

# On-line Detection of Winding Deformation

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*Abstract:* The problem of on-line control of deformations of transformers windings is stated and the method of their diagnostics is offered. The analysis of the reasons of failures at the decision of this problem earlier is given. The opportunity of simultaneous diagnostics of many other parameters is shown.

## INTRODUCTION

One of the main problems of transformer diagnostics is checking of winding mechanical deformation. At present there are few methods which enable to estimate the said mechanical condition of transformers. Among them is FRA, method of low voltage impulses and some other less well-known methods. Deviation of short circuit resistance ( $\Delta Z_{s.c.}$ ) traditionally remains the main parameter which points out the said defect. However all above mentioned methods require transformer disconnection, which significantly reduces possibility of operative and timely diagnostics. Therefore numerous attempts of measuring  $Z_{s.c.}$  (more exactly  $\Delta Z_{s.c.} = (Z_{s.c.} - Z_{s.c.0}) / Z_{s.c.}$ , where  $Z_{s.c.0}$  is  $Z_{s.c.}$  measured during short circuit test) during transformer operation (without its disconnection) are being known [1-3]. But all attempts of defining this parameter have not given satisfactory results so far. We shall try to analyze main reasons of this negative situation.

## ANALYSIS OF SOURCES OF ERRORS

Any diagnostics procedure is based on some theoretical concept of the process – so called diagnostic model. Using diagnostic model the required parameter, here  $Z_{s.c.}$  (or  $\Delta Z_{s.c.}$ ) is found by method of mathematical calculation and experience. In case [1-3] the model is classic three-polar circuit (fig.1) which forms voltage triangle, two sides of which represent winding effective voltage and the third – magnitude of transformer short circuit voltage  $U_{s.c.} = U_1 - U_2$  where  $U_i$  ( $i=k,1,2$ )- appropriate voltage vectors. The required parameter is  $u_{s.c.} \% = U_{s.c.} \cdot 100 / U_1 = Z_{s.c.} \%$ , where  $U_{s.c.}$ ,  $U_1$  are modules of appropriate vectors.

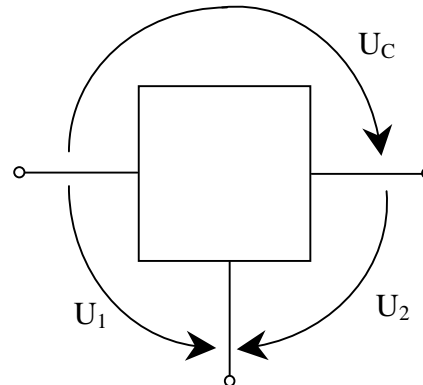


Fig.1

From experience of using such method we have learned that there is, at first sight, unpredictable error of 30% and more. Technical specialists referred the error to accuracy of current and voltage instrument transformers. All further perfection of the method consisted of complication of measuring circuits in order to reduce the said errors. However no positive result has been achieved yet.

By means of theoretical analysis we can show that true reason of the error occurrence and its instability is the imperfection of the theoretical model itself, in particular:

- 1) no allowance that required parameter depends on load value;
- 2) no allowance that required parameter depends on load type (resistive, inductive or capacitive);
- 3) no allowance that measured parameter has non-linear relationship with supply voltage, in other words, it depends on the core magnetizing level.

The third item is most important and error can reach 100% and more from the initial parameter magnitude. We shall analyze the reason of error appearance in details.

## The analysis of the reasons of non-linearity of parameters of dissipation field

There is a tradition to divide transformer electromagnetic field (fig.2) into two components:

main field and dissipation field. Main magnetic flow is coupled with both windings (fig.2). Dissipation magnetic flow is coupled with only one of the windings (fig.2).

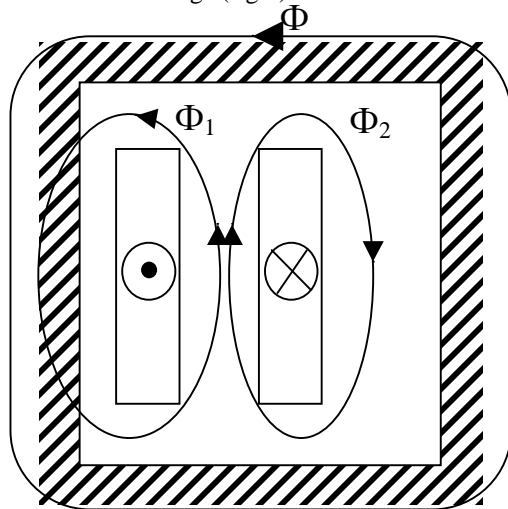


Fig.2

Roughly speaking main flow is concentrated mainly in the core (magnetic media), while dissipation flow – in dissipation channel (non-magnetic media). No-load characteristics (current and losses etc.) refer to the main field, while short circuit characteristics (voltage, resistance and losses) refer to dissipation field. At the same time it is being considered, that no-load characteristics have linear relationship to applied voltage, while short circuit characteristics on the contrary have non-linear relationship to applied voltage. Thus, we can conclude, that required parameter  $Z_{s.c}$  or  $U_{s.c}$  is linear.

There are few arguments in favour of such consideration. Force lines of dissipation field are concentrated mainly in non-magnetic media, which mainly have linear characteristics. With all this we can roughly divide total route of magnetic flow locking into three parts (fig.3a):

- 1) Dissipation channel area ( $R_{M1}$ );
- 2) Non-magnetic area beyond the dissipation channel and the core ( $R_{M2}$ );
- 3) Area inside the core ( $R_{M23}$ );

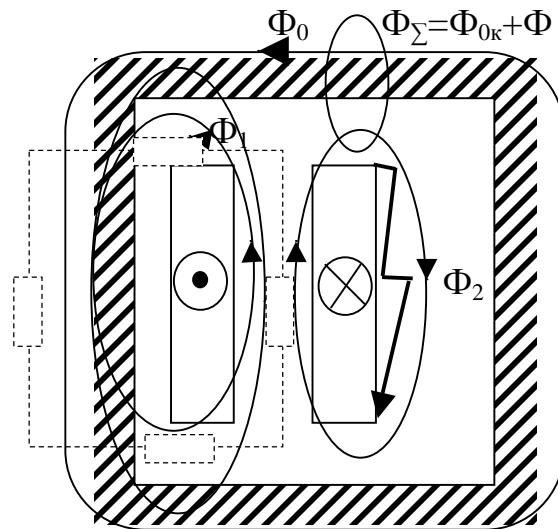


Fig.3a

Model in the form of magnetic circuit if shown on fig.3b.

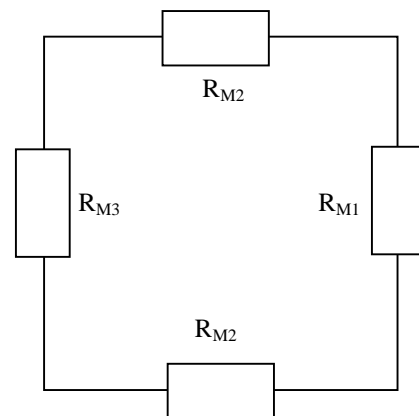
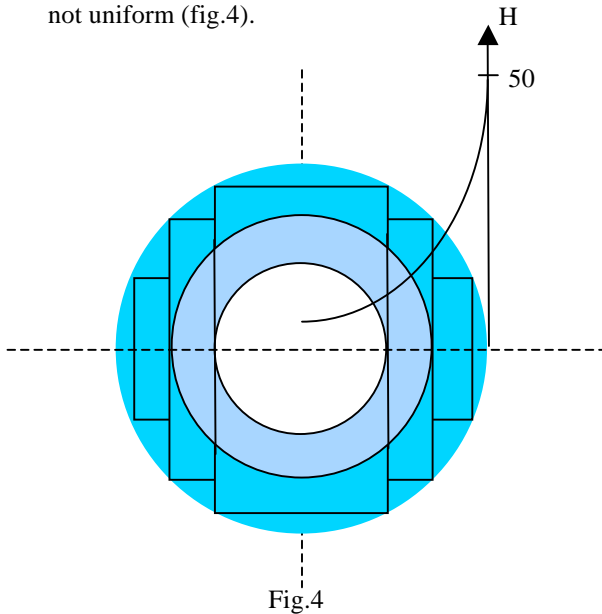


Fig.3b

According to traditional concept main magnetic resistance is concentrated in dissipation channel (domain of big length and little cross-section). Magnetic resistance of the second non-magnetic area is significantly lower because it is domain of little length with big cross-section. Resistance of the core (media with non-linear parameters) is characterized by high magnetic permeability (about  $1000\mu_0$ ), and so its value can be neglected with regard to total magnetic resistance. This is the approximate way of proving the linear relationship of dissipation field parameters in classic theory of transformers.

However, real picture of transformer electric field is much more complicated and qualitative different. At first we shall analyze processes in the core. For better understanding we shall

imagine core cross section as a circle with radius equal to the radius of surrounding circle. According to the law of Bio-Savar-Laplas distribution of magnetic field intensity  $H$  along the magnetic field cross section is distinctly not uniform (fig.4).



Field intensity in the centre and near the edge of the circle may differ in 50 times and more. Consequently distribution of magnetic flow is not uniform also. Experiment proves that induction in the middle and near the edge of the core differs in 5 and more times. This results in not uniform saturation of the core. Extreme laminations are in condition of deep saturation, while central ones have little saturation. Furthermore, we can surmise, that different domains of laminations are saturated differently. Parameters of saturated domains are practically linear and magnetic resistance increases sharply. This results in reducing of resulting magnetic dissipation flow (comparing to dissipation flow at short circuit), and consequently in reducing of the transformer total electric resistance  $Z_t$ . As according to traditional concept the transformer equivalent electric resistance in loaded condition is considered to be equal to short circuit resistance  $Z_{s.c.}$ , as a result we have error, that can reach 100% and more.

Now let us analyze non-linearity of resistance  $Z_t$  features. Bearing in mind the above mentioned, required diagnostic parameter is now  $Z_t$ , as it is equivalent to loaded transformer condition. One can see, that depth of saturation of various laminations depends on magnetizing current, which in its turn has non-linear relationship with applied voltage. Thus dissipation flow and, consequently, resistance  $Z_t$  have non-linear relationship from the voltage value.

There is one important consideration. One can see from experiments, that in short circuit condition transformer electric resistance  $Z_{s.c.}$  is practically linear. It is caused by the fact, that in short circuit condition transformer is not saturated. This means that short circuit condition is not adequate to loaded transformer condition. Therefore, while solving diagnostic problem of  $Z_t$  determination at operating transformer it is necessary to compare it with basic value of resistance, which is measured on certainly good unit in loaded condition. In another method loaded condition is approximated to short circuit condition. All this makes diagnostic problem much more difficult.

## THEORETICAL BASES OF THE OFFERED DIAGNOSTIC APPROACH [4]

### Statement of the problem

Let us specify our problem. We need to determine:

- 1) equivalent electric resistance  $Z_t$  of operating transformer, which is equal to short circuit resistance of saturated transformer;
- 2) approximate the measured value of  $Z_t$  to short circuit condition, i.e. make correction for non linearity of the measured parameter;
- 3) total error should exceed 2%.

The last term is stipulated by the fact that according to the Russian standard tolerance for short circuit resistance is 3%. Now we shall consider three ways of solving of the said problem.

### Diagnostic model

As diagnostic model of single-phase two-winding transformer we take classic model of four-polar circuit (bipolar circuit in American technical literature). From mathematical point of view we can represent transformer as four-polar circuit with system of equations, binding the values of winding current and voltage. Coefficients at current and voltage values in said equations have distinct physical meaning and theoretically can be used for calculation of all traditional parameters of short circuit and open circuit conditions (here we mean artificial short circuit condition of saturated transformer) and some other characteristics. Thus, we can consider these coefficients as diagnostic parameters, which reflect technical condition of transformer, including mechanical condition of its windings. Most of the above coef-

ficients are not linear. Specified above problem of transformer diagnostics is reduced in fact to the problem of determination of these new diagnostic parameters.

We can determine the coefficients of system of equations of four-polar circuit by the method of theory of electric circuits, in particular, diagnostics of electric circuits. To find all four required elements we need to make up a system of four equations. It can be formed on basis of the results of measurements of winding current and voltage in two operating conditions (at two load values). The difference of these two load values should be at least 10 %. At the same time stability of supply voltage is very important, as it provides the same saturation level of the core in two conditions. Expressions for all required diagnostic parameters for different variants of system of equations are given in tables 1 and 2. It shall be noted, that the above problem is rather difficult and laborious in mathematical (calculating) aspect, but it needs separate and special consideration. We shall only note here, that many factors were taken into account during the research process, in particular:

- non-linearity of transformers;
- not sinusoidal form of current and voltage;
- lack of information (insufficient number of measurements or their uncertainty);
- various numbers of winding and phases of transformers;
- strict requirements for quickness of solving of the diagnostic problem and some other factors.

### Estimation of the error

We shall touch the problem of estimating of the error of derivable solution. Such estimation can be derived using the linear theory of errors. Estimation value depends on accuracy of instrument current and voltage transformers and on computation error of solving the equation system. It being considered, that computation error can be minimized due to proper processing of measurement data, then resulting error can be estimated as the sum of errors of instrument current and voltage transformers.

The problem of approximating of derived solution (in particular,  $Z_t$ ) to short circuit condition is to be discussed separately. Such approximation can be performed by multiplying of  $Z_t$  on some coefficient of non-linearity  $\chi$  ( $\chi Z_t = Z_{s.c.}$ ). Coefficient of non-linearity can be determined in different ways. For example, using instant values of current and voltage.

Consequence shall be as follows:

1. According to measurement data we shall plot volt-ampere loop relationship (VAR) for one period of current and voltage variation (fig.5).

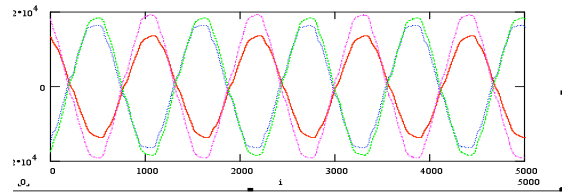


Fig.5

2. One-valued (not loop) VAR for instant values is found by calculation (fig.6).

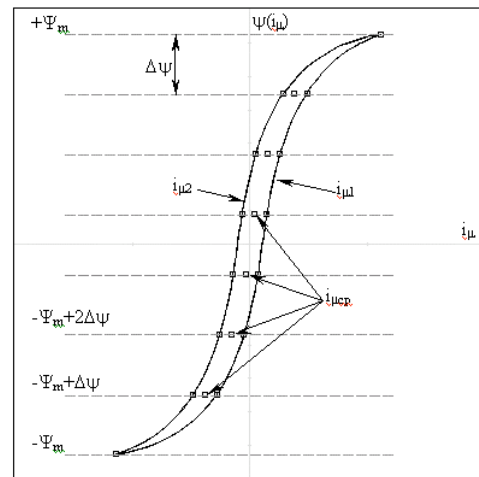


Fig.6

3. VAR for effective values is determined by calculation (fig.7).
4. The amplitude and phase of complex coefficient of non-linearity  $\chi$  is calculated by two points of VAR.

It is to be noted, that the above method enables to determine not only  $Z_{s.c.}$  and its variation, but some other electro-magnetic parameters, which are necessary for complex estimation of transformer condition.

### CONCLUSIONS

To prove the developed method by experiments a prototype of diagnostic device was designed and experiments were performed on physical model of transformer. Verification proved effectiveness of the method and helped in its improving.

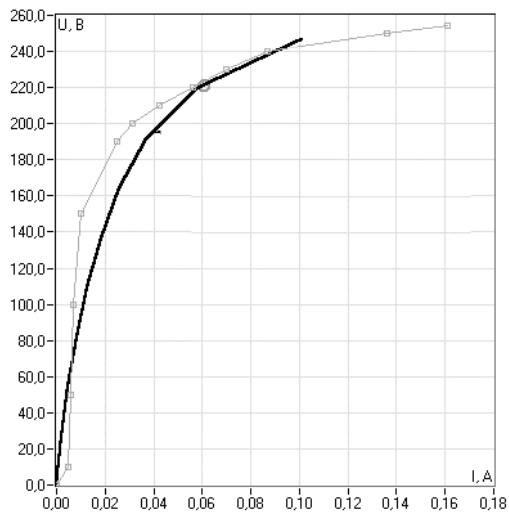


Fig.7

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