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Methods of Multi-Parameter Diagnostics of Electric Equipment Condition Within On-Line Monitoring Systems

A.S. Karandaev[a], I.M. Yachikov[b], V.R. Khramshin[b,]*

[a] *South Ural State University, 76, Lenin Avenue, Chelyabinsk, 454080, The Russian Federation*
[b] *Nosov Magnitogorsk State Technical University, Lenina Av. 38, Magnitogorsk, 455000, The Russian Federation*

Abstract

Provision of power equipment with on-line monitoring systems is a relevant and highly sought task. Designing up-to-date intelligent diagnostic systems requires development of methods for multi-parameter diagnostics (MPD) of the facility condition based on the total diagnostic features. As exemplified in a high-voltage oil-filled transformer, a list of jobs needed for generation of an effective diagnostic complex has been compiled. Trends for concentration of gases dissolved in transformer oil of the ladle furnace have been extrapolated. Time of matching the threshold values determining the facility conditions by these parameters has been forecast. Experiments have proved that a stationary on-line monitoring system enables disclosure of developing defects. At this, the use of stationary systems as fault indicators only is non-efficient both in the technical and economical terms. The paper substantiates the list of task to be solved when developing methods for MPD in the on-line systems. It is shown that condition diagnostics is most efficient at a complex estimate of independent and cross-correlated signals. The authors highlight possibility of extended application of the developed methods for diagnostics of any electro-technical systems, which data may be submitted as trends.

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1. Introduction

When operating power equipment, there is a need for continuous control of its technical conditions. This purpose is relevant for generators of thermal and nuclear power plants, equipment of sub-stations, powerful electric motors,

* Corresponding author. Tel.: +7-351-943-1256.
E-mail address: hvrmgn@gmail.com

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high-voltage switching devices, etc. At present, an established trend is an introduction of stationary diagnostic systems at the power oil-filled transformers at prolonged lifetimes. Independent on the lifetime, this task is urgent for transformer of high-power arc steel making and ladle furnaces (furnace transformers). This due to the fact that they are operated under severe conditions caused by abruptly variable non-symmetric load during electric arc steel melting [2]. Furthermore, RUL switching, which occurs at network transformers a few times in a year, is performed at furnace transformers up to 1,000 times in a day.

A number of parameters characterizing the state of an active part, insulation, high voltage inputs, cooling system, regulator of changing the number of windings under load (RUL), etc. determines the transformer condition. In recent years, stationary on-line systems for monitoring parameters of high-voltage network and unit transformers are being developed and commissioned. A comparative analysis of domestic and foreign systems is provided in [3, 4]. The systems for continuous control of furnace transformer conditions are also operated [5, 6]. They are developed based on the diagnostic equipment by OAO Dimrus (Perm) and Kelman's MINITRANS device for continuous control of gases and oil humidity.

The stationary condition control system is based on outcome of all on-line tests carried out at the operating transformer in an automated mode. The benefits of these systems in comparison with periodic complex checks is in a prompt personnel notification on the developing faults at early stages. This enables solutions both on the tactic level concerning condition control and at the strategic one in terms of repair and re-design planning up to a complete unit replacement.

Monitoring system field experience has revealed a number of methodological issues. The main issue limiting diagnostic capabilities of the on-line systems is an absence of available engineering methods for determination of a current equipment state according to the total of measured values. Recording and storing data supplied by channels 8-10 are of low efficiency and do not enable actual estimation of technical state. That is why, the systems being implemented are generally used as fault signal indications based on each parameter only.

The above problem defines a promptitude for developing methods and algorithms providing an on-line estimate of facility condition according to the total of diagnostic features. Condition evaluation according to some controlled parameters is termed as a multi-parameter diagnostics in specialized literature. Evidently, the tasks of MPD shall be substantiated at an initial phase of method development; the complex of action aimed at their solution is also needed.

2. Problem statement

It should be noted that the issues of developing MPD methods based on on-line monitoring data are understudied at present. Thus, according to recommendations of the guidance of the Rosenergoatom concern [7], the following classification levels shall be assigned for each parameter: norm, norm with deviations, norm with significant deviations, deteriorated and pre-emergency condition. In other words, the registered parameters are standardized according to their severity for the diagnosed facility. In addition, this document provides condition estimation based on the results of periodical measurements only. Similar international standards IEC 60076-1, IEC 60076-3, IEC 60599 and IEEE C57.104-1991 do not contain any recommendations on condition estimation according to results of continuous signal measurement, too.

[8] proposes to summarize heat monitoring, oil chromatographic analysis, measurement of partial discharge performance and control of the loss-angle tangent (tgδ) at inputs within the MPD framework . Without detailed analysis of the publications, it should be noted that the first two control types are not used at stationary monitoring systems. Consequently, the proposed MPD variant is also based on periodic measurements of diagnostic features and cannot be used in the data systems. Foreign publications, e.g. [9–11], consider most methods of condition control currently in use. However, they do not provide recommendations on the MPD implementation at the on-line monitoring systems. It substantiates the need for methods of complex estimation of the electric equipment condition according to the total of continuously measured diagnostic features. Below is feasibility of development of these methods as exemplified by power transformer of the 26 MVA, 110 kV voltage class installed at the ladle furnace (LF) of the electric steel-making steel works shop of OJSC Magnitogorsk Iron and Steel Works (OAO MMK).

3. Main part

An up-to-date diagnostic system shall primarily be a system of early recognition of developing defects. The following operations are required for effective control:

1. Revealing defects resulting in faults, their causes and development dynamics based on the operation experience.
2. Determination of observable characteristics (diagnostic features) of the facility, which changes is connected with defect occurrence and development.
3. Revealing the relation between parameter values and equipment technical condition. Substantiation of the limit values displaying the entity crossover to another class of technical conditions.
4. Development of methods for measuring these parameters under operation conditions.
5. Determination of the scope and rate of condition analysis based on results of on-line tests, development of the sequence (control algorithm).

However, as no methods of a complex condition analysis based on the total diagnostic features is available, it is rather difficult to solve the above tasks. Moreover, various features indicate development of different failures, by this, in different device parts in a number of cases. It obstructs localization and reduces reliability of fault identification.

As an illustration of the foregoing, an example of estimation and forecast of transformer condition according to humidity and gas concentration in oil is provided below.

3.1. Example of transformer fault diagnostics according to oil condition

It is known that severity of the most incipient failures is governed by the total volume of gases (CO, H_2, C_2H_2, C_2H_4, C_2H_6, CH_2) available in oil and their generation rate. High concentration of various gases is not intrinsically dangerous but it is a diagnostic indicator of destructive processes in the insulation: arc-over, discharge events, local overheating, heat exchange distortion, etc.

Table 1 shows an example of damage identification according to presence of oil-dissolved gases [12]. The gas content provided and diagnostic indicators specified display development of the same failure: a short circuit. However, they cannot help at determination of the defect source, that is, fault localization. Obviously, contemporary control of several transformer parameters is needed for fault localization and identification, which confirms the necessity for development of MPD methods.

Fig. 1 shows trends of humidity and concentration of three gases dissolved in oil of the tank of the furnace transformer under consideration. They are obtained with the MINITRANS device being an integral part of the stationary monitoring system installed at the transformer [6].

The dependencies provided demonstrate high rates of rising concentration of all gases, which indicates development of destructive processes in the solid insulation. Table 2 shows the limits of gas concentrations corresponding to the criteria of deteriorated and pre-emergency conditions approved for furnace transformers at OJSC Magnitogorsk Iron and Steel Works. Internal standard is approved and applied due to the fact that no statutory regulations are available for transformers of this class. Thus, GOST 14209-97 contains the following recommendation: "As for furnace transformers, the corresponding manufacturer's instruction shall be applicable due to their special load modes".

Table 1. Gas escape in oil and indicators of a short circuit

Key gases	Diagnostic indicator of a short circuit
Methane, ethane, ethylene and small amounts of acetylene	Heat acting on oil
Hydrogen, methane and small amounts of acetylene and ethane	Discharge events
Hydrogen, acetylene and ethylene	Long sparkling
Carbon monoxide and carbon dioxide	Heat acting on paper

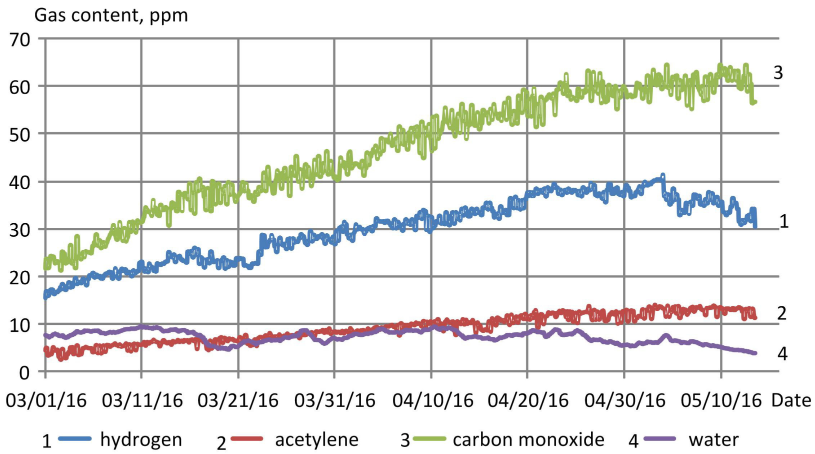

Fig. 1. Trends of humidity and main gases dissolved in oil of furnace transformer

Table 2. Thresholds of furnace transformer parameters

No.	Parameter	Threshold of impaired condition	Threshold of pre-emergency condition
1	Hydrogen content in oil (H2)	50 ppm	100 ppm
2	Acetylene content in oil (H2)	5 ppm	10 ppm
3	Content of carbon oxide in oil (CO)	300 ppm	600 ppm
4	Oil humidity ratio (H2O)	15 ppm	30 ppm
5	Temperature of cooling water	500C	700C
6	Power of partial discharges	60 mW	80 mW

Within the framework of a traditional approach to condition control, times of reaching the first and second thresholds (criteria of deteriorated and pre-emergency conditions) specified in the table has been forecast. It is found that acetylene concentration exceeds allowable values even within the controlled period (Fig. 2, a). Thus, the threshold of a deteriorated condition of 5 ppm was exceeded on March 5, 2015, that of a pre-emergency concentration of 10 ppm —approximately on April 10, 2015.

Approximation of linear dependencies and extrapolation were performed for other curves. Fig. 2, b shows an extrapolated curve of hydrogen concentration. For this purpose, an approximation based on data of 800 fixed points of the dynamic series was carried out previously. The curve shows also upper and lower thresholds of the confidence region for the regression line during monitoring and extrapolation. As we can see, the 50 ppm limit of the deteriorated condition will be expectably exceeded since the 4th–till 28th of May. When extrapolating a linear dependency, it is found that the 100 ppm threshold of the pre-emergency condition will be reached in 200 to 250 days since the date of measurement completion (not shown in Fig. 2,b).

Forecast related to achievement of the thresholds by the extrapolated curve of carbon oxide (curve 3 in Fig. 1) is more optimistic. The 300 ppm threshold of the deteriorated condition will be achieved less than in a year at the registered rate (average time – of about 400 days). The 600 ppm threshold of the deteriorated condition will be met in over 2 years. It is clear that this forecast based on data of monitoring for about 40 days should be carefully estimated.

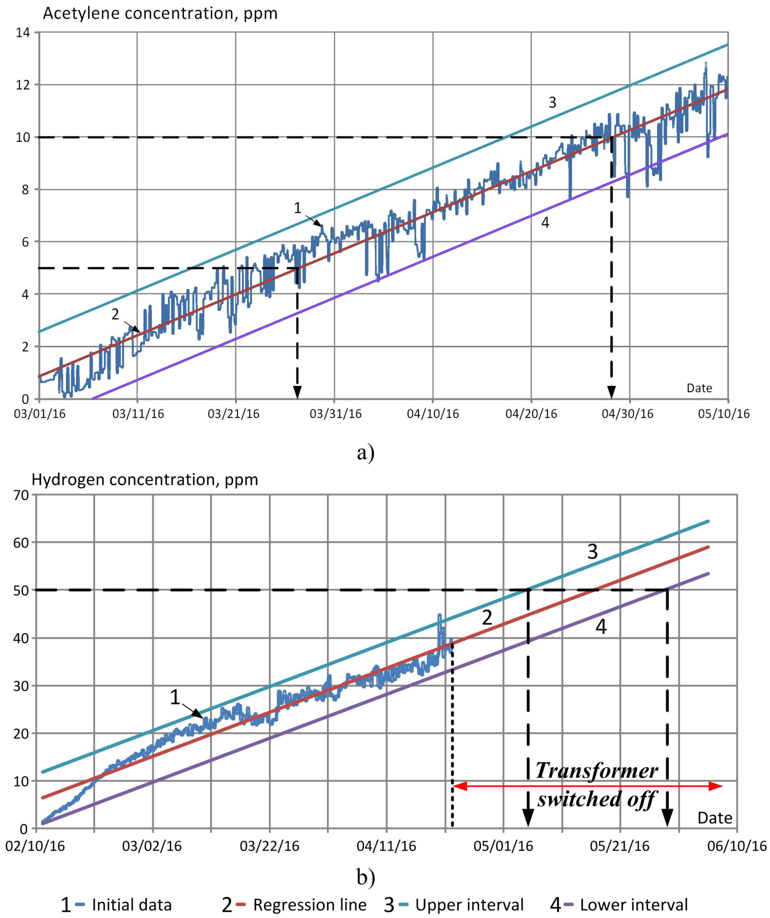

Fig. 2. Approximation of acetylene concentration (a), approximation and extrapolation of hydrogen concentration trend (b)

Apart from parameters characterizing oil condition, trends of partial discharges and vibration values measured at the tank body were constantly estimated. Result estimation proved the deteriorated transformer condition. Due to the current situation, it was removed out of service for repair on April 22, 2015. After dismounting the power circuit, damages of solid insulation, traces of discharge events, fastening melts, insert displacement and other defects were revealed. This provided with practical confirmation of presence of practically all failures detected with diagnostic monitoring methods.

Assessment of the material provided shows that indicators of gas concentrations are not informational enough with regard to fault identification. Non-permissible acetylene concentration and rise of hydrogen concentration are evidences of developing failure of an arc-over type [12]. High rate of rising carbon oxide concentration proves developing destructive processes in the insulation. This conclusion is yet rejected by a practically total absence of humidity growth. Oil humidity is within 5–8 ppm, which is significantly lower than the threshold specified in Table 2.

The considered example readily illustrates an effective functioning of the monitoring system as a fault signal indicator based on oil-dissolved gas concentrations. The trend analysis enables determining the rate of the destructive process development; at the same time, it cannot help at source localization and cause identification. At this, reliability of the set thresholds for controlled parameters plays an important part.

Here, it is evident that diagnostic capabilities of these systems are far from being reduced to functioning as fault indicators only. Provided there are corresponding methods, the may ensure, apart from a general estimation of entity condition, fault identification with a sufficient accuracy for practical purposes. This is attained by a complex analysis of both uncombined and cross-correlated parameters.

As independent (non-correlated) parameters characterizing transformer condition, the following shall be classified: temperature of the upper oil layers, vibration characteristics, PD variables: intensity, power, apparent discharges, etc. Independent are also parameters specific for conditions of separate assemblies: high-voltage inputs, RUL, oil pumps, air-cooling vents or coolant pumps of the oil-water system, etc.

Common examples of cross-correlated parameters are temperature, oil humidity, composition of dissolved gases, loss-angle tangent etc. As noted above, they characterize destructive processes in the solid insulation. Accordingly, joint control and estimation of trends of these characteristics provide with the most accurate identification of this fault type. Joint analysis of interrelated indicators also improves accuracy of condition forecast.

3.2. MPD tasks in monitoring systems

To summarize the above, the following tasks to be solved when developing methods for MPD in the on-line systems may be defined.

1. Estimation of validity of correlation of the measured values. It helps defining the most important dependent and independent parameters and substantiating an optimal number of controlled signals for each transformer class (network, unit, furnace transformers). This task is relevant as a non-reasonable increase of the number of processed signal improves the system performance by no means always. At the same time, it results in cost gain and complication of personnel jobs.

2. Trend smoothing and their extrapolation for forecasting time intervals of threshold exceeding. It enables detecting the most dangerous processes, timely personnel notification, thus, emergency prevention.

3. The most accurate substantiation of the thresholds according to the expanded condition criterion list (norm, norm with deviations, etc) [7]. This task shall be solved by comparing trends of diagnostic indicators and similar characteristics obtained at periodic checks, for instance, at oil chromatography. With database accumulated, the thresholds should be reviewed.

4. Elaboration of the generalized criterion of the entity condition with due regard to the cumulative features at continuous control of the parameter complex. This challenge is brand new as the main regulatory document RD EO-0188-00 provides for condition estimation based on results of periodic measurements only [9]. At this, the most essential diagnostic indicators– trends of parameter changes –are neither monitored and nor taken into consideration at condition assessment. Furthermore, this document does not define the term "generalized condition criterion" itself, correspondingly, no methodological approach to its estimation is elaborated. This criterion may be represented as a generalized integral characteristic or non-linear mean value of specific parameters with designation of the relevance (weight) of each parameter.

5. Development of scientifically grounded methods for calculation of remaining lifetime according to the total of diagnostic features. Available methods for transformer stipulate estimation according to one parameter. As per recommendations of the SIGRE, this shall be a humidity of paper insulation or temperature dependencies at the hottest point [13]. The most general approach to solution of this task is proposed in publications of V.P. Vdoviko [14, 15-22]. Unfortunately, his investigations do not substantiate the criterion for condition estimation based on the parameter change trends to a sufficient degree.

Apparently, the proposed control of the destruction development rate can be realized at the stationary monitoring systems only. This implies that the MPD methods together with continuous condition control will provide with an undeniable advantage at generating diagnostic complexes compared with the known counterparts.

The proposed methodological approach may be applied not only for the systems for transformer condition control. These methods are applicable at analyzing condition of any entities, which data may be submitted as trends of several measured values.

4. Conclusion

The listed objectives make up a foundation of the methods of multi-parameter diagnostics of electric equipment condition based on cumulative features obtained at continuous measuring some signals.

Development of the MPD methods is a relevant, complex and science-intensive task. At the first phase, its solutions should be based on mathematical processing data received from the existing on-line monitoring systems. The most important benefit from the MPD implementation in these systems is a possibility of analysis of both independent and cross-correlated parameters.

Ultimate outcomes of the multi-parameter diagnostics of electric equipment conditions are:

- emergency prevention due to continuous control and analysis of the technical parameter complex;
- accumulation and application of experience at operation of diagnosed facility and other similar entities, in particular, data on dynamics of the diagnostic features and generalized criterion;
- increasing lifetime owing to fault detection at early stages;
- effective generation of integral estimation of a current technical state;
- maintenance and repair cost reduction.

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