A NOVEL METHOD TO MEASURE RATIO AND NON-STANDARD PHASE DISPLACEMENTS OF SPECIAL TRANSFORMERS USING A SINGLE-PHASE SUPPLY AND MERITS OF USING HIGHER TEST VOLTAGE

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Abstract: Three-phase voltage supplies together with phase vector meters have been traditionally used for measuring voltage ratio of transformers having non-standard phase displacements. Non-standard phase displacements refer to phase-shifts that do not follow 30° clock steps (example, -7.5°, 22.5°, etc). Some examples being: phase-shifters, rectifier, arc-furnace, quad-boosters and traction transformers. In the new method, instead of using a 3-phase voltage supply, 3-phase equivalent voltages are simulated at different terminals of a transformer by energising a pair of the terminals and interconnecting certain other terminals in a custom defined manner to generate the necessary 3-phase equivalent voltages. This permits determination of the ratio and phase displacement using common ratio bridges, which use single-phase voltage supplies. In the first part of the paper, theoretical background of this method and results obtained from the field to validate this approach are presented. In the second part of the paper, it is shown analytically as to how the test voltage level can affect the flux distribution in the transformer and ultimately the measured ratio accuracy. This is followed by a presentation of a few field results to show how the test voltage plays a significant role on the measurement accuracy, which hitherto is unknown to many in the industry.

Introduction

Transformer ratio measurement is one of the frequently used tests in the industry as a part of the factory acceptance tests mandated in the standards, before the transformer is put to service and as a valuable diagnostic test.

Ratio and phase displacement measurements of special transformers having non-standard phase-displacements have been traditionally practised by using either a cumbersome combination of three phase voltage source and phase vector meter or a specially designed three-phase ratio bridge. Both these solutions necessitate the use of a three-phase AC voltage supply or 1-phase to 3-phase voltage supply converter. Having the necessity for a 3-phase supply is disadvantageous because it is usually difficult to source one during field tests. The solution with an additional kit to generate 3-phase supply from a 1-phase source means extra hardware and is equally inconvenient.

In the first part of this paper, an alternate approach of achieving the ratio and non-standard phase displacement using a single-phase 90-265V supply is described. This discussion starts with the basic principle of working of a single-phase ratio bridge, the conditions that need to be satisfied for the principle to work and why the standard technique is insufficient when non-standard phase-displacements have to be measured. This is followed by an elaboration of the theoretical basis of the new method and field measurement results of some representative special type transformers.

The second part of the paper is about how the test voltage used for ratio measurements on large power transformer plays a significant role on the measured accuracy, which is unknown to many in the industry.

The IEEE standard [1] states that when rated voltage is applied to one winding of the transformer, all other rated voltages at no load shall be correct within one half of one percent (± 0.5%) of the nameplate readings Similar requirements are spelt out in the IEC 60076-1 standard [2].

Over the years, some of our customers have reported that for large power transformers (> 100 MVA) where use of tertiary windings is either mandatory or prevalent, using a higher test voltage leads to a better accuracy in the ratio results. Upon further investigations and several field measurements at large power transformer test laboratories, the findings were that higher test voltage indeed leads to a better accuracy and has a technical basis as explained later in this document.

During the period of our field investigations at large power transformer factories, there were few instances of transformers with a tertiary winding failing to meet the ± 0.5% tolerance, if tested at 100 V and the same tested at a higher voltage

(250 V [3]) gives a result within the tolerance limit prescribed in the standards.

Some transformer manufacturers, who were aware of this phenomenon, practised a combination of 3-phase excitation voltage and an arrangement of 2 to 6 multi-meters connected to different transformer bushing terminals to simultaneously read the voltages of several multi-meters and calculate the ratio. The accuracy of this method depended on how accurately the multi-meters were synchronized with each other and the measurement accuracy of the used meters.

Finally at the end of the second part of this paper, directly after the analytical explanation as to how the test voltage level affects the measured ratio accuracy, a presentation of several field results is given to show how the test voltage plays a significant role on the measurement accuracy, which hitherto is unknown to many in the industry.

1 RATIO AND ANGLE MEASUREMENT OF TRANSFORMERS HAVING NON-STANDARD PHASE-ANGLES

1.1 Basic working principle of a single-phase ratio bridge.

The basic working principle of single-phase ratio meters is illustrated in figure 1.

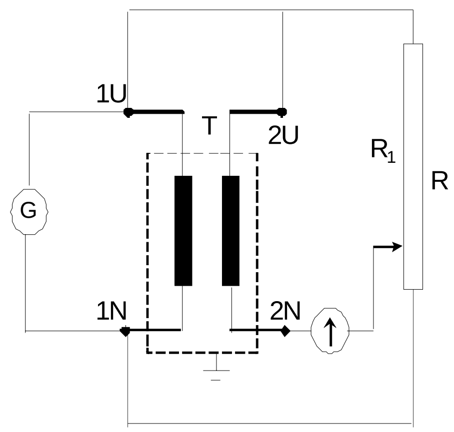

Fig. 1: Simplified illustration of a 1-ph ratio bridge

The high and low voltage windings are connected in phase opposition by decade resistances (for the case shown) and voltages are compensated. When the bridge is balanced, the load on the transformer is either very light or negligible and the turns ratio equals $U_{2U\text{-}2N}$ / $U_{1U\text{-}1N}$.

1.2 Conditions imposed by the classical single-phase ratio bridge

Turns ratio measurement of a three-phase transformer using the classical single-phase ratio bridge is possible only if the following conditions are met:

1. The applied magnetic flux should link all the windings, winding segments and their combinations.
2. All necessary winding terminals should be available externally either for measurement or interconnection.
3. External interconnections don’t lead to short circuits with internal bridge terminals.

1.3 Limitations of classical single-phase ratio bridge

An example case, of a locomotive transformer having arbitrary phase shift is illustrated in figure 3. This represents a case where the classical single-phase ratio bridge cannot be used, as it does not meet all the conditions elaborated in the preceding section.

1. In the example shown, all the windings are linked by the same magnetic flux (through the core).
2. In the example shown, for turns ratio measurements between the primary and secondary winding, terminals 2U’, 2V’, 2W’ and 3U’, 3V’ and 3W’ are not externally accessible.
3. Some external interconnections lead to short-circuit with the internal terminals of the bridge.

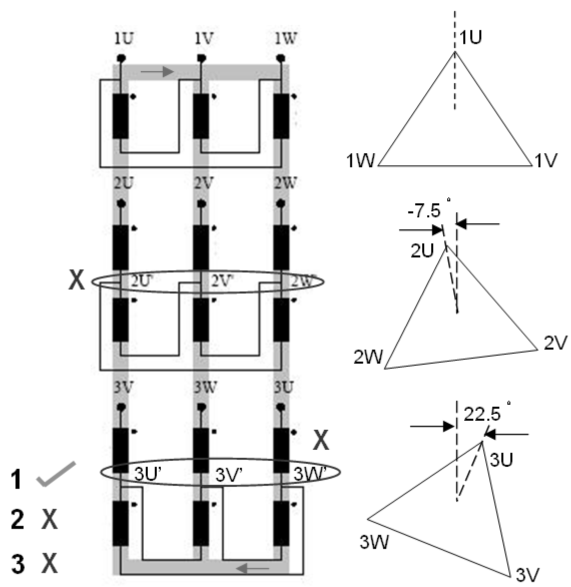

Fig. 2: Locomotive Transformer having vector group Dd11.75d0.75

1.4 New Method

In the alternate approach, instead of using a 3-phase supply, 3-phase-equivalent voltages are simulated at different terminals of the transformer by energising a pair of the terminals and interconnecting certain other terminals in a custom defined manner to generate the necessary 3-phase equivalent voltages. This permits determination of the ratio and phase displacement using a classical single-phase ratio bridge.

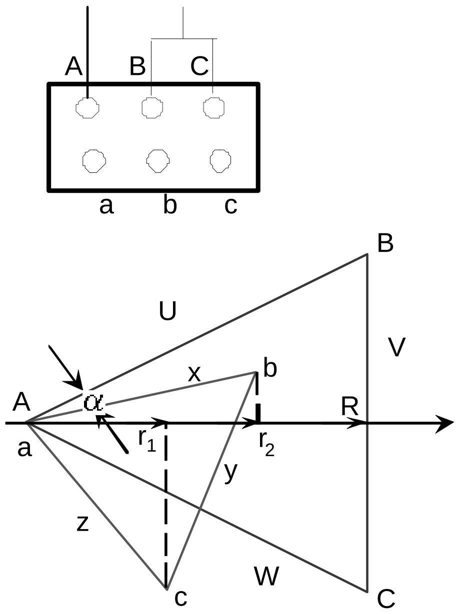

Fig. 3: Illustration of the alternate approach

For a symmetric 3-ph system,

$$|U| = |A - B| = |V| = |B - C| = |W| = |C - A|$$

and $|x| = |a - b| = |y| = |b - c| = |z| = |c - a|$

with 1-phase measurements, where B and C are short-circuited and the voltage is applied between A-[B-C], then following 3-phase equivalent voltages are generated.

$$|U| = \frac{R}{\cos\frac{\pi}{6}} \quad |x| = \frac{r_2}{\cos\left\{\frac{\pi}{6} - \alpha\right\}} \quad |z| = \frac{r_1}{\cos\left\{\frac{\pi}{6} + \alpha\right\}}$$

Ratio = $\frac{|U|}{|x|} = \left|\frac{U}{z}\right|$

1.5 Measurements on a phase-angle controlled 240MVA 220/115kV Auto-transformer

This is an example of a special transformer, where the power transfer is regulated by changing both the ratio and phase-angle. In contrast to quad-boosters where the winding pair is in phase-quadrature and fixed, here it is at an angle, so the power transfer involves both ratio and angle changes. Furthermore, the angles at both the extreme tap positions do not have the same value.

Table 1 below summarizes the design values of ratio and phase-displacements for different tap positions. As, can be seen the phase-angle ranges between -8.03° to +6.92°.

Table 1

		HV nom	LV nom	Design Values	
Tap		(kV)	(kV)	Ratio	Angle, (deg)
1	retard	238.220	115	2.0715	6.92
8	retard	229.844	115	1.9990	4.03
17	mid	220.000	115	1.9130	0
18	advance	218.976	115	1.9041	-0.47
19	advance	217.967	115	1.8954	-0.94
33	advance	205.497	115	1.7869	-8.03

The measured values of the ratio and phase angle at a test voltage of 250V are shown in Table 2. The ratio and phase deviations are respectively less than +/- 0.14% and +/- 0.05°.

Table 2

Phase A	Design		Measured		Deviation	
Tap	Ratio	Angle, deg.	Ratio	Angle, deg.	Ratio	Angle, deg
1	2.0715	6.92	2.0711	6.90	0.02	-0.02°
8	1.9990	4.03	2.0006	4.06	-0.08	-0.03°
17	1.9130	0	1.9128	0.05	0.01	+0.05°
18	1.9041	-0.47	1.9024	-0.49	0.09	-0.02°
19	1.8954	-0.94	1.8948	-0.98	0.03	-0.04°
33	1.7869	-8.03	1.7848	-8.07	0.12	-0.04°

Phase B	Design		Measured		Deviation	
Tap	Ratio	Angle, deg.	Ratio	Angle, deg.	Ratio	Angle, deg
1	2.0715	6.92	2.0739	6.90	-0.12	-0.02°
8	1.9990	4.03	2.0000	4.06	-0.05	-0.03°
17	1.9130	0	1.9145	0.05	-0.08	+0.05°
18	1.9041	-0.47	1.9062	-0.49	-0.11	-0.02°
19	1.8954	-0.94	1.8961	-0.98	-0.04	-0.04°
33	1.7869	-8.03	1.7872	-8.07	-0.02	-0.04°

Phase C	Design		Measured		Deviation	
Tap	Ratio	Angle, deg.	Ratio	Angle, deg.	Ratio	Angle, deg
1	2.0715	6.92	2.0719	6.90	-0.02	-0.02°
8	1.9990	4.03	2.0001	4.06	-0.06	-0.03°
17	1.9130	0	1.9117	0.05	0.07	+0.05°
18	1.9041	-0.47	1.9014	-0.49	0.14	-0.02°
19	1.8954	-0.94	1.8958	-0.98	-0.02	-0.04°
33	1.7869	-8.03	1.7853	-8.07	0.09	-0.04°

2 INFLUENCE OF TEST VOLTAGE ON RATIO MEASUREMENT ACCURACY

2.1 Analytical Explanation

Why higher test voltage is needed for accurately measuring the voltage/turns ratio of a large transformer is analytically explained hereafter. In the derivation that follows, consider the case of a three winding transformer with a delta connected tertiary. Figure 4 shows a simplified dimensional representation of a three-winding transformer. The middle-limb has been omitted for simplicity. The winding close to the iron-core is the tertiary winding, the middle winding and the outermost is the high voltage winding.

Two Leakage fluxes - $\varphi_{\lambda1}$, $\varphi_{\lambda2}$ and mutual fluxes φ_{21}, φ_{12} are shown respectively as closely spaced (red) and widely spaced (blue) dotted lines. Assume that the transformer has a core of magnetic material whose permeability is constant. With this assumption, the principle of superposition can be applied, and the resultant flux linking each winding can be expressed as the sum of the components due to each current acting on its own.

These components are:

1. The leakage flux due to the current in the winding
2. The component mutual flux due to the current in the winding;
3. The component mutual flux due to the current in the other winding.

Thus the resultant flux, φ_1 and $\varphi_{2,}$ for each of the winding-pair tested, can be expressed as

$$\text{Eq. 1} \rightarrow \varphi_1 = \varphi_{\lambda1} + \varphi_{21} + \varphi_{12}$$

Winding 1 is usually either the primary or the secondary of a 3 winding transformer –

$$\text{Eq. 2} \rightarrow \varphi_2 = \varphi_{\lambda2} + \varphi_{12} + \varphi_{21}$$

Winding 2 is usually the tertiary winding.

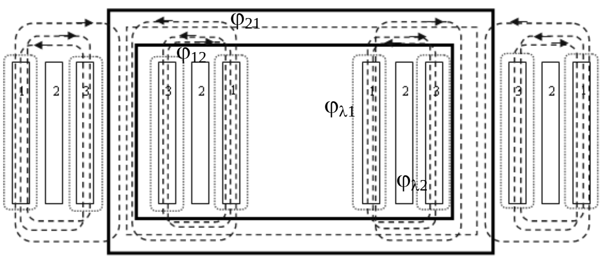

Fig. 4. Flux distribution in a transformer.

The fluxes with double subscripts are the components produced by a single current acting by itself. That is, $\varphi_{\lambda1}$ and $\varphi_{\lambda2}$ are the component leakage fluxes produced by each current; φ_{21} is the component mutual flux produced by current in winding, I_1 and φ_{12} is the component mutual flux produced by I_2.

The transformer voltage equations become

$$V_1 = R_1 \times I_1 + N_1 \times \frac{d\varphi_{\lambda1}}{dt} + N_1 \times \frac{d\varphi_{12}}{dt}$$

For Winding 1, Eq. 3

$$V_2 = R_2 \times I_2 + N_2 \times \frac{d\varphi_{\lambda2}}{dt} + N_2 \times \frac{d\varphi_{21}}{dt}$$

For Winding 2, Eq. 4

Each terminal voltage is thus expressed as the sum of a resistance drop, a voltage induced by leakage flux, and a voltage induced by the resultant mutual flux.. The component leakage fluxes $\varphi_{\lambda1}$and $\varphi_{\lambda2}$ induce voltages in only the winding with which each is associated, but the resultant mutual flux φ_{21} or φ_{12} links both windings and induces in them voltages whose ratio equals the turns ratio, as in an ideal transformer.

During a ratio test, only a pair of the winding is tested and the winding that is excited is the one with a higher voltage rating than the other. For example if the winding pair tested is high voltage (HV): tertiary (TV), the test voltage is applied to the HV winding as it is the higher in voltage class than the other. This is done to prevent the generation of dangerously high voltages in the measured winding, which is connected to the ratio meter.

The amount of flux transferred from the excited to the measured winding and the core depends on the physical location of the excited winding with respect to the measured winding and the iron core. During a voltage ratio test, the voltage across the winding 1 ($v1$) is fixed and $v2$ is measured. It follows from Eq. 4 that $v2$ is largely a function of the mutual flux (φ_{12}, φ_{21}). Higher test voltage leads to the generation of higher excitation current, resulting in more flux in the excited winding (HV winding in our example) and a corresponding increase in the component flux levels, $\varphi_{\lambda2}$ and φ_{21}. Consequently this leads to an increase in the measured value of v_2 and a corresponding decrease in the estimated value of the voltage ratio (v_1 / v_2). This drop in the ratio value is slight and subtle.

The component flux that makes this difference is largely due to the mutual flux φ_{21} and to a limited extent by the leakage flux ($\varphi_{\lambda2}$). The role of the mutual flux (φ_{21}) is governing because its coupling is affected by the physical size of the winding pair tested and their proximity to each other. In simple terms, this means that the ratio accuracy is more affected between the winding pair – HV: tertiary than HV: middle-winding. There may be however some exceptions. The role of $\varphi_{\lambda 2}$ is limited because its increase or decrease is proportional to the current flowing in the measured winding, i2 (=i1* N1/N2). In other words, the increase in the test voltage leads to a proportional increase in the value of $\varphi_{\lambda 2}$ and thus is not a factor in the estimated value of the voltage ratio.

This trend in drop in the ratio values at higher test voltages is almost always seen in the field results, thereby confirming that at a higher excitation voltage the mutual flux coupling is more representative of a real situation and thus the reason behind the improvement in the ratio measurement accuracy.

2.1 Ratio measurements on a 275/132/33 kV, 240 MVA Test Transformers

The influence of the test voltage is demonstrated on a three phase auto transformer of following name plate rating: 275/132/33 kV 240 MVA using two methods: (a) combination of 3-ph voltage source and 6 multi-meters synchronised to each other and (b) using a 250V TTR. The ratio was measured between the 275 kV (HV) and 33 kV (tertiary) winding. The results of the measurements are presented in Table 3 and in figures 5 and 6.

As can be seen from the results, the drop in ratio deviation is quite steep at test voltages below 150V and then slowly flattening out at higher test voltage levels.

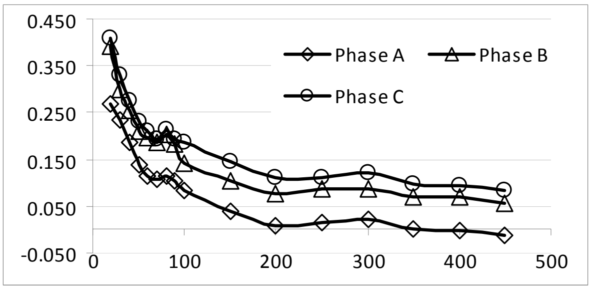

Figure 5: Variation of ratio deviation with test voltage. Measuring device → combination of three-phase voltage source and six multi-meters synchronised with each other. X-axis: test voltage in volts and Y-axis: ratio deviation.

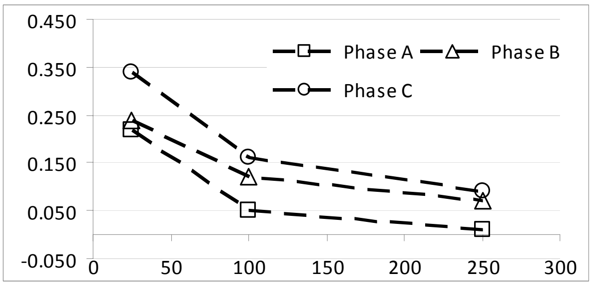

Figure 6: Variation of ratio deviation with test voltage. Measuring device → 250 V single-phase ratio bridge. X-axis: test voltage in volts and Y-axis: ratio deviation

Table 3:

U_{test} [V]	calculated ratio	Measurement Setup: Combination of 3-ph source and 6 multimeters						250V TTR		
		A-N / 3A-3B		B-N / 3B-3C		C-N / 3C-3A				
		measured ratio	deviation [%]	measured ratio	deviation [%]	measured ratio	deviation [%]	'A' dev. [%]	'B' dev. [%]	'C' dev. [%]
20	4.8113	4.8242	0.269	4.8302	0.393	4.8309	0.408			
30	4.8113	4.8226	0.235	4.8257	0.300	4.8271	0.330	0.220	0.240	0.340
40	4.8113	4.8203	0.187	4.8235	0.254	4.8245	0.275			
50	4.8113	4.8180	0.139	4.8214	0.210	4.8224	0.231			
60	4.8113	4.8167	0.113	4.8207	0.196	4.8214	0.211			
70	4.8113	4.8164	0.108	4.8202	0.187	4.8206	0.194			
80	4.8113	4.8167	0.113	4.8210	0.203	4.8216	0.215			
90	4.8113	4.8163	0.106	4.8201	0.183	4.8205	0.193			
100	4.8113	4.8152	0.083	4.8181	0.142	4.8202	0.186	0.050	0.120	0.160
150	4.8113	4.8131	0.039	4.8162	0.103	4.8182	0.144			
200	4.8113	4.8116	0.007	4.8149	0.077	4.8167	0.112			
250	4.8113	4.8120	0.016	4.8155	0.088	4.8167	0.112	0.010	0.070	0.090
300	4.8113	4.8124	0.023	4.8154	0.085	4.8171	0.122			
350	4.8113	4.8113	0.001	4.8147	0.071	4.8159	0.098			
400	4.8113	4.8111	-0.004	4.8146	0.069	4.8158	0.094			
450	4.8113	4.8107	-0.011	4.8139	0.055	4.8153	0.084			

Furthermore, the accuracy with the 250V TTR is better than the one using a combination of three-phase source and several multi-meters.

2.2 Ratio measurements on a 464/100/30 kV, 350 MVA Transformer

Figure 7 graphically summarises the results of the ratio measurement on a 464/100/30 kV, 350 MVA transformer having vector group YNyn0d5. Voltage ratio was measured between the 464 and 30kV winding.

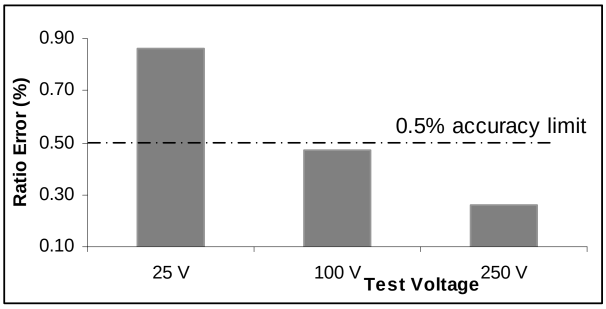

Fig. 7: Ratio Measurement results of tests on a 350MVA transformer.

2.3 Ratio measurements on a 388/240/21 kV, 600 MVA Transformer

Figure 8 graphically summarises the results of the ratio measurement on a 388/240/21 kV, 600 MVA transformer having vector group YNyn0d11. The accuracy of measurements between the HV (338 kV) and tertiary (21 kV) winding at test voltage levels 2, 25, 100 and 250 volts were respectively 1.47%, 1.09%, 0.48% and 0.23%. The ratio measurement accuracy is barely met at 100V.

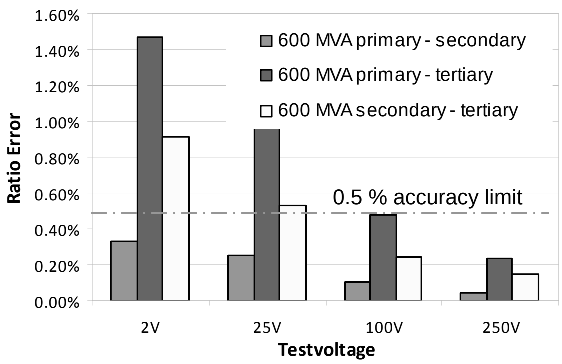

Fig. 8: Ratio Measurement results on a 600MVA transformer

As can be clearly seen the influence of the test voltage on the accuracy is greatly felt by this winding pair – high voltage: tertiary. As explained in section 2.1, the amount of mutual flux transferred from the excited winding (HV) to the measured winding (TV) is reduced, when there is an intermediate winding between HV and TV.

3 Conclusions

In the first-part of the paper an alternate approach to measure the turns ratio and phase angle of special type transformers that do not follow 30° clock shifts using a single phase voltage supply was presented. The measured phase angle accuracy was also shown to be better than the classical combination of three-phase voltage supply and phase vector meter.

In the second-part of the paper, the reason for the higher test voltage leading to a higher measured accuracy on large power transformers with tertiary winding was analytically explained. The influence of the test voltage on the measurement accuracy was demonstrated by presenting results from transformers having ratings between 240 and 600 MVA. Measurements with the 250V TTR gave an accuracy that was better than a traditional combination of three-phase voltage supply and several multi-meters synchronised to each other.

4 References

1. IEEE C57.12.00, clause 9 (2000); General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers.
2. IEC 60076-1, clause 9 (2000); Power Transformers – Part I: General.
3. Operating Instructions TTR2796 V.1 05-2011, Haefely Test AG.