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A METHOD OF POWER TRANSFORMER WINDINGS CONDITION MONITORING

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ABSTRACT

Among foreground tasks of modern power engineering there is a task of transition from planned maintenance system to the true condition based equipment management by means of technical condition monitoring of electrical equipment.

The use of a comprehensive approach for monitoring and diagnostics is preferable as a way for solution of that task. In this approach, the decision about further power transformer operations can be taken according to the results of its constructional elements inspection and estimation of high number of its operating parameters.

However, the known difficulties of power transformer control under load greatly complicate use of the comprehensive approach.

Moreover, not all conventional methods of diagnostics can be used in transformer load regimes and their alternatives can have significant weaknesses. One of such methods is a method of transformer windings condition control – the method of short circuit impedance. Problems of application of this method are observed and a method for their solution is proposed in the paper.

Index Terms – monitoring, on-line diagnostics, power transformer testing, transformer windings

1. INTRODUCTION

The modern market of monitoring and diagnostics equipment is widely performed both by products, allowing to realize automated testing of switched off transformer (using different methods such as measuring of dielectric loss angel, winding resistance and short circuit impedance, turn ratio and etc.) and hardware-and-software complexes, intended for on-line monitoring and diagnostics of power transformers.

However, in contrast to the methods of diagnostic testing that have already proved oneself, the methods, using for on-line diagnostics, are still in improvement stage.

As known, the application of conventional diagnostic methods for power transformers control under load is become complicated by influence of great number of negative factors (electromagnetic fields, complex heat-exchanging processes, vibrations and etc.) and can lead to the erroneous diagnosis.

Moreover, some conventional methods cannot be adopted for on-line diagnostics, because they can be used only in edge operating conditions such as short-circuit and open-circuit conditions.

At the same time, a lack of new methods of on-line diagnostics, which can substitute the conventional methods, leads to the validity decreasing of decision-making about the possibility of further power transformer operations.

2. THE METHOD OF POWER TRANSFORMER IMPEDANCE CONTROL

The conventional method of power transformer windings mechanical condition control by the value of short circuit impedance Z_k, commonly used for diagnostic testing of switched off transformer [1], cannot be applied for on-line control of power transformer under load.

Therefore, as an alternative for this method, a method of estimation of power transformer total impedance Z_Σ is used in some on-line monitoring systems.

The method consists in measuring of primary current I_1 and voltages of primary U_1 and secondary U_2 transformer windings. A value of total impedance is calculated by the following formulas:

$$\Delta U_{12} = \sqrt{U_1^{\,2} + U_2'^{\,2} - 2 \cdot U_1 \cdot U_2' \cdot cos(\varphi_{u1,u2})} \quad (1)$$

$$U_2' = U_2 \cdot K_{12}\,, \quad (2)$$

where K_{12} – primary to secondary turns ratio.

$$Z_\Sigma = \frac{\Delta U_{12}}{I_1}\,. \quad (3)$$

However, this method contains three weaknesses:

- the necessity of using reduced values for calculations, because of this additional errors, concerned with probable change of turn ratio during transformer lifetime, occur;
- the absence of approaches for selection of a «reference quantity» of controlled parameter, relative to which can be drawn the diagnostic conclusion;

- the neglecting of the dependence between the controlled parameter and transformer load conditions.

Outlined weaknesses make impossible to use this method as an equal substitute for the conventional method of short circuit impedance in transformer load regimes.

3. NEW METHOD OF POWER TRANSFORMER WINDINDS CONDITION MONITORING

For providing an alternative to the method of short circuit impedance in transformer load regimes, the proposal for using the phase shift between voltages of primary and secondary transformer windings as a controlled parameter has been made by the authors of this paper.

A graphic illustration of this statement is shown in Fig.1, where the dependence between the phase shift and the ratio of active and reactive components of power transformer total impedance Z_Σ can be revealed easily.

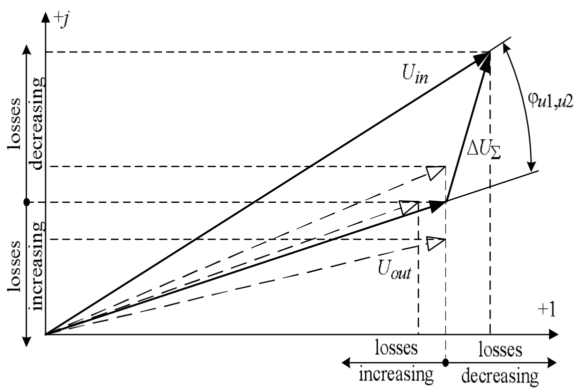

Fig. 1. The dependence between the phase shift and the ratio of active and reactive components of power transformer total impedance.

In Fig.1, the angle between the vectors of input and output voltages is in the direct relation with reactance losses of transformer and in the inverse relation with resistance losses. The positions of output voltage vector, represented by dash line, demonstrate these relations.

The new method of transformer winding condition monitoring by results of the estimation of the phase shift between voltages of primary and secondary windings can be realized in two stages.

I. At the first stage:

For three of the most typical transformer load regimes, accepted as «basic» regimes (as a first approximation, the selection of the «basic» regimes can be done accordingly to a daily-load pattern of power transformer) and for each phase of power transformer, the following calculation sequence is carried out:

- Instantaneous values of the primary $|u_1(t_j)|$ and secondary $|u_2(t_j)|$ voltages, and primary current $|i_1(t_j)|$ are registered.
- Effective values of the voltages, current and the phase shift between voltages of primary and secondary windings $\varphi_{u1,u2}$, are calculated according to the formulas from [2]:

$$A = \sqrt{\frac{\sum_{j=1}^{N} \left[\left| a(t_j) \right| \right]^2}{N}} \; ; \qquad (4)$$

$$\varphi_{a,b} = \arccos\left(\frac{\sum_{j=1}^{N} \left| a(t_j) \right| \cdot \left| b(t_j) \right|}{A \cdot B \cdot N} \right), \qquad (5)$$

where $|a(t_j)|$, $|b(t_j)|$ - arrays of instantaneous values of a current (voltage);

A, B – effective values of a current (voltage);

N – number of fragmentations during the period T of a current (voltage).

- The current of primary winding is reduced to its nominal voltage and nominal frequency of supplying circuit:

$$I_1' = \frac{U_{nom}}{U_1} \cdot \frac{f_{nom}}{f} \cdot I_1 \cdot \qquad (6)$$

- The phase shift between the primaries current and voltage $\varphi_{i1,u1}$ is obtained from (1), and then active and reactive components of primary current are calculated:

$$I_{1a}' = I_1' \cdot \cos(\varphi_{i1,u1}); \qquad (7)$$

$$I_{1p}' = I_1' \cdot \sin(\varphi_{i1,u1}). \qquad (8)$$

- Using the equation of plane from [3]:

$$A \cdot \left(I_{1a}'^{n} - I_{1a}'^{1} \right) + B \cdot \left(I_{1p}'^{n} - I_{1p}'^{1} \right) + C \cdot \left(\varphi_{u1,u2}^{n} - \varphi_{u1,u2}^{1} \right) = 0 \,, \qquad (9)$$

the dependence between the phase shift $\varphi_{u1,u2}$ and the values of active I_{1a}' and reactive I_{1p}' components of primary current can be approximated. For this purpose the coefficients A, B, C, characterizing plane position in space are determined by the following formulas:

$$A = \left[\left(I_{1p}'^{3} - I_{1p}'^{1} \right) \cdot \left(\varphi_{u1,u2}^{2} - \varphi_{u1,u2}^{1} \right) - \left(\varphi_{u1,u2}^{3} - \varphi_{u1,u2}^{1} \right) \cdot \left(I_{1p}'^{2} - I_{1p}'^{1} \right) \right];$$

$$B = -\left[\left(I'^{3}_{1a} - I'^{1}_{1a}\right)\cdot\left(\varphi^{2}_{u1,u2} - \varphi^{1}_{u1,u2}\right) - \left(\varphi^{3}_{u1,u2} - \varphi^{1}_{u1,u2}\right)\cdot\left(I'^{2}_{1a} - I'^{1}_{1a}\right)\right];$$

$$C = \left[\left(I'^{3}_{1a} - I'^{1}_{1a}\right)\cdot\left(I'^{2}_{1p} - I'^{1}_{1p}\right) - \left(I'^{2}_{1a} - I'^{1}_{1a}\right)\cdot\left(I'^{3}_{1p} - I'^{1}_{1p}\right)\right], \quad (10)$$

where upper index (1, 2, and 3) is the «basic» regime number.

II. At the second stage:

For *n*-th load regime, the values of the phase shift between the voltages of primary and secondary windings $\varphi^{n}_{u1,u2}$, active I'^{n}_{1a} and I'^{n}_{1p} reactive components of primary current are calculated according to the formulas (4)-(8) given above.

- From the equation of plane (9) the value of the control phase shift («reference quantity» of the phase shift for *n*-th load regime) can be expressed as:

$$\varphi''^{n}_{u1,u2} = \frac{-\left[A\cdot\left(I'^{n}_{1a} - I'^{1}_{1a}\right) + B\cdot\left(I'^{n}_{1p} - I'^{1}_{1p}\right) - C\cdot\varphi^{1}_{u1,u2}\right]}{C} \quad (11)$$

The deviation between the phase shift $\varphi^{n}_{u1,u2}$, calculated by the formula (5) for *n*-th regime, and the control phase shift $\varphi''^{n}_{u1,u2}$, calculated by the formula (11), is obtained as:

$$\Delta = \frac{\varphi''^{n}_{u1,u2} - \varphi^{n}_{u1,u2}}{\varphi''^{n}_{u1,u2}}\cdot 100\% \quad (12)$$

According to the value of deviation Δ, a diagnostic conclusion about changing of power transformer windings technical condition can be drawn. As shown in the Fig. 1, the value of the phase shift depends on the both active and reactive components of the total impedance, but, in fact, the values of active component much smaller than reactive one and deviations of the phase shift caused by changing of active component are hardly recognizable and cannot serve as a diagnostic value.

Thus, it is possible to identify only deviations of the phase shift caused by the changing of reactive component of the total impedance. These deviations correspond to the two types of defects: winding movement (negative values of Δ) and turn-to-turn fault (positive values of Δ).

As a preliminary, the control limit can be taken to be equal to the total error of the method; but it can be revised during the method implementation on a concrete power transformer.

4. THE RESULTS OF THE METHOD APPROBATION

The efficiency of the method has been proved by experiments with transformer of the electrodynamic model of «High Voltage Direct Current Power Transmission Research Institute» (St. Petersburg, Russia) and by the processing of data, captured during the digital recording of power transformers load regimes.

Table 1 presents the results of the approbation obtained for 1kV single-phase two-winding transformer of «High Voltage Direct Current Power Transmission Research Institute»

Table 1. Results of approbation for 1kVA (220/280V) transformer.

Regime		U_1, V	I_1, A	$\varphi_{i1,u1}$, deg.	$\varphi_{u1,u2}$, deg.	$\varphi''_{u1,u2}$, deg.	Δ,%
Basic	1	212.39	1.90	5.6	1.41		
	2	193.52	3.11	55.8	1.39		
	3	191.97	4.18	39.7	2.8		
Control	4	214.57	2.80	84	0.083	0.0841	1.31
	5	107.21	1.40	83.8	0.081	0.0801	-1.1
	6	85.988	1.39	56.1	1.39	1.3942	0.3
	7	105.44	0.94	5.5	1.4	1.4067	0.48
	8	105.18	2.29	40	2.79	2.781	-0.32

The results obtained for phase A of the three-phase two-winding 75MVA (110/10kV) generator transformer of Tomsk Power System are presented in table 2.

Table 2. Results of approbation for 75MVA (110/10kV) transformer.

Regime		U_1, kV	I_1, kA	$\varphi_{i1,u1}$, deg.	$\varphi_{u1,u2}$, deg.	$\varphi''_{u1,u2}$, deg.	Δ,%
Basic	1	6.008	3.06	19.9	4.729		
	2	6.001	2.83	14.9	4.549		
	3	6.001	3.24	29.7	4.565		
Control	4	6.078	3.03	22.5	4.631	4.543	-1.94
	5	5.919	2.91	16.6	4.645	4.679	0.74
	6	5.935	2.74	22.2	4.090	4.228	3.25
	7	6.012	2.86	14.6	4.609	4.599	-0.21
	8	6.025	2.71	15.7	4.297	4.325	0.65

Since there were no progressing defects of controlled transformers, the error of the method can be inferred by the values of the deviation Δ, represented in tables 1, 2.

As the table 2 shows, the results, obtained for the transformer from the power system, contain greater errors than the results for the model transformer (table 1). This is because the data have been obtained by means of prefault fault recording system and contain the synchronization error of measuring channels.

5. CONCLUSION

The general results of experiments affirm that the proposed method can be used in an expert monitoring system for on-line condition monitoring of two-winding power transformers windings.

The developed method does not contain weaknesses which inhere in the method of transformer total impedance. Therefore, the implementation of this method, as alternative to the conventional method of short-circuit impedance test, will allow providing more effective control of transformer windings technical condition for a whole range of load regimes.

At the present time the researches for application of a similar approach for the control of three-winding transformer are carried out by the authors.

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