Application of power transformer winding admittance measurements for FRA interpretation

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SUMMARY

Frequency response analysis (FRA) is widely used to assess the mechanical and electrical condition of windings of power transformers and shunt reactors. The requirements on FRA measurement method and equipment have been standardized in IEC 60076-18. However, there are still a lot of issues with interpretation of FRA measurement results.

It is well known that electrical and severe mechanical faults of certain transformer winding lead to significant changes in winding frequency responses obtained from FRA measurements. In general, transformer winding under measurement is coupled with other windings, which influences the obtained frequency responses and complicates the assessment of the winding condition. In this report, using the transformer representation in the form of a multiterminal circuit, defined by the admittance matrix, it is shown that the frequency responses measured with the standard schemes are determined by a complex combination of admittances of the measured winding and other windings coupled with it. It is also shown that the mutual influence of the windings can lead in practice to an incorrect condition assessment of individual phases of the delta-connected windings.

The report discusses the use of non-standard measurement schemes, including the schemes for measuring elements of the windings admittance matrix, with the aim of obtaining additional diagnostic information and improving the interpretation of FRA measurement results.

KEYWORDS

Power transformers, condition assessment, frequency response, frequency response analysis, FRA interpretation.

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1. INTRODUCTION

For many years Frequency response analysis (FRA) is widely used to assess the mechanical and electrical condition of windings of power transformers and shunt reactors.

Requirements on FRA measurement method and equipment have been standardized in IEC 60076-18 [1]. To date, a lot of experience has been gained in the field of FRA interpretation [1 – 3]. However, many issues remain regarding the interpretation of FRA measurements. Developing an objective methodology for the interpretation of FRA measurements is the main goal of CIGRE working group A2.53.

In practice the comparison of frequency responses with the use of correlation analysis and various indices showing the differences in the frequency responses in a wide frequency range has become widespread [3 – 4]. Alternatively the interpretation of the FRA measurements with respect to winding type and its design peculiarities can be made using analysis of winding natural frequencies [5 – 7], since electrical and severe mechanical winding damages lead to significant changes in the winding natural frequencies.

The natural frequencies of a stand-alone winding can be easily obtained from frequency response measurements, since the measured resonant frequencies correspond to the natural frequencies of the winding. However, if there are several windings on the same magnetic core, the frequency response of a particular winding, obtained by measurements with end-to-end scheme according to IEC 60076-18, has additional resonant frequencies associated with the following interaction between coupled windings:

1) electromagnetic coupling between windings – leads to appearing of additional resonance peaks in the mid-frequency range of frequency responses;

2) capacitive coupling between windings – if the primary winding is measured via standard end-to-end scheme, the secondary winding becomes under a floating potential; as a result, there is a capacitive current component through the measuring impedance of the FRA device, caused by current flowing from the floated secondary winding and other ungrounded metal parts [7];

3) electrical connection between windings – series connection of two or more windings can lead to changes in the resulting resonant frequencies compared to the resonant frequencies of individual windings.

The presence of components from other windings in the frequency response of a particular winding makes it difficult to interpret the results of frequency response measurements and to assess the condition of the measured winding.

The contribution of the electromagnetic and capacitive coupling between the windings can be identified using the method of identification of windings natural frequencies [5 – 6] based on the comparison of measured winding frequency responses with open- and short-circuited secondary winding and on the detection of coincident resonant frequencies with calculation of the active component of winding admittance. In practice the use of this method makes it possible to identify the natural frequencies of helical- and disc-type windings, including windings with large series capacitance, for which the resonance peaks at natural frequencies may not be evidently seen in the original frequency response.

The effect of capacitive coupling between the windings can be eliminated by conducting measurements with short-circuited and earthed secondary windings, which have floating potential in standard measurement schemes.

The situation is different with the contribution of the electrical connection between the windings. The transformer windings can be delta-connected, and in this case the measurements with standard end-to-end scheme according to IEC 60076-18, both with open- and short-circuited secondary windings, give a complex frequency response of three phases simultaneously, despite the fact that it is measured by connecting only to two line terminals. Other examples are series-connected windings (e.g., autotransformer windings connection) and star-connected windings without neutral brought out.

In general, the presence of electrical connection between windings leads to smoothing of frequency response deviations in the case when some resonant frequencies have changed as a result of damage in one phase of a three phase winding.

A typical example of the influence of electrical connection is the parallel connection of windings placed on different magnetic cores. In [7] it is shown that if there is a damage in one of the parallel windings, the new resonance frequencies or double resonance peaks appear in the frequency response.

2. A PRACTICAL EXAMPLE – FREQUENCY RESPONSES OF DELTA-CONNECTED WINDING

The results of frequency response measurements of a distribution transformer 630 kVA 10/0,4 kV (figure 1) with winding connection Yyn0 and Dyn11 are presented below.

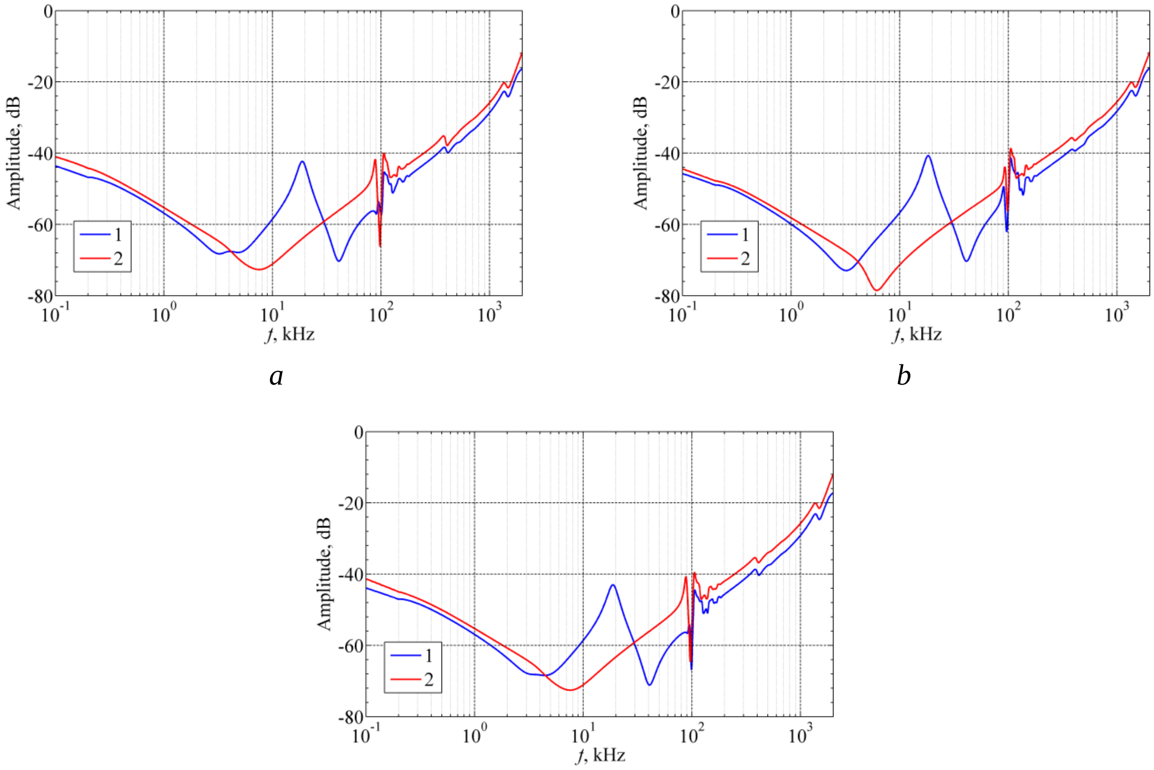
Figure 1 – Distribution transformer 10/0,4 kV under measurement

The frequency responses of high voltage (HV) winding were measured according to the standard schemes with open- (HVOC) and short-circuited (HVSC) low voltage (LV) winding.

Figure 2 shows that frequency response of certain phase of delta-connected winding is significantly different from the original frequency response of a single phase of the HV winding: there are new resonance peaks and a shift of the frequency response along the vertical axis.

To imitate the winding damage, a short-circuit jumper was installed at the terminals of the first disc of phase “A” in HV winding. The obtained frequency responses for delta-connected HV winding are shown in figure 3.

As it can be seen from figure 3, in case of short circuit in the phase “A” in HV winding which ends are connected to terminals A and B (Dyn11), the most significant changes occurred in the frequency response measured from terminal B to terminal C. In practice it can lead to an erroneous assumption on the presence of a fault in the phase “B” of HV winding which is connected to terminals B and C.



a

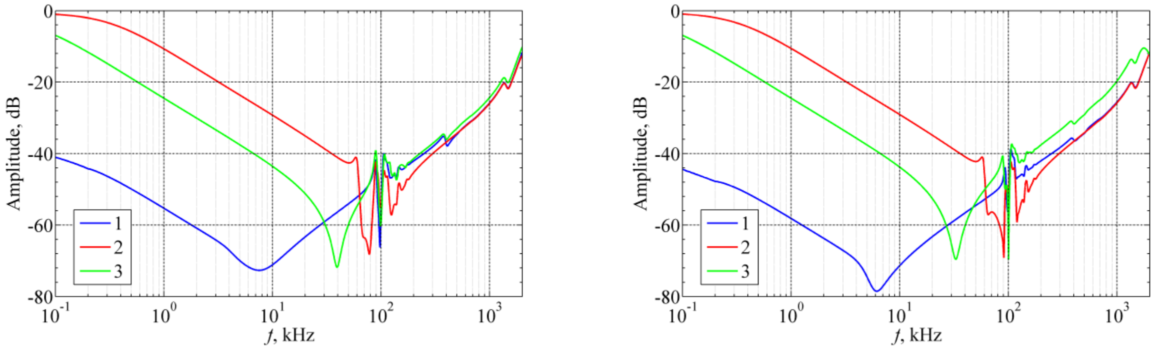
b

c

Figure 2 – HVOC frequency responses of star- (1) and delta-connected (2) HV winding:

a – between terminals A-N (1) and A-B (2); *b* – between terminals B-N (1) and B-C (2);

c – between terminals C-N (1) and C-A (2).



a

b

Figure 3 – Frequency responses of delta-connected HV winding measured between line terminals A-B (*a*) and B-C (*b*) with open- and short-circuited LV winding

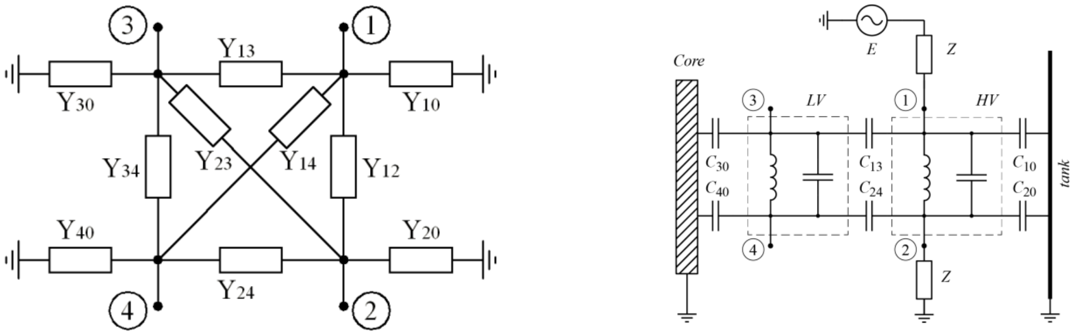
1 and 2 – HVOC и HVSC without short-circuit jumper in phase “A”;

3 – HVOC with short-circuit jumper in phase “A”.

3. WINDING ADMITTANCE MATRIX

The results presented above can be explained using the representation of a transformer in the form of multiterminal circuit (“black box” model) and a windings admittance matrix [8].

Let us consider this in more detail on the example of a simplified equivalent scheme of a two-winding transformer (figure 4).



а

б

Figure 4 – Simplified equivalent schemes of a two-winding transformer

Using the scheme of figure 4*a* the voltage ratio U_2/U_1, obtained in case of applying the source voltage U_1 to terminal “1” and measuring the output voltage U_2 at terminal “2” via measuring impedance Z, can be expressed as:

$$\frac{\dot{U}_2}{\dot{U}_1} = \frac{\dot{Y}_{12}(\dot{Y}_{33}\dot{Y}_{44} - \dot{Y}_{34}{}^2) + \dot{Y}_{23}(\dot{Y}_{34}\dot{Y}_{14} + \dot{Y}_{13}\dot{Y}_{44}) + \dot{Y}_{24}(\dot{Y}_{33}\dot{Y}_{14} + \dot{Y}_{34}\dot{Y}_{13})}{\dot{Y}_{33}\dot{Y}_{44}\dot{Y}'_{22} - \dot{Y}_{33}\dot{Y}_{24}{}^2 - \dot{Y}_{44}\dot{Y}_{23}{}^2 - 2\dot{Y}_{34}\dot{Y}_{23}\dot{Y}_{24} - \dot{Y}'_{22}\dot{Y}_{34}{}^2} \tag{1}$$

where $\dot{Y}'_{22} = \dot{Y}_{22} + 1/Z$.

From the equation (1) it can be seen that when one of the windings is measured according to the standard measurement scheme, the obtained voltage ratio U_2/U_1, that is defined as frequency response, is determined by a complex combination of admittances, which in addition to the admittance of the measured winding Y_{12} includes admittances associated with the secondary winding (Y_{33}, Y_{34}, Y_{44}).

When the secondary winding is short-circuited, the corresponding admittance Y_{34} is shunted, and the equivalent circuit becomes slightly simplified (figure 5). The equation for the voltage ratio U_2/U_1 of the primary winding takes the form:

$$\frac{\dot{U}_2}{\dot{U}_1} = \frac{\dot{Y}_{12}\dot{Y}'_{33} + \dot{Y}'_{13}\dot{Y}'_{23}}{\dot{Y}'_{22}\dot{Y}'_{33} - \dot{Y}'_{23}{}^2} \tag{2}$$

where $\dot{Y}'_{13} = \dot{Y}_{13} + \dot{Y}_{14}$; $\dot{Y}'_{22} = \dot{Y}_{22} + 1/Z$; $\dot{Y}'_{23} = \dot{Y}_{23} + \dot{Y}_{24}$; $\dot{Y}'_{33} = \dot{Y}_{30} + \dot{Y}_{40} + \dot{Y}_{13} + \dot{Y}_{14} + \dot{Y}_{23} + \dot{Y}_{24}$.

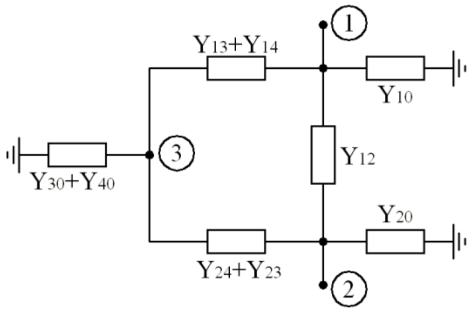


Figure 5 – Equivalent scheme corresponding to short-circuited secondary winding

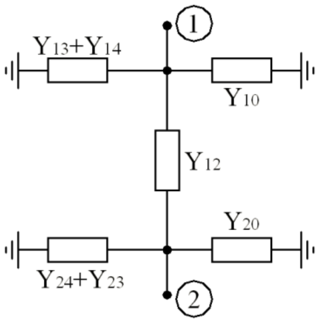


Figure 6 – Equivalent scheme corresponding to short-circuited and earthed secondary winding

In the case of earthed secondary winding, the equivalent scheme (figure 6) and the equation for the frequency response become even more simple:

$$\frac{\dot{U}_2}{\dot{U}_1} = \frac{\dot{Y}_{12}}{\dot{Y}'_{22}} \tag{3}$$

where $\dot{Y}'_{22} = \dot{Y}_{20} + \dot{Y}_{23} + \dot{Y}_{24} + \dot{Y}_{12} + 1/Z$.

Using the measured frequency responses, the admittance of winding under measurement $\dot{Y}_{FRA}$ can be evaluated as the ratio of the winding current $I_{12} = U_2 / Z$ and voltage $U_{12} = U_2 - U_1$. It can be shown from equation (3) that the admittance obtained this way is also the combination of self and mutual admittances:

$$\dot{Y}_{FRA} = \frac{\dot{U}_2}{(\dot{U}_1 - \dot{U}_2)Z} = \frac{\dot{Y}_{12}}{Z(\dot{Y}_{20} + \dot{Y}_{23} + \dot{Y}_{24} + 1/Z)}\,, \tag{4}$$

which is approximately equal to the self-winding admittance Y_{12} only if $|Y_{20} + Y_{23} + Y_{24}| << 1 / Z$.

For the simplified equivalent scheme of figure 4b, in which the admittances Y_{20}, Y_{23} and Y_{24} are determined by the capacitances of the primary winding to earth and to the secondary winding, the ratio can be written as $2\pi f \cdot (C_{20} + C_{23} + C_{24}) << 1 / Z$. Capacitances of windings to earth and between windings of oil-immersed power transformers are typically in the order of several nF. To estimate the boundary frequency, let us assume $C_{20} + C_{23} + C_{24} \leq 10$ nF. So $2\pi f \cdot 10^{-8} << 1 / 50 = 0{,}02$ or $f <<$ 320 kHz. Thus the matching of the result obtained from equation (4) with winding admittance Y_{12} can be expected in frequency range up to few hundreds of kHz, while at higher frequencies the contribution of the capacitances to earth and between windings leads to differences between Y_{FRA} from Y_{12}. This should be taken into account when measured frequency responses are used to calculate the admittance and impedance of the windings.

When the measured winding is delta-connected, the frequency responses measured by standard end-to-end scheme are determined by the combination of the admittances of all three phases. For two-winding transformer with connection scheme Dyn11 the admittance matrix has a dimension of 7 by 7. Due to the large dimension of the admittance matrix, the derivation of the equation for the frequency response of a phase of the HV winding with open-circuited LV winding is difficult. So, the equations only for the case of short-circuited and earthed LV winding (figure 7) are given below.

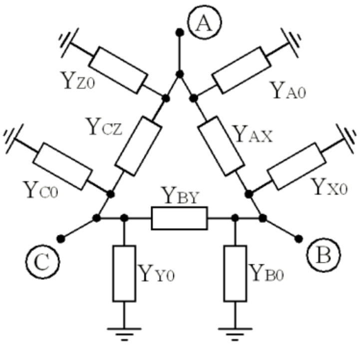


Figure 7 – Equivalent scheme of delta-connected HV winding

In matrix form the relations between currents and node voltages can be written as:

$$\begin{bmatrix} \dot{Y}_{AA} & -\dot{Y}_{AX} & -\dot{Y}_{CZ} \\ -\dot{Y}_{AX} & \dot{Y}_{BB} & -\dot{Y}_{BY} \\ -\dot{Y}_{CZ} & -\dot{Y}_{BY} & \dot{Y}_{CC} \end{bmatrix} \cdot \begin{bmatrix} \dot{U}_A \\ \dot{U}_B \\ \dot{U}_C \end{bmatrix} = \begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix}, \tag{5}$$

where $\dot{Y}_{AA} = \dot{Y}_{A0} + \dot{Y}_{AX} + \dot{Y}_{Z0} + \dot{Y}_{CZ}$; $\dot{Y}_{BB} = \dot{Y}_{B0} + \dot{Y}_{BY} + \dot{Y}_{X0} + \dot{Y}_{AX}$; $\dot{Y}_{CC} = \dot{Y}_{C0} + \dot{Y}_{CZ} + \dot{Y}_{Y0} + \dot{Y}_{BY}$.

Assuming $\dot{U}_A = 1$ and excluding first row in the matrix equation (5), the following system of equations can be obtained:

$$\begin{bmatrix} \dot{Y}_{BB}' & -\dot{Y}_{BY} \\ -\dot{Y}_{BY} & \dot{Y}_{CC} \end{bmatrix} \cdot \begin{bmatrix} \dot{U}_B \\ \dot{U}_C \end{bmatrix} = \begin{bmatrix} \dot{Y}_{AX} \\ \dot{Y}_{CZ} \end{bmatrix},$$

where $\dot{Y}_{BB}' = \dot{Y}_{BB} + 1/Z$, from which the equation for winding terminal voltage ratio can be found:

$$\frac{\dot{U}_B}{\dot{U}_A} = \frac{\dot{Y}_{AX}\dot{Y}_{CC} + \dot{Y}_{BY}\dot{Y}_{CZ}}{\dot{Y}_{BB}' \cdot \dot{Y}_{CC} - \dot{Y}_{BY}^{2}} \tag{6}$$

Similarly the equations for voltage ratios at other terminals can be written:

$$\frac{\dot{U}_C}{\dot{U}_B} = \frac{\dot{Y}_{BY}\dot{Y}_{AA} + \dot{Y}_{CZ}\dot{Y}_{AX}}{\dot{Y}_{CC}' \cdot \dot{Y}_{AA} - \dot{Y}_{CZ}^{2}} \tag{7}$$

$$\frac{\dot{U}_A}{\dot{U}_C} = \frac{\dot{Y}_{CZ}\dot{Y}_{BB} + \dot{Y}_{AX}\dot{Y}_{BY}}{\dot{Y}_{AA}' \cdot \dot{Y}_{BB} - \dot{Y}_{AX}^{2}} \tag{8}$$

From equations (6) – (8) it follows that the frequency responses of delta-connected winding, measured according to standard schemes, are the sum of the products of the winding admittances of the measured phase and other phases, which explains the results shown above in figure 3.

4. APPLICATION OF THE WINDING ADMITTANCE MATRIX FOR INTERPRETATION OF FRA MEASUREMENTS AND RECOMMENDATIONS FOR MEASUREMENT SCHEMES

From the comparison of equations (1) – (3) it follows that in case of measurement according to standard schemes the obtained frequency responses are determined by a combination of admittances corresponding not only to the measured winding, but also to other windings associated with it. To reduce the mutual influence of neighboring windings on the measured frequency response of a certain winding, it is preferable to use schemes with short-circuited secondary windings. Additional reduction of mutual influence can be achieved if the secondary windings are both short-circuited and earthed.

It is important to note that presently the use of schemes with earthed secondary windings is not standardized by IEC 60076-18, and such schemes are not widely used in practice. It seems appropriate to consider the application of such measurement schemes in the subsequent revision of IEC 60076-18.

For the purposes of FRA interpretation, the measurements of elements of winding admittance matrix are also of interest, since such measurements can provide additional diagnostic information in cases where it is necessary to analyze the transformer winding condition in more detail.

In [8] it was shown that measurements of the winding admittance matrix elements can be performed using the conventional FRA measuring system and non-standard measurement schemes. In general, the admittance matrix has dimension *N* x *N*, where *N* is the number of line terminals of the transformer. In the case of a two-winding transformer with YNd winding connection the dimension of the admittance matrix is 7 x 7, and computation of all matrix elements will require 7·7 = 49 frequency response measurements, which is time consuming. Therefore, it is impractical to carry out such measurements in all cases. However, it can be performed in certain cases where additional diagnostic information is required to identify the damaged phase winding and to assess the type and scale of its damage.

If the condition of one of the transformer delta-connected windings, for instance, needs to be investigated in more detail, the number of measurements can be reduced by eliminating the measurement of admittances associated with the line terminals of other windings. The analysis requires mainly the admittance of the winding under test, which requires two measurements per phase. Thus, for a delta-connected winding the measurements of only 6 admittances will be required, namely, Y_{AA}, Y_{AX}, Y_{BB}, Y_{BC}, Y_{CC} and Y_{CA}, so, the desired admittances of the phases of the studied winding (Y_{AX}, Y_{BC} and Y_{CA}) can be obtained without a significant increase in the number of measurements.

CONCLUSIONS

1. The frequency responses of the windings obtained by standard measurement schemes are determined by a combination of winding admittances, which, in addition to the admittances of the measured winding, includes the admittances associated with secondary windings. The contribution of the secondary windings can be reduced by performing measurements using non-standard schemes with these windings being short-circuited and earthed.

2. For a delta-connected winding, the measured frequency responses are determined by a combination of admittances of all three phases, which complicates the phase-by-phase analysis of the frequency responses and needs to be taken into account during FRA interpretation

3. The non-standard schemes for measuring the elements of the admittance matrix can be used to obtain additional diagnostic information in order to improve the interpretation of FRA measurement results.

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