2022 Paris Session

B3 Substations & Electrical Installations
PS 3 Integration of Intelligence on Substations
IoT and machine learning applications based on protection automation and control data including asset management, monitoring and data analysis

Integrated Intellectual Automated System of Monitoring, Diagnosis and Control of Power Transformer Stock Technical Condition

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ABSTRACT

The paper is devoted to an integrated intellectual automated system for monitoring, diagnosis and control of the technical condition of a power transformer (PT) or a fleet of power transformers, which uses an online monitoring system and an offline knowledge base – PT specifications, operating parameters, conventional testing and measurement results, expert assessments and forecasts – for analysis of a PT condition. The structural and functional schematic diagram of the designed system is given. The online and offline algorithm of interaction of intelligent subsystems is described. Attention is paid to the automatic assessment of reliability of online monitoring data and to the adjustment of readings, taking into consideration the materials aging processes, using the offline data. A special emphasis is placed on methods for adaptive prediction of online monitored parameters, bearing in mind the mutual influence of processes, occurring in the transformer, including for the purpose of predicting the concentrations of gases contained in the transformer oil.

The developed system not only assesses the current technical condition of a transformer, but also generates control signals and recommendations to personnel for necessary changes in the transformer's operating mode, maintenance and repair.

The authors hope that the suggested integrated intelligent monitoring system will enable to use, with greater confidence, the results of calculations of online monitoring systems in the course of operation and make the work with such systems useful and automated to the maximum possible extent, without involving personnel in the diagnostic process, and providing a concise end result.

KEY WORDS

Automated monitoring system, transformer diagnosis, online monitoring, intelligent monitoring system, adaptive prediction.

INTRODUCTION

With the development of digital, information, analytical technologies as well as in the context of increased requirements to reliable operation and monitoring of the technical condition, against the background of a tendency towards the increase in the age of equipment in service, the need for use of operational data from automated monitoring and technical diagnostic systems (AMDS) increases.

As far back as 2015, the CIGRE Working Group A2.44 issued the study “Guide on Transformer Intelligent Condition Monitoring (TICM) Systems” [1], in which a number of important aspects were noted. For example, it reports that the market offers a variety of sensors, devices, online continuous monitoring systems for assessment of the current condition of equipment. However, all these systems make it possible to reach a conclusion, with a certain degree of probability, on the condition of not all the transformer systems and assemblies. At the same time, there is not a common practice of calculating and using the assessment of a PT condition, in general, in online mode. A properly implemented process of AMDS functioning should not only collect online monitoring data, but also analyze them, correlating the results with other conventional practices of offline monitoring, for proactive detection and diagnosis of developing defects in all the systems and assemblies of a power transformer, providing users with a list of possible relevant actions.

By the number of facilities of the integrated power grid, the electric power sector of the Russian Federation is one of the largest in the world. A lot of experience was gained by facilities operating AMDS in Russia. By summarizing this experience, the absence or limited functionality of software analyzing online data has been noted. The problem of insufficiently deep and poor-quality analysis of online monitoring data is caused by two reasons: firstly, by a smaller set of monitored parameters as compared to the offline monitoring; secondly, by an insufficient number of regulated values of online parameters and their trends that define the boundaries of classes of the transformer technical condition. On the other hand, transformer diagnostic systems using artificial intelligence (AI) assess the technical condition of a facility based on offline measurement data for the past instance of time; therefore rapidly developing defects can be missed.
The purpose of development of an integrated intelligent automated system for monitoring, diagnosis and management of the PT technical condition (II ASMDM), described in this paper, is to minimize the disadvantages and to strengthen the advantages of online and offline monitoring approaches.
The current trend towards digitization of substations (SS), the widespread introduction of assets condition monitoring systems, and the use of artificial intelligence systems make this purpose exceptionally relevant.

INTEGRATION OF THE TWO APPROACHES OF OFFLINE AND ONLINE DIAGNOSIS OF TRANSFORMERS

The work of the group of authors on II ASMDM began in February 2020. Currently, the software has been created and is now being implemented at a number of 110-500 kV electrical substations in Russia. Described below is an actual experience from practical implementation of the system.

This section offers a diagram of the completed integrated intelligent automated system for monitoring, diagnosis and management of the technical condition of the power transformer fleet, which integrates the online and offline diagnosis approaches, and discloses the synergetic effect of integrating these approaches. The II ASMDM schematic diagram in Fig. 1 shows subsystems for online and offline data collection and analysis, a data exchange unit, as well as information flows of their interaction

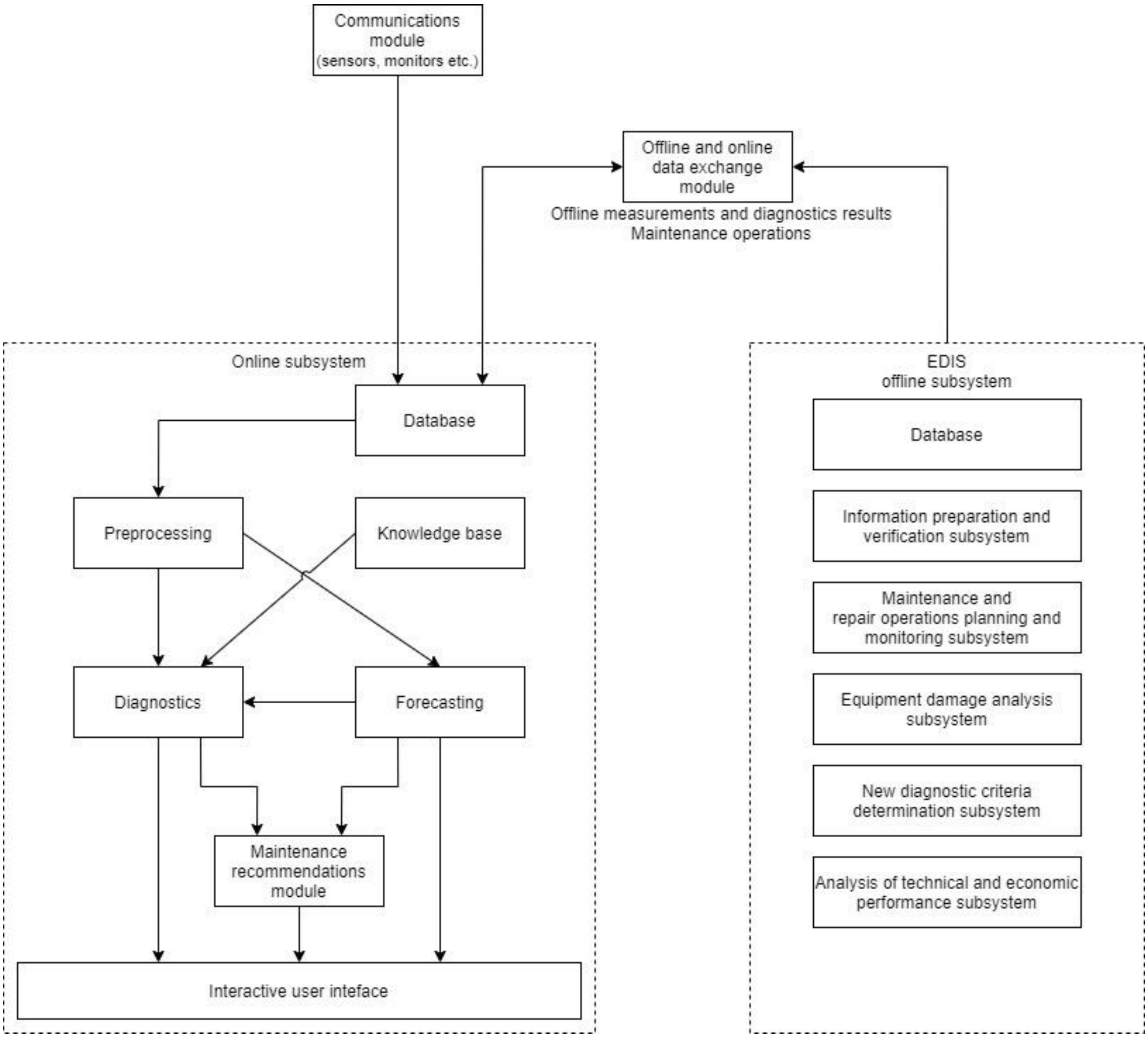

Figure 1. Online and offline data collection and analysis subsystems

The flowchart shows the flow of information through the data exchange module:

- to the offline subsystem: information about operating mode changes and online monitoring readings to complement the offline database with actual values and for potential adjustments in diagnostic conclusions and calculation of the current health index;
- to the online subsystem: information on operational impacts, assessment of technical condition by the offline subsystem and the offline measurement data necessary for the online analysis, which are used to verify the online data, taken into consideration in the algorithms for assessment of the technical condition, in calculation of the remaining useful life, in recommendations to personnel on changing the operating mode of PT and on necessary maintenance and repair operations (MRO). Note that the amount of information about the PT condition is transmitted as on the last monitoring date in the past period. This is not only particular data of offline measurements, but also information of diagnostic and assessment.

Particular attention in II ASMDM is paid to data verification.
The verification is achieved by the following means:

- a natural range of values, when an outlier parameter is indicative of a measurement error;
- a check of changes in correlated parameters;
- a check of change in trends in similar parameters of the online and offline monitoring as well as in correlated parameters of online and offline monitoring.

As a result of the verification procedure, temporarily mutually verified and updated data series with no errors are formed in databases of online and offline CI AMDM modules.

In addition to data verification, the offline information in the online data analysis subsystem is required to implement the following tasks.

Firstly, the information about performed repair operations (degassing, oil regeneration, oil replacement, drying of solid insulation, etc.), received from the offline subsystem, has an effect on:

- changes in parameters of models for prediction of DGA values, insulation moisture, remaining useful life, etc.;
- changes in assessment criteria of online monitoring parameters.

For example, when replacing an oil of one type with another one, the oil saturation value may change significantly, thus resulting in changes in coefficients used to calculate the absolute oil moisture, as well as changes in regulated values of this indicator.

Secondly, some of the data from offline tests and measurements are used to revise results of calculations, made using online data: for example, consideration of influence of the oil oxidation degree when calculating the solid insulation ageing.

Thirdly, the assessment of the PT technical condition, made by the offline data analysis subsystem in the form of the nature and type of defect, the degree of its development (localization), is used in the unit for generation of operational recommendations to personnel regarding necessary MRO operations: for example, consideration of influence of the oil oxidation degree when calculating the solid insulation ageing.

Fourth, the assessment of the PT technical condition, made by the offline data analysis subsystem in the form of the index of the PT winding technical condition, is used to predict the load capacitance of a particular PT.

The online data in the offline information analysis subsystem are required for on-the-fly calculation of the technical condition index for a particular PT and assessment of the transformer fleet condition as a whole. Based on these data, the plan for maintenance and repair of a power utility's transformer fleet may be adjusted promptly.

Moreover, when making a decision on the PT technical condition, the offline subsystem considers jointly online operational data and latest offline data of several types of measurements. This enables using all available information regarding the asset being diagnosed at a specific point in time, which increases the efficiency and quality of performed assessments of the PT technical condition and generated recommendations to personnel for its further operation mode.

Structure and functions of the II ASMDM offline subsystem

Historically, expert diagnostics and information systems (EDIS) handling offline measurement data predated AMDS. In the Russian Federation, such systems have been implemented since late 1980s to early 1990s. The development of information technologies, growing requirements to expansion of the systems' functionality and the depth of analysis of equipment operation data result in the development of EDIS. The modern EDIS use elements of artificial intelligence to a greater extent, solve not only tactical tasks of real-time control of electrical equipment operation, but also strategic tasks of electrical equipment operation.

In our opinion, the list of tactical tasks of electrical equipment operation includes:

- assessment of the electrical equipment technical condition in order to determine the type of defect, the degree of its development and localization (stage of in-depth diagnosis);
- planning and monitoring of personnel actions for subsequent operations (for example, preparation of a MRO plan taking into consideration the electrical assets technical condition, including ranking of the electrical assets fleet by the health index);
- prediction of the course of events (for example, prediction of insulation ageing);
- personnel training, i.e. explanation of used categories and concepts, cause-and-effect links, identification of key points in reasoning, formation of skills for analysis of a situation.

The list of strategic tasks for operation of the electrical equipment stock may include:
- preparation of a MRO plan taking into consideration the assessment of the electrical equipment technical condition and risks;
- determination of investment patterns, including on the basis of a technical and economic assessment and an analysis of reliability of the electrical assets fleet;
- automation of scientific research elements in order to gain a new knowledge (for example, reliability indicators, criteria for assessment of monitored parameters and recognition of defects, etc.);
- identification of shortcomings in HR and investment policies, operations policies, including in arrangement of diagnosis, assignment and performance of MRO;
- support of decision-making, i.e. analysis of a situation and ways out of it, development of a set of recommendations.

To create an integrated intelligent system, the EDIS, which solves not only the tactical tasks of 6-750 kV power transformers operation, but also most of the strategic tasks of equipment operation and continues to increase its functionality, has been selected. Besides, the reliability of solutions, issued by this system, has been well proven: it has a long (more than 25 years) history of operation, covers a large number of utilities, is well known to personnel (420 workplaces). Principal functions of the system are diagnosis and assignment of dates and scopes of maintenance and repair operations in respect of all types of electrical assets (both oil-filled and non-oil-filled). Below is a description of the EDIS structure and functions applied to PT and its assemblies.

EDIS comprises a database, knowledge base and 6 data analysis subsystems, shown in Figure 1

The database contains PT rating data, testing and measurement data, information on PT operating conditions and modes, and performed maintenance and repair operations. The assessment of technical condition of power transformers is made based on the following offline measurements:
- analysis of gases dissolved in oil (DGA);
- expanded physical and chemical analysis (FCA) of oil (34 monitored parameters);
- moisture and degree of polymerization of solid insulation;
- measurement of insulation characteristics;
- ohmic resistance of windings;
- short-circuit resistance;
- results of no-load testing.

The results of PT diagnosis using special inspection methods (thermal imaging and vibration testing, partial discharge testing, etc.) are also stored in the database.

The subsystem of information preparation and verification:
- prepares (including calculation) operational data for analysis;
- identifies errors in data, received by the system, which arise due to failure to observe the measurement procedure, carelessness of personnel, imperfections of measurement methods and equipment, etc.•
- checks information for incompleteness, relevance and consistency.

This subsystem ensures the quality of source information to be used by EDIS to solve tactical and strategic tasks.

The maintenance and repair operations planning and monitoring subsystem automatically generates operational action plans based on a library containing conditions and frequency of measurements and other maintenance and repair activities.

The subsystem of equipment damage analysis contains:

- defect description, formalized using normative classification reference bases;
- scenarios of defect analysis based on defect reports and calculated reliability indicators;
- a database of development of transformer defects, confirmed by later investigations. The development of defects is shown by a history of changes in values of monitored parameters of 6 types of measurements, including DGA.

The subsystem for determination of new diagnostic criteria calculates criteria for assessment of monitored parameters based on the operation data of the entire PT fleet, accumulated in the system database.

The subsystem of analysis of technical and economic performance of the PT fleet enables:

- analysing the trends of changes in the number of PT set to a frequent maintenance control (with development of defects requiring MRO);
- analysing the statistical samples using both rating data of equipment and operational information (results of measurements and maintenance and repair operations, external influences);
- calculating specific costs and labour intensity of maintenance and repair operations by equipment groups.

The purpose of the subsystem for MRO priority selection, taking into consideration the assessments of the technical condition and the risks of failure, is clear from its name. The calculation of the technical condition index of transformer equipment and the assessment of the risk of its failure are made using the EDIS authors' methods.

The most valuable and fast-developing component of EDIS is the knowledge base (KB). The constant updating and seeding of the knowledge base is a key feature making EDIS in-demand and increasing its life cycle. The knowledge base of the system comprises:

- libraries of criteria for assessment of monitored offline parameters and their trends;
- algorithms for determination of a type, nature of a defect, a degree of its development, danger and, if possible, localization;
- an algorithm for determination of an assembly (subsystem) of a power transformer, in which a defect develops, based on the basis of machine learning using data of transformer damages;
- an algorithm for search for a case, similar to the one under consideration, in the transformer damages database;
- algorithms for scheduling maintenance and repair operations (their scopes and dates), taking into consideration the type, degree of development and danger of a defect and its localization.

Even though such systems as EDIS perform an in-depth analysis of the technical condition and its change over time for both an asset entity and for an asset fleet as a whole, it is obvious that results of operation of such systems are not shown in real-time. Their conclusions are based on offline measurements, performed on a timely basis ranging from once every 6 months for DGA to once in several years for other types of measurements. Consequently, this approach does not allow operating personnel to promptly identify and prevent damage to transformers that takes several months or less to develop. The conclusions regarding the PT technical condition based on offline measurements are also not prompt enough for operator's control of transformer modes.

Structure and functions of the CI AMDM online subsystem

The online part of II ASMDM is an open-architecture software and hardware product, created for monitoring, diagnosis and control of the technical condition of oil-filled transformers, auto transformers and reactors.

The following information flows are involved in the operation of the online subsystem:
- parameters characterizing the transformer condition (operating parameters from local control systems, data from sensors and monitoring devices);
- EDIS data (offline data).

In II ASMDM, the online module is built based on classical principles. Among sources of the monitored parameters are a dissolved gases monitor and relative humidity of oil (gas and moisture content, GMC), high voltage bushing monitors, top oil temperature sensors as well as other temperature parameters, if they are available by the PT design or the AMDS technical specifications.

II ASMDM is arranged in such a way to provide the possibility of scaling the system to a large number of transformers under monitoring. New assets to be monitored are added by a user in the ASMDM interface.

The main elements of the online monitoring subsystem are:

- online and offline databases;
- preprocessing unit that performs the deletion/replacement of anomalous data from further analysis, smoothing of anomalies, calculations of trends necessary for analysis, etc.;
- knowledge base that stores regulated values of controlled online (measured, calculated and diagnostic) parameters, diagnostic models constants and parameters, calculation algorithms, etc.;
- prediction unit that calculates predicted values of parameters, estimates the time before entering a dangerous mode of operation or a dangerous technical condition, a dangerous rate of paper insulation life utilization;
- recommendation generating unit, in which, based on the prediction and diagnostic results, recommendations are generated, including information about necessary changes in the transformer operation mode, additional tests to be made on the transformer and the transformer elements, in which a defect is most likely to develop. Besides, this unit gives recommendations on the PT load capacitance, generates warnings about overload and overheating durations, etc.

The online subsystem provides an in-depth data analysis in the following areas:

- temperature modes of operation, including mutual calculations of top oil and winding hotspot temperatures;
- moisture content of oil and paper insulation of windings, taking into consideration temperature, oil composition and oil ageing data;
- assessment of the technical condition based on results of analysis of concentrations of gases, dissolved in transformer oil;
- various assessments of the remaining insulation life, including its ageing rate, taking consideration the operating mode and technical condition of the paper-oil insulation system as well as the maintenance and repair operations performed;
- monitoring the load capacitance, taking into consideration the PT service life as well as the technical condition index, calculated based on offline and online monitoring data.

We’ll separately focus on the problems of gas-moisture content (GMC) monitors. Data samples from such monitors often contain anomalies. Also, when examining the archive of GMC monitors data, a flaw has been found, which is specific, to one or another extent, to a range of monitor types: this is a temperature drift of readings. The software of the online II ASMDM subsystem cannot ignore such data fluctuatios, because they may be a sign of a rapidly developing defect and at the moment, when the system records them, the system can save an expensive transformer.

If the online algorithm classifies the anomalous readings of such GMC monitors as errors, self-diagnosis signals are generated by the system and sent to the relevant utility's departments, as well as the unreliable values are recovered from historical data or results of predictive models.

This practice in the online subsystem applies not only to GMC monitors data, but also when assessing other online-monitored parameters.

The main personnel, involved in the utility's operations as well as in the diagnostics, should spend minimum time working with the system, but at the same time achieve the maximum benefit.

To implement this idea, the software provides three important types of notifications:

- informing the user of the current level of the monitored parameters exceeding their notification or alarm thresholds, including predicted parameters;
- nature and type of an alleged defect, rate of its development;
- recommendations generated from the offline module's knowledge base statistical data, regarding power transformers and assessments of diagnostic models results.

For example, a significant increase in the concentration of hydrogen or hydrocarbon gases in transformer oil may be caused by a defect in the interlayer insulation. To ensure the reliability of this conclusion, it is necessary to perform power loss measurements under no load or partial discharge activity measurement in offline mode.

Prediction of online DGA results

Even though the offline diagnostic approaches have been proven long ago and are highly trustworthy, it becomes obvious that, when analysing them, it is necessary to take into consideration the PT operating mode. On the other hand, in automated monitoring and technical diagnostic systems (AMDS), the gas concentration data are not used with sufficient efficiency, because the criteria for assessing the level of gas concentrations and their trends, measured offline, are not always applicable to online measurements. There are no regulatory documents regulating the notification or alarm threshold values of concentrations and their trends, measured online. The plot of online data of carbon dioxide concentrations, measured on a 220kV PT under various operating temperature and load over a time span of 2 months, is shown in Fig. 2 (blue line). The plot demonstrates the obviousness of changes in concentration under the influence of variation in a PT load and temperature. Consequently, the criteria for online assessment of gases concentrations should take into consideration this influence.

II ASMDM's prediction unit uses a model of gas concentrations change. The model is generated by the system automatically, using machine learning methods, based on the history of measurements of gas concentrations, operating mode and ambient temperature for a particular PT. The predictive model is a combination of autoregression and regression models. It connects dissolved data concentration values with historical concentration values and ambient temperature, oil temperature and PT load values.

Then this predictive model is used to make a short-term prediction of gas concentrations, taking into consideration current values, transformer load, top oil and ambient temperature.

The predicted values of gas concentrations are used to assess the remaining time to reach notification or alarm thresholds. In addition, the model is used to identify abnormal deviations in the online measurement process from the predicted values, which mean either a problem with correctness of measurements, obtained from sensors, or a rapidly developing defect. The algorithm for analysing abnormal deviations of gas concentrations differentiates between these causes.

The developed approach of constructing a predictive model of DGA results has a good accuracy. According to the results of comparing the predicted values and the actual measured ones, their difference ranges from 3.2 to 5.4% with point-to-point comparison. Fig. 2 shows two plots of changes in concentration of carbon dioxide: the blue line corresponds to the measured (true) values, and the orange one corresponds to the forecast made by the model.

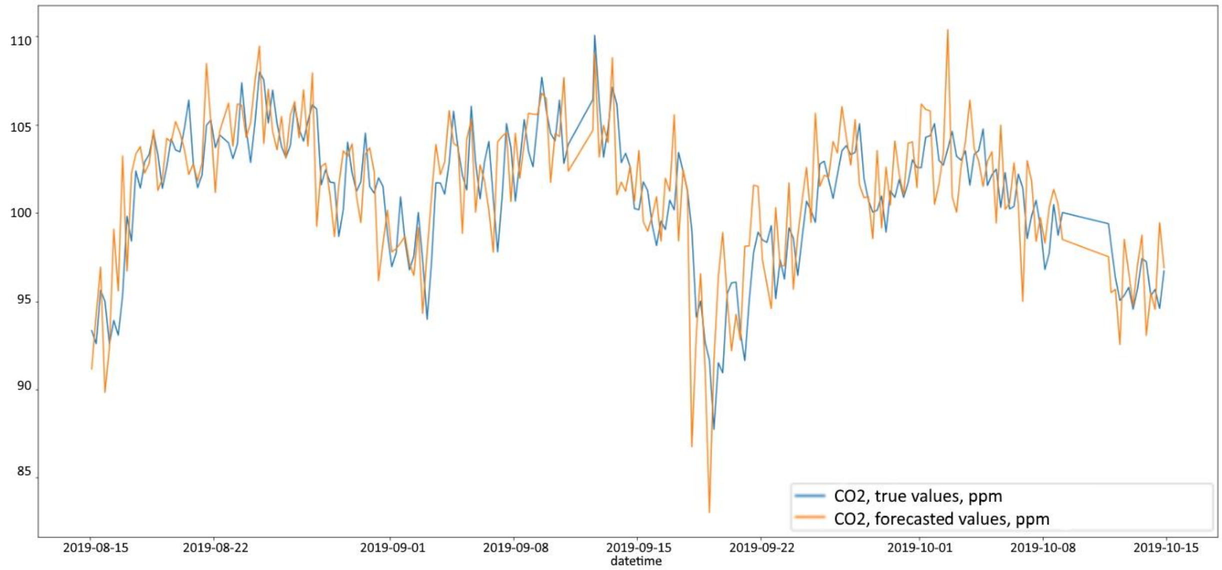

Figure 2. Actual and predicted development of carbon dioxide concentration

It is known that the prediction of DGA results may be performed using neural networks and other artificial intelligence methods. In this instance, there is often a low interpretability of models, i.e. the results obtained from the model, may be poorly explainable from the point of view of industry knowledge. Based on results of testing, made by developers of II ASMDM, the used model provides the best combination of accuracy, interpretability and computational costs compared to other prediction methods.

When making a prediction of gas concentrations development using the model, a question arises regarding the values of influencing parameters such as temperature and load, according to which the predicted values will be calculated. It is impossible to predict exact values of such parameters even for a short period of time; therefore an approach using a range of values of such parameters, for example, an expected daily range of PT load changes or daily fluctuations in ambient temperature, is more practical. In view of this, the software implements a three-dimensional representation of the prediction. Fig. 3 shows that each point of the predicted value surface corresponds to the concentration value (vertical axis), which will be reached in the future for each load and temperature value (horizontal axes) from a certain range. The colours of the surface areas correspond to the areas of gas concentration exceeding the notification threshold (yellow) or alarm threshold (red). It is assumed that such a presentation, along with the possibility of using a colour indication, is user-friendly.

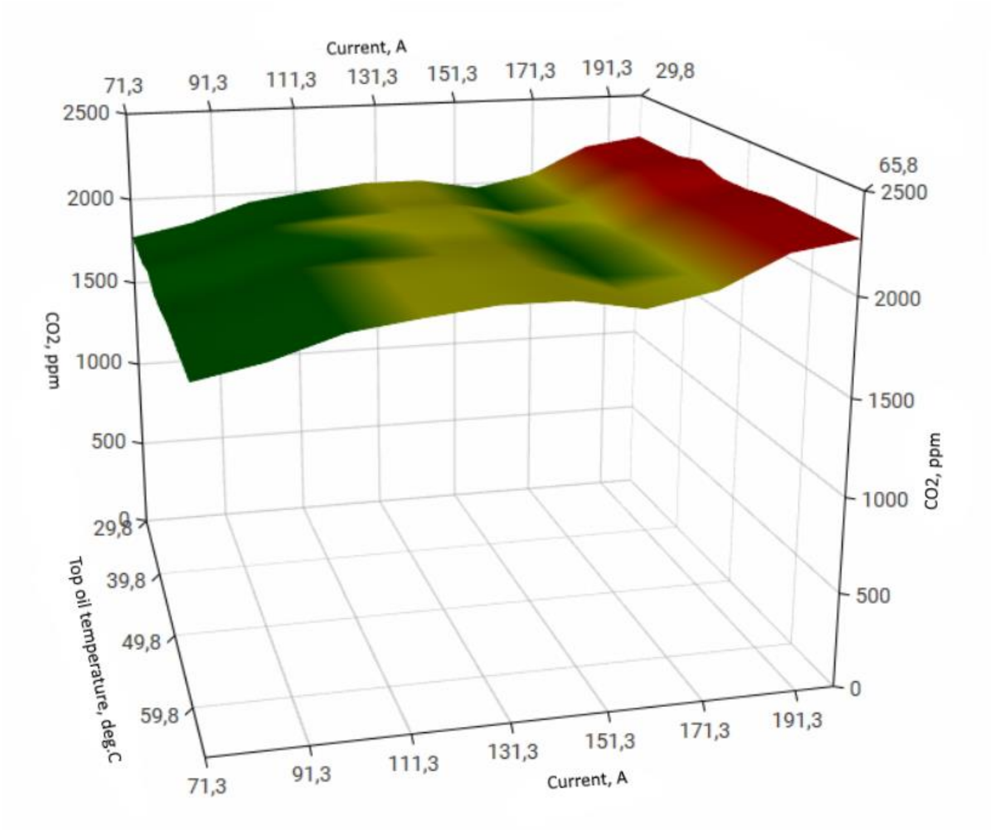

Figure 3. Predicted distributions of concentrations (different points of view)

II ASMDM with the prediction function was tested in pilot operation at a 500 kV electrical substation, where two auto transformers, subject to special monitoring, were equipped with the systems. The system was operated at the substation for more than a year. Under normal operating modes, the prediction of DGA results showed good results. The discrepancy between the actual and predicted values of hydrocarbon gas concentrations did not exceed 5 ppm. In addition, during the trial operation of II ASMDM, degassing was carried out on one of the transformers, and there was a sharp increase in load on the other one. In both cases, after the initial corresponding increase in errors in predicted concentration, the model returned to better accuracy fast enough.

The integrated approach to prediction has a practical value for prevention of defects at an early stage. Also, among the conclusions obtained as part of the pilot operation of the software with the prediction function, it is worth noting the need to use DHW monitors with known accuracy (and not indicator devices) to be set for measurements once an hour for transformers with a certain technical condition index.

CONCLUSION

Everywhere, there is a need for a multifactorial in-depth analysis of information received from online monitoring systems, primarily, for key, particularly important facilities, for facilities under more frequent monitoring. Integration of online and offline measurement data into a single system with their subsequent processing by artificial intelligence enables:

- increasing the practical value of online monitoring data for assessment of the technical condition of the transformer and its components, and, consequently, increasing the efficiency of application and trustworthiness level for the online monitoring systems among personnel;
- reducing the number of false alarms provided by the online monitoring system;
- mutually verifying and supplementing the data received from the offline and online monitoring;

- taking into consideration the results of offline measurement data analysis and the data itself when forming the online subsystem results, including in order to control the PT load capacity;
- recording data of the online measurements in diagnosis and calculation of the current technical condition index both for a piece of equipment and in the course of analysis of the transformer fleet technical condition, as a whole, in the offline part of II ASMDM;
- increasing the response time to fast-developing defects, in particular, giving more prompt and balanced recommendations to personnel regarding necessary changes in the transformer operating mode, maintenance and repair;
- further improving the quality of transformer operation management, among other things by improving the accuracy of the transformer remaining useful life assessment due to the mutual consideration of the online and offline data.

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