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Development of the On-line Power Transformer State Monitoring System

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Abstract - Creating an integrated energy system for efficient operation of power networks requires performing accurate monitoring of electrical equipment. According to current definitions, monitoring should include both automatic observation and assessment of the object state. In this article presented the concept of online monitoring system, which involves power transformers state assessment. Proposed to present the architecture of the system in the form of four levels performing certain functions. The information is given on the transformer physical characteristics models used to assess its condition.

***Keywords* - Power Transformer, Electricity Supply System, Monitoring, State Assessment, Thermal Model**

1. Introduction

A continuous high qualified monitoring in the transmission and distribution electricity networks is a key factor in the success of the Smart Grid concept implementation. Taking into account the increasing of load, power sector should be able to use the capacity of all power components of electricity supply systems with maximum efficiency. For this reason, a critical factor for the electricity supply organizations should have an understanding of the effects on the condition of the equipment that certain external factors may cause. This problem can be solved by monitoring electrical equipment with subsequent transfer of information in a variety of management and decision-making systems [1]. Such way of monitoring in the electricity sector may include assessment of the equipment itself [2].

The major problem that currently requires intensive development of tools and methods for monitoring is the current state of the transformers is the problem of their exploitation outside the nominal service life. This situation is particularly relevant for Ukraine, because in the next few years, there will be no economic and technical reasons, and it is not expected to change the power transformers, which exceeded their lifetime.

Currently, the control of limit values of parameters of the power transformers is performed which does not assess the quality of their current technical state, and the dynamics of their defects. To detect defects in transformers at an early stage of their development the most effective tool is continuous monitoring system that evaluates the current state. Right decisions to eliminate malfunction timely to an emergency, ensuring a high rate of availability of equipment, reduces downtime, lowers costs for repairs and extends the life of the transformer.

2. Monitoring System Architecture

The architecture of the state assessment system is convenient to be introduced in the hierarchical form using four levels. Each level will be submitted to the appropriate modules that are responsible for a particular function.

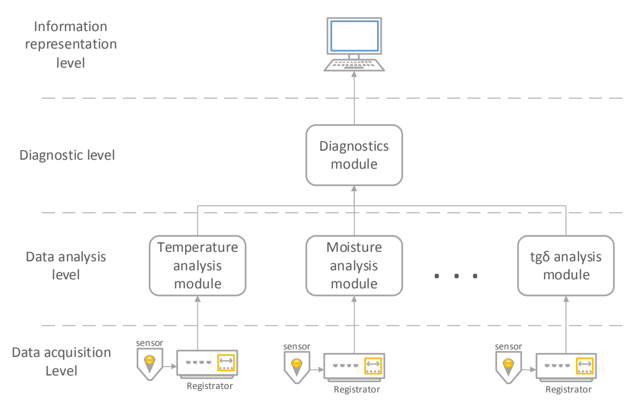

Fig.1 Architecture of transformer condition monitoring

The lower level is the level of data acquisition from sensors and performance factors of monitoring systems. This level includes specific hardware measurement of physical quantities, and is strongly dependent on the specific transformer, which is monitored. Also all the necessary information pre-processing is held on this level. The list of derived parameters should include parameters, which can cause the development of the most possible number of defects. The set of installed sensors and monitoring systems is determined by economic expediency according to voltage and transformers capacity.

The next level is the level of data analysis. It is the function of converting data into information suitable for further assessment of the indicators. Modules of this model should include basic parameters of power transformer that affect its condition. Algorithms involve real-time comparison of the measured values with one's derived from their models. Input parameters for the models are environmental data and load characteristics of the transformer.

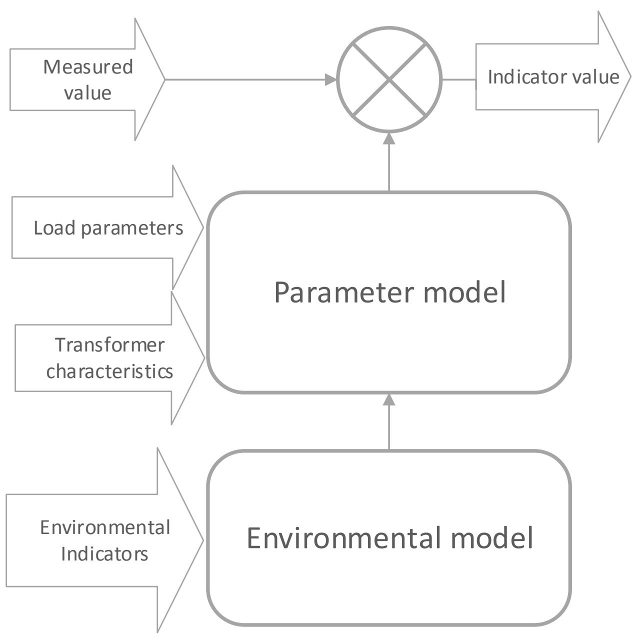

Fig. 2 Structure of the transformer parameters analysis module

The third level is responsible for the diagnosis of transformers condition. There is an integration of all indicators of a transformer, which come from the parameters analysis module at this level. As a result, we obtain the assessment of the transformers condition. The diagnosis module should include information that characterizes the level of influence of each of the characteristics to the overall assessment of the condition. This information should be prepared by the experts or by statistical processing of large amounts of data from existing systems.

The last level is the "information presentation" level. It is responsible for mapping the results obtained in the diagnostic level for service engineering staff. In addition, this module can provide recommendations on specific measures and control actions derived from the assessment of the transformers state.

3. Models of the Power Transformer Basic Parameters

Let us consider the model of the basic parameters of power transformer proposed for use at the level of analysis. The model described in [3] transformer is proposed to use monitoring the condition of moisture. Differential equations describing the moisture content of the oil in the discrete form are as follows:

– oil pump is turned on

$$M_m(t) = k_{1hf} M_m(t-1) + k_{2hf} M_m(t-2) + k_{3hf} M_{oil-ss}(t) + k_{4hf} M_{oil-ss}(t-1); \quad (1)$$

– natural cooling

$$M_m(t) = k_{1hn} M_m(t-1) + k_{2hn} M_m(t-2) + k_{3hn} M_m(t-3) + k_{4hn} M_{oil-ss}(t) + k_{5hn} M_{oil-ss}(t-1). \quad (2)$$

In these equations $M_m(t)$ – the moisture content in oil at a certain time; $M_{oil-ss}(t)$ – the equilibrium moisture content in oil at steady state, found under the relevant characteristics; $k_{i.hf}$ and $k_{j.hf}$ - factors that characterize a particular transformer and are responsible for the fine tuning of the model.

To set up the model, the first step which is necessary to do is to find the moisture content in the paper insulation at steady state. This value is determined using a stationary model for moisture content measured according to moisture content in oil and temperature for a normal steady state operation. In addition, more precise number of the moisture content in paper insulation can be found by laboratory tests during routine repair of the transformer. Factors $k_{i.hf}$ and $k_{j.hf}$ are determined by using the least squares method to a set of measured input and output data of normal operation of the transformer. This procedure of pre-setting of the model parameters should be performed after each repair and other serious interference with state of the elements of the transformer.

So using the above equation theoretical value of moisture content of oil can be obtained. For each sampling interval knowing the measured rate of the factor, relative magnitude of difference from the theoretical value can be determined, which in its way is an indicator for monitoring moisture analysis model:

$$\nu_M = \frac{M_{m.t}(t) - M_{m.p}(t)}{M_{m.t}(t)}, \qquad (3)$$

where $M_{m.t}(t)$ - the theoretical value of moisture content of oil found from equation (1) or (2) under the regime of the cooling system; $M_{m.p}(t)$ - practical level of moisture content measured by the corresponding sensor.

As a thermal model for the use in the monitoring of power transformer a model described in the standard IEC [4] and IEEE [5] may be proposed, and more accurate models described in Swift [6] and Susa [7]. These models are characterized by the following differential equations:

- Swift

$$\theta_o(t) = \theta_o(t-1) + \frac{\Delta t}{T_0}\left(\frac{1+RK^2(t)}{1+R}\Delta\theta_{or}^{1/n} - \left(\theta_o(t) - \theta_a(t)\right)^{1/n}\right); \qquad (4)$$

- Susa

$$\theta_o(t) = \theta_o(t-1) +$$
$$+\frac{\Delta t}{T_0}\left(\frac{1+RK^2(t)}{1+R}\Delta\theta_{or} - \frac{1}{(\mu(t)\Delta\theta_{or})^{\frac{1-n}{n}}}\left(\theta_o(t) - \theta_a(t)\right)^{1/n}\right); \qquad (5)$$
$$\mu(t) = \frac{1{,}3573\cdot 10^{-6}\cdot e^{\frac{2797{,}3}{\theta_o(t)+273}}}{\mu_{н}}.$$

As for the moisture model the way to find the equations parameters are proposed by using the least squares method on real measured data in the normal state of the transformer. This will improve the accuracy of the theoretical model and adapt it to the real initial transformers state, which can vary significantly across different previous operating conditions.

Monitoring factor for the oil temperature analysis model in this case is defined as:

$$\nu_\theta = \frac{\theta_{o.t}(t) - \theta_{o.p}(t)}{\theta_{o.t}(t)}, \qquad (6)$$

where $\theta_{o.t}(t)$ - the theoretical value of the oil temperature is found from the equation (4) or (5), $\theta_{o.p}(t)$ - the practical value of the temperature measured by the corresponding sensor.

In addition to the analysis of the oil temperature, the thermal model of the transformer should be used to determine the estimated temperature of the hottest point of the winding. The temperature of the hottest point is a measure of the winding unacceptable overheating, which can lead to critical defects in the transformer. Direct use of this indicator for the assessment is pointless, since it only indicates the mode of operation of the transformer, not its status. However, the calculation of the temperature of the hottest point of the winding is required in the monitoring system to provide the support staff with information for the protection of unacceptable overloading of the transformer and the need for full or partial disconnection of consumers.

The value of the dielectric loss tangent tgδ gives averaged volumetric description of the state of the dielectric. As tgδ increases with increasing temperature, to assess the level of winding insulation corruption it is recommended to bring the measured values of temperature measurement of insulation made in the factory. For example, if tgδ of winding insulation measured at a temperature $t_ф$, differs with temperature t_0, recorded in the passport of the transformer, then brought to the factory temperature $tg\delta_{пр}$ of winding insulation can be determined as follows:

$$tg\,\delta_{пр} = \frac{tg\,\delta_ф}{1{,}26^{\frac{t_ф - t_0}{10}}}. \qquad (7)$$

Obtained from (7) factor should be compared with normal values of dissipation factor for the transformer, which is possible to take the value measured during factory testing and provided in the passport. By monitoring indicators for analysis model of dissipation factor in this case is as follows:

$$\nu_{tg\delta} = \frac{tg\,\delta_н - tg\,\delta_{пр}}{tg\,\delta_н}, \qquad (8)$$

where $tg\,\delta_н$ - normal values of dissipation factor for this transformer; $tg\,\delta_{пр}$ - measured sensor values corresponding tgδ reduced to a nominal temperature (the temperature at which the resulting normal value is obtained).

4. Subsystem of the Transformer State Assessment

The criteria for assessment of the transformers state can be measured values, their difference from the corresponding prediction model and the ratio values. It is proposed to perform the assessment of the status of the transformer based on the definition of the "condition index" that is presented as some continuous variable, and that will depend on all the indicators available for the transformer. A transformers state classification can be performed based on the values of this index. According to the derived class a conclusion about the performance of the required frequency of preventive maintenance or to replace the transformer can be drawn.

The monitoring indicators acquired from these levels of data in general can be considered as random variables. Among these values, certain "emissions" caused by temporary short-term problems in the sensor data transmission lines or other subsystems can be determined. Therefore, to improve the reliability and stability of the results of the monitoring system there is a preposition to carry out a preliminary statistical analysis of these values to obtain statistically reliable performance data. For this purpose, the following algorithm can be used:

– the probability distribution functions $F_i(x)$ of each of the indicators ν_i are determined in a given interval $T_б$, which is proposed to take equal to the 24 hr time, because for such period the major change in external factors such as load and ambient temperature are characterized

$$F_i(x) = P(\nu_i \le x); \tag{9}$$

– using the obtained distribution functions $F_i(x)$ we find $\nu_{i.\alpha}$ corresponding values for certain probabilities α_i, which are selected based on analysis of historical data bundle or engineering expert opinions;
– the expected value $\bar{\nu}_i$ of random variables ν_i in the interval $T_б$ are calculated

$$\bar{\nu}_i = \frac{1}{T_б} \int_{T_б} \nu_i(t)dt. \tag{10}$$

The obtained statistical characteristics give integrated statistical evaluation of each of the monitoring indicators. Most of the monitoring indicators have been selected so that their module growth signals the worsening of the transformer. E.g., the greater the difference between the statistical characteristics and the zero, the worse the condition of the transformer is.

To combine estimates of initial characterization and to obtain integral transformer condition index S_I we propose to find the geometric mean value obtained by the statistical characteristics of certain weights. This may be calculated by the following formula

$$S_I = \left(\prod_{i=1}^{n} \nu_{i.\alpha}{}^{z_i} \prod_{i=n+1}^{2n} \bar{\nu}_i{}^{z_i} \right)^{\frac{1}{\sum_{i=1}^{2n} z_i}}, \tag{11}$$

where z_i – weights, n – number of monitoring indicators. If we'll use the condition that $\sum_{i=1}^{2n} z_i = 1$, then (11) will transform to:

$$S_I = \prod_{i=1}^{n} \nu_{i.\alpha}{}^{z_i} \prod_{i=n+1}^{2n} \bar{\nu}_i{}^{z_i}. \tag{12}$$

The monitoring system should differentiate the assessment of the transformer deterioration caused by external influences. As an example of such an index, the value of the temperature of the hottest point (HP) can be used. Out of its value HP factor may be caused by either a significant load change that exceeds the nominal or abnormally high temperatures of coolant air, which is a medium for cooling the transformer. In addition, the significant temperature excess can be caused by failures of the cooling system, such as failure of the fan that already apply to assessment of transformer. However, in this case there will be a strong difference between the actual temperature of the oil from the theoretical obtained via thermal model that will affect the value of the indicator monitoring. The diagnostic level of monitoring system should include a processing unit corresponding response to such situations.

The results of monitoring of the state come from the transformer diagnostic level in the form of certain digital indicators that should be displayed in an easy way to understand and analyze for the staff. This problem can be solved within the software information and diagnostic systems that allow displaying windows with certain messages on the screens of local or remote workstations to bring performance in indicators monitoring database, print the information and so on.

4. Conclusions

The implementation of the continuous monitoring of the state of the transformer facilitates the preventive care for such equipment. Information about the actual state of the transformer allows making preventive measures to the appearance of specific defects in the transformer or to abnormal operating modes. This makes possible to increase the time between overhaul and reduce the number of diagnostic measures for transformer requiring disconnected.

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