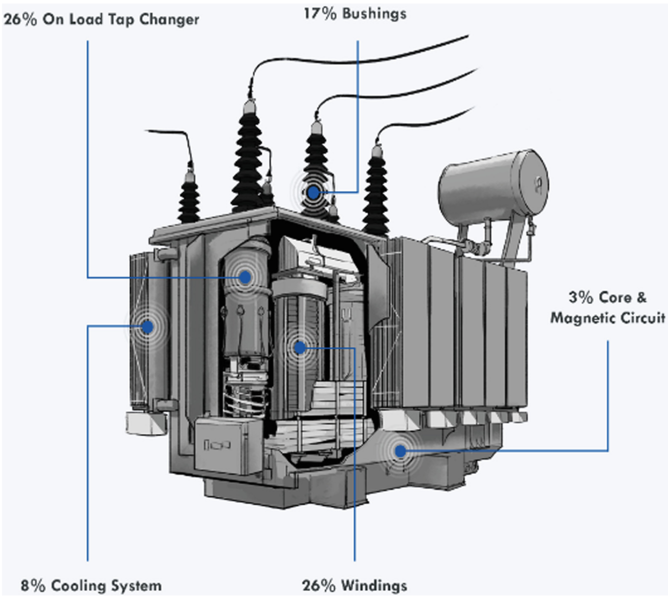

Fig. 2. Major failure locations on power transformers.

Transformer monitoring is continuous monitoring of the transformer condition, which basically includes measuring certain value and monitoring the condition of the transformer equipment, i.e. certain diagnostics of the condition of individual parts of the transformer (cooling system condition, sensor condition, etc.). Furthermore, it is possible to estimate certain parameters based on measurements and mathematical models, and to archive measured and estimated parameters. Monitoring of power transformers also contains a user interface for access to monitoring results (HMI—Human-Machine Interface).

Additionally, some monitoring systems have the ability to exchange data with other systems and devices in the station, such as SCADA system (Supervisory Control And Data Acquisition) which is shown in Fig. 3. Those systems have the ability to access the monitoring system from a remote location [3, 4], and transformer cooling system control options [5].

The following goals can be achieved by installing a monitoring system on the transformer:

- detection of faults as they occur and prevention or reduction of the consequences of those faults,
- constant insight into the operating conditions and condition of the transformer,
- condition-based maintenance,
- increase availability,
- optimization of transformer management,
- more detailed analysis of the causes of fault,
- increase in system security.

This method can detect changes in certain parameters that are measured using sensors or estimated using a specific mathematical model. Thus, for example, due to increased thermal or electrical stresses in the vicinity of the insulating material, it degrades its insulating properties, decomposes cellulose and oil and the forms various gases in the oil. Additionally, moisture and other decomposition products can occur.

Very reliable indicators in diagnosing mechanisms that can lead to transformer faults are:

- increase in oil and winding temperature,
- occurrence of partial discharges,
- change in capacitance and dielectric loss factors of conductors.

There are a wide range of indicators that can detect the symptoms of transformer failure by monitoring the cooling system, load tap changer, dissolved gas, bushing power factor and capacitance, partial discharge, oil levels, pressure, temperatures and more. Some of them will be described in the following text.

Analysis oil dissolved gases. Analysis of oil dissolved gases is one of the most reliable diagnostic methods introduced in the mid-1960s [8]. It is most often performed by periodically taking oil samples from transformers, typically once a year. In laboratory conditions by chromatographic analysis the concentrations of gases dissolved is then determined. These gases most often consist of: hydrogen, carbon monoxide, carbon dioxide, ethylene, ethane, methane, acetylene and oxygen. The development of sensors

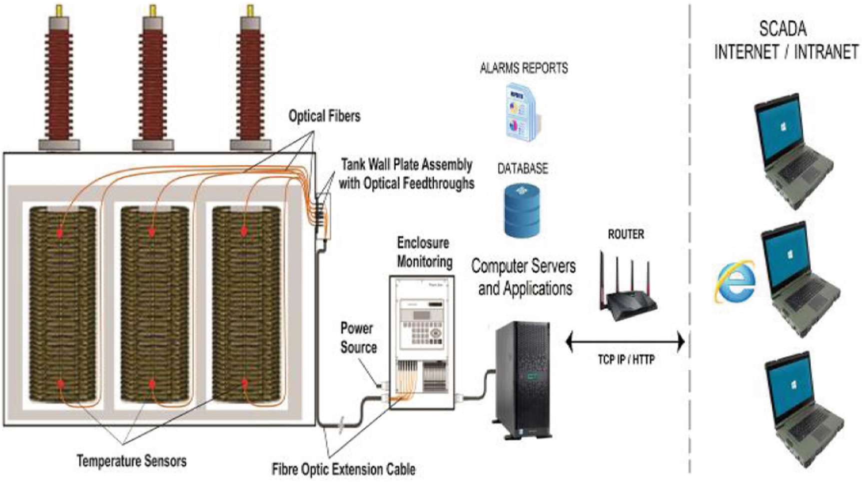

Fig. 3. Monitoring system integrated within power transformer and presented in SCADA system [7].

for on-line measurement of the concentration of gases made it possible to bridge the time between periodic tests of oil samples in the laboratory. These devices allow the measurement of a mixture of gases dissolved, and are mainly used to warn of the increased generation of gases in oil.

In addition to measuring oil dissolved gases, these sensors also allow the measurement of the increase in moisture dissolved, which is a product of degradation of paper insulation that reduces the dielectric strength of the insulation of the transformer.

Temperature Monitoring. By monitoring the temperature, it is possible to determine the phenomena of overheating in the transformer, to assess the efficiency of the cooling system of the transformer, and to assess the state of insulation of the transformer. The most important temperature, on which the aging of the insulation directly depends on, is the temperature of the hottest point of the winding.

The temperature of the hottest point of the winding can be measured directly by installing special optical thermometers that measure the temperature at one point or along the entire winding. Such models take into account the oil temperature, the load factor of the transformer and the inclusion of pumps and fans.

Voltage and current monitoring. Voltage monitoring is most often performed by measuring the voltage at the measuring connection of the conductor. In addition to voltage, it is also possible to measure changes in conductor capacity, which is a direct indicator of potential conductor failure. Conductors are exposed to high electrical and mechanical stresses, and the most common failure mechanisms are moisture penetration and partial discharges.

Current is most often measured using current measuring transformers. It is an extremely important monitoring parameter, because, in combination with temperature monitoring, it allows estimating the temperature of the hottest winding point, which results in the aging speed of paper insulation and estimating the remaining life, and allows transformer overload planning.

Partial discharge monitoring. Partial discharges occur as a result of an increase in voltages, insulation damage, moisture in the insulation, cavities in the solid insulation, loose metal parts, and gas bubbles in the oil. An increase in partial discharges in the transformer insulation is a sign of weakening the insulation properties of the material and as a result, insulation breach is possible.

Electrical and acoustic methods are available for the detection of partial discharges. Acoustic sensors are installed in the transformer or are mounted externally on the transformer boiler. They are more sensitive to external interference (rain, wind, loose vibrating parts, core noise, etc.) but they are easier to install on an old transformer. The biggest advantage of the acoustic method is the ability to locate partial discharges within the transformer itself using an adequate algorithm and good sensor placement.

If partial discharges occur in the oil, there will be an increase in the hydrogen concentration which can be detected by some of the gas detection sensors.

Tap changer monitoring. Most transformer faults are caused by the tap changer. Although these are generally faults with minor consequences, they reduce the reliability of the transformer, which is why monitoring of the tap changer is desirable. Faults of the tap changer are mainly mechanical and electrical in nature. To diagnose mechanical faults, the torque of the switch drive motor is usually monitored. By measuring the oil temperature in the control switch boiler and comparing it with the oil temperature in the transformer boiler, it is possible to determine whether there is an increase in oil temperature of the tap changer.

Cooling system monitoring. Generally, the states of the pumps and fans are most often monitored. If some fans or pumps are not turned on when they should be, there will be an increase in the temperature of the transformer. By monitoring the condition of the cooling system, it is also possible to better estimate the temperature of the hottest point of the winding.

2.2 Further Development of the Transformer Monitoring System

Today, monitoring systems are recognized as an important tool for more efficient transformer management as well as an important component of any power station. From the current point of view, two directions for further development of the monitoring system are predictable.

The first involves the further development of sensors and measurement methods in order to improve existing ones in both technological and economic terms as well as developing new ones. It is primarily expected to improve the existing methods for monitoring partial discharges in the form of reducing external interference, followed by oil gases and conductors. One of the most promising new methods is the monitoring of vibrations of the tap changer [9] as a tool for the detection of mechanical and electrical disturbances in operation, as well as the development of sensors for measuring the content of furfural in oil.

In parallel with the development of sensors, the development of automated data analysis collected by the monitoring system into clear and meaningful information (knowledge of the state of the transformer) that is presented to the user is expected. Namely, as the number of parameters that can be monitored by the monitoring system increases daily, an increase in the amount of data collected also increases. To analyze such a large amount of data, it is necessary to spend some time, and equally important, to have the knowledge to interpret the results. Precisely because of the limited human resources with specialist knowledge, users are looking for a way to enable more effective interpretation of monitoring results. One of the ways to achieve this is to reduce the number of monitored quantities, which in turn directly reduces the value and limits the functionality of the monitoring system.

The solution to this problem is the development of a system that will, as an upgrade of the monitoring system, enable automated processing of monitoring results and, as a result, will provide better diagnostics of transformer conditions. In the technical literature, which covers the field of observation, a number of papers on this topic have been published in recent years. These are various attempts to process the data collected by the monitoring system using some of the artificial intelligence techniques and as a result generate certain recommendations, warnings, alarms etc.

The most frequently mentioned techniques are neural networks, expert systems, fuzzy logic, etc. These techniques are most often used to interpret the results of measurements of oil dissolved gases [10, 11], and to calculate the hottest winding point [12]. The results obtained show how neural networks can be successfully implemented as a tool for the classification of certain transformer states (fault predictions) as well as for the estimation of certain parameters. Neural networks are a suitable tool when there is monitoring data in normal operation of the transformer as well as in the fault condition, and when the connections between the input parameters in the algorithm and the output parameters from the algorithm are complex. The main advantages are the ability to learn and the resistance to noise in the signal.

Main disadvantages are the need to have data available in normal operation and at the time of fault as well as poor convergence of results. The main feature of fuzzy logic is the ability to process fuzzy information, which often appears in diagnostics (e.g. the amount of gas in the oil is "large", so it is not very precise). Fuzzy logic provides the possibility of combining neural networks and expert systems and upgrading them [13].

It is expected that the best results in online diagnostics could be achieved by integrating various methods into a single diagnostic tool. Apart from the combination of methods, other observed quantities should be taken into account, not only the concentration of gases in oil, which is the most common case.

3 Use of Thermovision in Transformer Diagnostic Control

Thermography of infrared, IR or thermal radiation has a very distinct place in the maintenance of installations, equipment and stations. The infrared scanning method itself aims to test the thermal distribution on the external, visible surfaces of electrical equipment and parts of the station that are in operation, without the need to turn them off or put out of operation. This technique, using the so-called "thermogram" visualizes, otherwise invisible, thermal radiation emitted by bodies, so this method is used in practice to detect increased heating of electrical and mechanical components during normal operating condition without contact with the object under test [14].

It is basically a method, which is based on thermal comparison of different objects, the so-called "measurement with reference", and refers to the comparison of identical spots, in different phases (L1, L2, L3) of the same bay or system. This requires a systematic scan of all three phases (preferably simultaneously) to determine any deviation from the "normal" thermal image.

Special attention is paid to coupling and suspension equipment, connection points of switches, disconnectors, measuring transformers, cable heads and insulators, and as for insulated parts (transformers, low-oil switches, metal-shielded SF_6 plants) thermal distribution is controlled over the entire outer surface. The criterion for determining the condition (severity of the fault) of the equipment on which the heating was observed, i.e. the degree of urgency of the required intervention, is taken as ΔT, the temperature difference between the observed "warm" and the reference point. This criterion was determined on the basis of long-term statistical monitoring of results and a large number of thermal imaging tests. When assessing the degree of urgency of the intervention, the voltage level of the equipment being controlled and the operating load at the time of the test have to be taken into account. This is quite important, as for higher voltage levels (i.e. larger dimensions and larger masses) relatively small increases in temperature can indicate quite serious faults. Condition of electrical equipment on which an increase in temperature has been observed can be estimated on the basis of the following criteria with an assumed 100% load. Table 1 shows an estimation of the degree of urgency of the intervention based on the temperature difference.

Table 1. Estimation of the degree of urgency for intervention based on the temperature difference.

T increase	State	Recommended measures
$0 \leq \Delta T < 5$ °C	0	Repeat the thermotest in 6–12 months
5 °C $\leq \Delta T < 10$ °C	1	Intervene as soon as possible
10 °C $\leq \Delta T < 35$ °C	2	Intervene the first time the operation is stopped

This diagnostic method prevents serious malfunctions, i.e. indicates poor or inadequate thermal insulation. In this way, the number of unplanned power outages is reduced, and thus the total downtime due to fault. On the other hand, it is possible to perform maintenance activities more rationally, which, in addition to shortening the time required for overhaul, also contributes to the quality of the performed interventions by concentrating on the thermal imaging detected problems.

The direct effects are manifested in the acceleration of the process of diagnosing faults and checking the undertaken interventions, saving energy, protecting capital equipment as well as reducing insurance premiums. Furthermore, by maximizing the availability of equipment, in addition to confirming its reliability but also pointing out possible critical spots, the total operating time is increased. From the aspect of safety, thermal imaging can effectively contribute to the detection of defects in material construction or monitoring of high risk processes.

In electrical engineering, electrical equipment testing most often indicates problems caused by current-resistance relationships. In general, a “hot spot” in an electrical circuit occurs as a result of insufficiently tightened, oxidized or corroded connection, but also improper operation of the appliance itself. Figure 4 shows an example of a hot spot.

When creating a station maintenance program, it is recommended to introduce the so-called maintenance cycle by means of thermal imaging monitoring of the state of electric equipment, which is schematically shown in Fig. 5, and which can be adapted to almost any industrial environment.

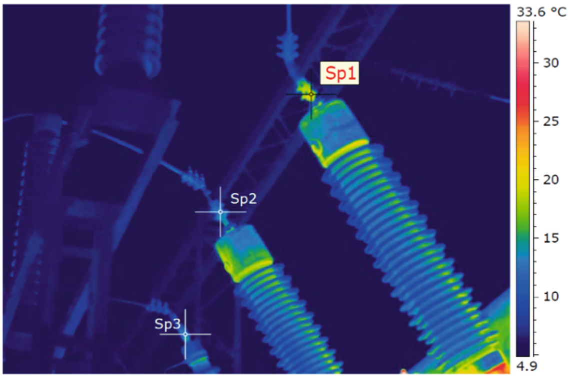

Fig. 4. “Hot spot” on the HV side of the power transformer.

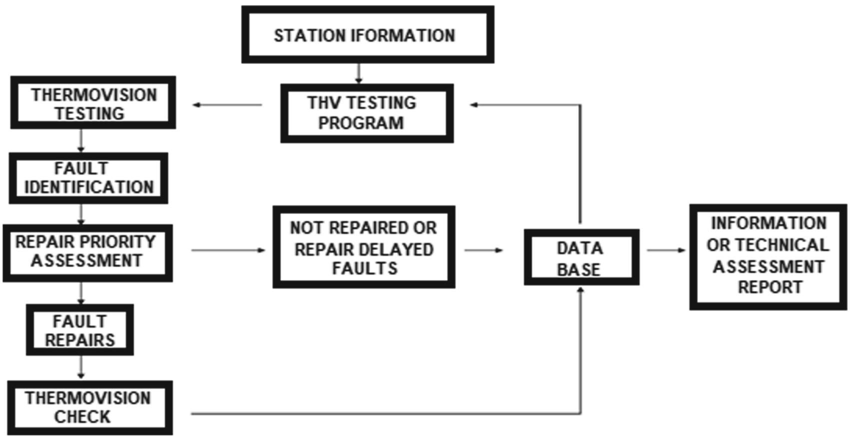

Fig. 5. Schematics of a thermovision state assessment maintenance cycle.

One of the more important actions that need to be performed is the classification of the equipment to be tested with regard to its strategic importance, possibility of replacement, operating age, safety standards and place of installation in the station. Based on this data, it is possible to create a thermal imaging program. After the test has been performed and the faults have been identified, it is necessary to start forming a list of priority repairs, based on the measured results, adopted criteria for assessing the condition, physical laws and empirical indicators.

The assigned priority determines the urgency of the intervention and refers to:

- emergencies requiring immediate shutdown and repair,
- situations where reparation can be delayed until the first expected downtime,
- situations where the object that can be kept in operation under special control.

In some cases, when, for example, there are no spare parts needed for the repair process or it is not possible to stop the operation, the repair is delayed. This decision, as well as the details related to the detected fault, are entered into the database. When fault repairs are completed, the work order record may indicate that individual failures, for whatever reason, could not be solved, which should also be entered into the database.

Repairs that have been completed are recommended to be re-inspected thermally. This retesting may also indicate that some faults have not been completely rectified, either due to improper installation, adjustment, poor construction, or factory failure. This result is re-entered into the database and the cycle can be repeated.

4 New Approaches in the Field of Power Transformers Maintenance

Recent studies in the field of transformer monitoring and diagnostics are generally focused on automated diagnostic systems, i.e. those which would be able to make a conclusion based on all available data. Those systems would then give credible advice on any possible problem.

An example of these monitoring systems based on dissolved gas analysis (DGA) is described in [15]. This system is uses the Duval Triangle method to determine the transformer state and fault type. Generally, stand-alone functions have limited success.

Neural networks (NNs) are also widely used in the field of transformer monitoring and fault analysis. Some of the commonly used methods include:

- Multi-Layer Perceptron NN [16],
- Back Propagation NN [17],
- Granular Computation NN [18],
- Cerebellar Model Articulation controller (CMAC) NN [19],
- Learning Vector Quantization NN [20].

Additionally, other intelligent systems such as fuzzy logic systems [21], decision trees [22], Support Vector Machine [23], k nearest neighbor (KNN) [23], evolutionary algorithms [24] and many more.

Generally, as stand-alone techniques show limited success due to their many restrictions, more combined techniques are used. These systems are known as hybrid systems

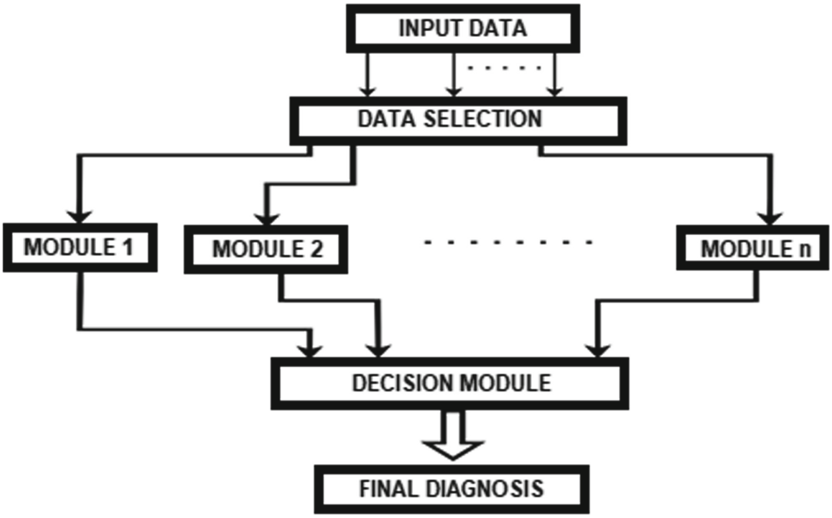

Fig. 6. Architecture of a hybrid diagnostic system.

where a different number of techniques are used to mitigate the negative effects of each individual technique. Figure 6 shows an example of a hybrid system architecture.

The general assessment of the diagnostic systems is based on its accuracy to determine state and/or fault correctly. It has been observed that systems with neural networks achieve better accuracy than other systems. This is due to the NN ability to learn nonlinear relationships between input and output data. Given the fact that the number of types of power transformers is somewhat large, it is reasonable to doubt the general applicability and reliability of a sole neural network only tested on only a relatively small data set.

On the other hand, DGA interpretation methods, which have been used in practice for over thirty years, have been developed based on the analysis of a large number of diagnosed transformer states with associated gas concentrations and have been applied to hundreds of thousands of examples worldwide. It is therefore certain that they cover the full range of types of power transformers [25]. However, all of these methods have relatively weak classification power so different methods and their combination can possibly show different results. These result can even be contradictory. Different methods using the same data set may conclude different fault types, recognize normal operating condition or even fail to conclude anything.

Tables 2 and 3 show some examples of the same data on gas concentrations using eight interpretation methods (IEC78, IEC99, MDT, RG3, RG4, KG, LN and DB).

Interpretation of DGA results is an extremely demanding procedure because, in addition to the application of an automated diagnosis method, it also requires extensive users experience. The DGA method achieves good results in the transformer condition analysis by combining interpretive methods as well as user knowledge and experience.

Due to the complexity of the fault mechanisms that are detected, as well as due to the complexity of applying the interpretive DGA methods themselves it is extremely

Table 2. Transformer fault types and distinct diagnosis over different methods [25].

Diagnosis	IEC78	IEC99	MDT	RG3	RG4	KG	LN	DB
NF	D1	ND	DT	D2	ND	ND	ND	NF
NF	ND	ND	T3	ND	ND	ND	ND	NF
PD	PD	T1	T1	PD	PD	PD	DT	NF
PD	ND	T1	PD	ND	D1	PD	T	ND
T1	T1	ND	T2	T1	T3	ND	DT	NF
T1	NF	T1	PD	NF	NF	PD	DT	ND
T2	T1	T1	T3	ND	T1	ND	T	T
T2	ND	ND	DT	ND	T3	ND	T	T
T3	T2	T2	T3	T2	ND	ND	T	T
T3	T3	T2	T2	T3	T3	ND	T	T
DT	ND	ND	D2	ND	ND	T3	D2	ND
DT	ND	ND	DT	ND	T3	ND	T	ND
D1	D1	D1	D2	ND	D2	PD	D2	ND
D1	ND	ND	T2	ND	ND	PD	ND	NF
D2	ND	T1	D2	ND	ND	D	D2	ND
D2	ND	T1	D1	ND	ND	PD	D2	NF

Table 3. Content of the diagnosis indexes [15].

Symbol	Diagnosis
NF	Normal state of the transformer
PD	Partial discharges
T	Thermal fault (regardless of temperature)
T1	Thermal fault $t < 300$ °C
T2	Thermal fault 300 °C $< t <$ 700 °C
T3	Thermal fault $t > 700$ °C
DT	Mixed thermal and electrical fault
D	Discharge (low or high energy)
D1	Low energy discharge
D2	High energy discharge
ND	The diagnosis cannot be determined

unlikely that there will be a fully automated method for transformer condition assessment and fault detection.

5 Conclusion

Transformer monitoring systems have found their application in power stations around the world and proved their importance in terms of preventing transformer faults, protecting staff and the environment, and better transformer management, which was especially evident after the liberalization of the electricity market. Knowledge of the state of the transformer, not only at the time of occasional diagnostic tests, but also during its operation, is becoming increasingly important. In order to make the best use of the monitoring system data, automatic diagnostic systems are being developed. On-line diagnostics of transformers are still mostly in the research phase and have yet to be confirmed in practical application. If its application is deemed promising, it is to be expected that its results and recommendations will not be a direct trigger for decision-making, but an auxiliary tool in making decisions about transformer management.

Thermal imaging tests are carried out preventively, with the aim of early detection of the causes of dangerous warming. In this way, it is possible to intervene in a timely manner and prevent forced downtimes, major damage, accidents, and in connection with this, large financial costs.

The best results can be achieved by applying automated diagnostics based on DGA results. However, the key problems to be solved in the development of a DGA-based automated diagnostic system are the development of a method for evaluating diagnostic findings obtained by interpretive methods and the development of a method for making a final diagnosis. The combination of the method for evaluating diagnostic findings and the method for making a final diagnosis must be effective enough to sufficiently compensate for the knowledge and experience of experts who are key elements of traditional application of DGA interpretation and are not available in automated diagnostics.

References

1. Sturm, F.A.: Efficient operations—intelligent diagnosis and maintenance. VGB Power Tech e.V., vol. 1003, pp. 195–303. Essen (2003)
2. Keith Mobley, R.: An Introduction to Predictive Maintenance; Butterworth Heinemann. New York (2002)
3. Banović, M., Keitoue, S.: Enhanced remote access to the monitoring system. In: International Conference on Condition Monitoring and Diagnosis CMD 2006, paper 659. Changwon, Korea (2006)
4. Banović, M., Keitoue, S.: Mobility support for the access to a monitoring system. In: IMEKO XVIII World Congress Brazil, Rio de Janeiro (2006)
5. Dropulić, T., Banović, M., Keitoue, S.: Inteligentno upravljanje rashladom transformatora sustavom motrenja transformatora Končar TMS. HO CIGRE 7. simpozij o sustavu vođenja EES-a, Cavtat (2006)
6. CIGRE Brochure 642: Transformer Reliability Survey, Final report of working group A2.37 (2015)
7. Nicola, M.: Monitoring system for power transformer windings hot spot temperature using fiber optic sensors, Kalman filter and integration in SCADA system. Am. J. Signal Process. **8**(2), 33–44 (2018)
8. McCalley, J.D., et al.: Automated integration of condition monitoring with an optimized maintenance scheduler for circuit breakers and power transformers. Final Project Report, Power Systems Engineering Research Center (2006)

9. Bengtsson, C.: Status and trends in transformer monitoring. IEEE Trans. Power Delivery **11**, 1379–1384 (1996)
10. Davidenko, I.V.: The development of diagnostics criteria of power transformers and instrument transformers using the results of the chromatograph analysis of gases dissolved in oil. In: International Conference on Condition Monitoring and Diagnosis CMD 2006, paper 839. Changwon, Korea (2006)
11. Akbari, A: Dissolved gas analysis based on information fusion to enhance reliability of power transformers diagnosis. In: International Conference on Condition Monitoring and Diagnosis CMD 2006, paper 597. Changwon, Korea (2006)
12. He, Q., Si, J., Tylavsky, D.J.: Prediction of top-oil temperature for transformers using neural networks. IEEE Trans. Power Delivery **15**, 1205–1211 (2000)
13. Sparling, B.D.: Moving forward from monitoring to diagnostics. IEEE/PES Trans. Distrib. Conf. Exposition **2**, 960–963 (2001)
14. Chandavong, P., Wiroteurairuang, D.: The development of power transformers diagnosis framework using infrared thermograms analysis. Int. J. Inf. Electron. Eng. **8**(1) (2018)
15. Duval, M., Dukarm, J.: Improving the reliability of transformer gas-in-oil diagnosis. IEEE Electr. Insul. Mag. **21**(4), 21–27 (2005)
16. Salami, A., Pahlevani, P.: Neural network approach for fault diagnosis of transformers. In: 2008 International Conference on Condition Monitoring and Diagnosis (2008)
17. Wang, Y., Zhang, L.: Transformer fault diagnosis based on back-propagation neural network optimized by cuckoo search algorithm. In: 2017 3rd IEEE International Conference on Control Science and Systems Engineering (ICCSSE) (2017)
18. Maumela, J., Nelwamondo, F., Marwala, T.: Condition monitoring of transformer bushings using rough sets, principal component analysis and granular computation as preprocessors. In: 2013 International Conference on System Science and Engineering (ICSSE) (2013)
19. Pai, N.-S., Lai, Y.-C.: Fault diagnosis of electric power system transformer on CMAC neural network approach. In: 2012 International Conference on Fuzzy Theory and Its Applications (iFUZZY2012) (2012)
20. Liu, J., Liang, Y., Sun, X.: Application of learning vector quantization network in fault diagnosis of power transformer. In: 2009 International Conference on Mechatronics and Automation (2009)
21. Wu, T., Tu, G., Bo, Z.Q., Klimek, A.: Fuzzy set theory and fault tree analysis based method suitable for fault diagnosis of power transformer. In: 2007 International Conference on Intelligent Systems Applications to Power Systems (2007)
22. Zhao, F., Su, H.: A decision tree approach for power transformer insulation fault diagnosis. In: 2008 7th World Congress on Intelligent Control and Automation (2008)
23. Benmahamed, Y., Teguar, M., Boubakeur, A.: Diagnosis of power transformer oil using PSO-SVM and KNN classifiers. In: 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM) (2018)
24. Hong-xia, X., Li-ping, S., Zheng-yun, H., Hui, X.: Power transformer fault diagnosis based on chaos immune evolutionary clustering algorithm. In: 2010 2nd International Conference on Signal Processing Systems (2010)
25. Banović, M.: Automatska dijagnostika energetskihtransformatora, kvalifikacijski doktorski rad, FER