ABSTRACT

The transformer turns ratio test is one of the fundamental routine tests for transformer inspection. This test is used as an indicator of various problems with the transformer windings, such as shorted turns. According to international standards, the pass / fail criterion for turns ratio deviations is ± 0.5 %. This places high demands on the accuracy of the test devices. The measurement accuracy depends on the test device accuracy and test voltage applied. A higher test voltage applied to the high voltage (HV) transformer side will induce a higher voltage on the low voltage (LV) side, providing a more accurate measurement. Also, higher test voltage will result in higher transformer saturation, leading to more accurate results. The relation between test voltage and accuracy will be elaborated, and the implications for the turns ratio test will be discussed. Case studies that support the importance of using the higher test voltage when the transformer turns ratio test is performed will be presented as well.

KEYWORDS:

condition assessment, maintenance, measurement accuracy, power transformer, test device

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In the case of field routine tests, the turns ratio test is performed by applying a reduced test voltage to HV terminals and measuring an induced voltage at LV terminals under no-load transformer conditions

Importance of using high test voltage for transformer turns ratio test

1. Introduction

The transformer turns ratio test is one of the fundamental transformer routine tests declared by both IEC 60076-1 and IEEE C57.12.90. standards. When the transformer has an on-load tap changer (OLTC), this test should be performed for each tapping. Usually, the turns ratio test also includes additional tests such as phase angle, connection symbol (winding configuration or transformer vector group), and excitation current measurement [1].

The transformer turns ratio represents the ratio of the number of turns in the HV windings to that in the LV windings. In the case of field routine tests, the turns ratio test is performed by applying a reduced test voltage to HV terminals and measuring an induced voltage at LV terminals under no-load transformer conditions. The ratio of those measured voltages is approximately equal to the transformer turns ratio.

IEC 60076-1 and IEEE C57.12.90 standards declare that the turns ratio test shall be conducted at a rated or lower test voltage and rated frequency by applying voltage on the HV side and measuring the induced voltage on the LV side. This is the most popular method used by most commercially available test devices. Other available test methods, such as the comparison method, the capacitance, and the power factor bridge method, are rarely used in practice. The turns ratio needs to be checked on each tap position. In the case of three-phase transformers, when each phase is independent and accessible, single-phase power should be used, although, when convenient, three-phase power may be used [2].

When generating a single-phase excitation voltage, the test device supplies a single-phase excitation test voltage to each of the three transformer primary windings. The induced voltages across each of the corresponding unloaded transformer windings are then measured; the ratio of these voltages is calculated and shown on display. It is repeated for all three phases.

When generating a true three-phase voltage, the test device generates and applies a true three-phase excitation test voltage to the three transformer primary windings. The induced three-phase voltages across the unloaded transformer windings are measured, and the transformer turns ratio is calculated for all three phases [3].

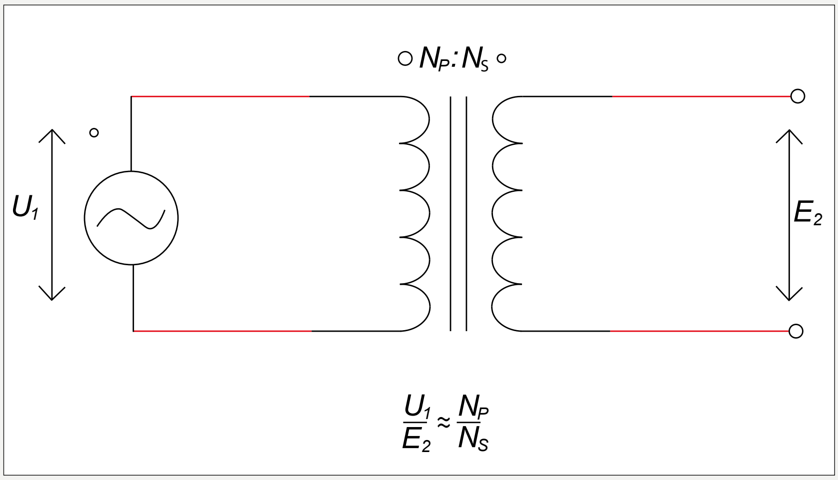

Figure 1. Transformer turns ratio measurement

The tolerance of the turns ratio should be within ± 0.5 % of the specified nameplate ratio, however, the turns ratio can be slightly different between phases mostly because of the "half-turn-effect"

2. Interpreting the transformer turns ratio test results

Both previously mentioned standards specify the tolerance of the turns ratio should be within ± 0.5 % of the specified nameplate ratio. The measured turns ratio can be slightly different between phases mostly because of the "half-turn-effect" but are not a subject of concern unless the difference is > 0.5 %. The correct turns ratio value is very important for the transformer operation especially when transformers operate in parallel connection. If the turns ratios of two parallel transformers are not equal, the voltage difference will appear between transformer outputs. This will cause the equalization current through busbars that provide a parallel connection. Even low turns ratio deviation causes significant equalization currents, which stress the transformer thermally and increase the power losses. This justifies the strict turns ratio deviation threshold declared by international standards. Additionally, according to the CIGRE guide [5], the turns ratio test can be used to detect transformer failures such as shorted winding sections or turns. This failure can be indicated by the Buchholz relay tripping.

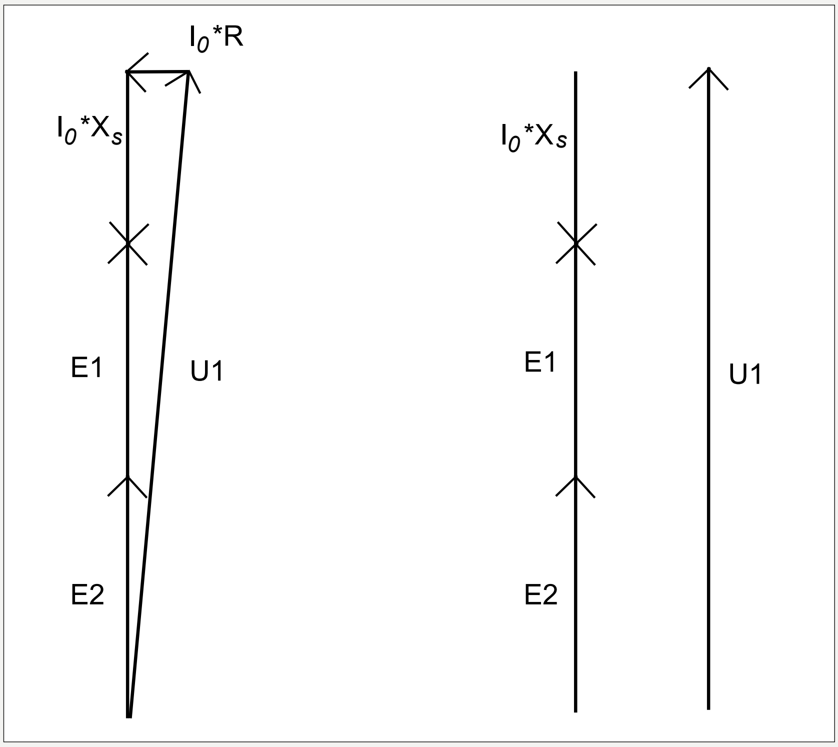

Figure 2. Voltage drop crated by inductive no-load current involves the turns ratio measurement error

3. Measurement accuracy

Turns ratio measurement accuracy depends on two main factors:

- The test instrument accuracy
- The nonlinear magnetic core characteristic, B(H) curve

Because of the importance of the very strict turns ratio deviation threshold, it is highly recommended to use the turns ratio test instrument with very high accuracy. For example, if the test instrument accuracy is, for example, ± 0.2 %, the measured turns ratio value should not exceed ± 0.3 % when compared to the transformer voltage nameplate ratio. In the case of instrument accuracy of ± 0.03 %, the measured turns ratio tolerance is ± 0.47 %. As instrument accuracy is higher, the measured turns ratio tolerance is wider. Nowadays, modern and advanced electronic turns ratio devices have measurement accuracy less than ± 0.1 %, some can reach even ± 0.03 % [6]. Usually, the measurement procedures require the testing instrument with accuracy 5 to 10 times better than the required measurement tolerance, meaning that the turns ratio tester should ensure accuracy from ± 0.05 % to ± 0.1 %.

Besides the required high accuracy of the test instrument, the voltage drop caused by no-load current needs to be taken into consideration. The transformer turns ratio is defined as a ratio of the applying transformer nominal voltage with nominal frequency on the HV side and measured no-load voltage on the LV side. Here the voltage drop caused by the no-load current is also taken into consideration. However, it is not practical to use nominal transformer voltage in-field testing. Using the reduced test voltage is an accepted practice in this case. Because of the transformer saturation effect, the no-load current is not linearly decreasing with voltage. This introduces the measurement error, which influences the final measurement accuracy.

The transformer no-load test can be presented through the vector diagram in Fig. 2. Since the no-load current is dominantly inductive (creates a voltage drop $I_0 \cdot X_s$, where X_s represents stray inductance), the active (resistive) current component (creates a voltage drop $I_0 \cdot R$) can be neglected. Thus, the vector diagram

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from the left-hand side on Fig. 2 can be presented as the diagram from Fig. 2 on the right-hand side. Real transformer ration is $\frac{E_1}{E_2}$, but test device measures $\frac{U_1}{E_2}$. The voltage U_1 is the applied voltage to the transformer HV side and E_2 is the measured voltage on the transformer LV side.

According to the vector diagram, the turns ratio measurement error ΔU % caused by the no-load current can be calculated.

$$U_1 = E_1 + I_0 X \qquad [1]$$

$$\Delta U = U_1 - E_1 \qquad [2]$$

$$\Delta U\,\% = \frac{(U_1 - E_1)}{E_1} \cdot 100 = \frac{I_0}{E_1} X \cdot 100\ (\%) \qquad [3]$$

If the voltage is increased above the transformer nominal voltage, the segment ΔU % (which introduces the measurement error) is increased. In the linear part of the saturation curve, the

With the lower voltages, the measurement error is significantly increased, which may be problematic if the low voltage (like 100 V) is used for the turns ratio test

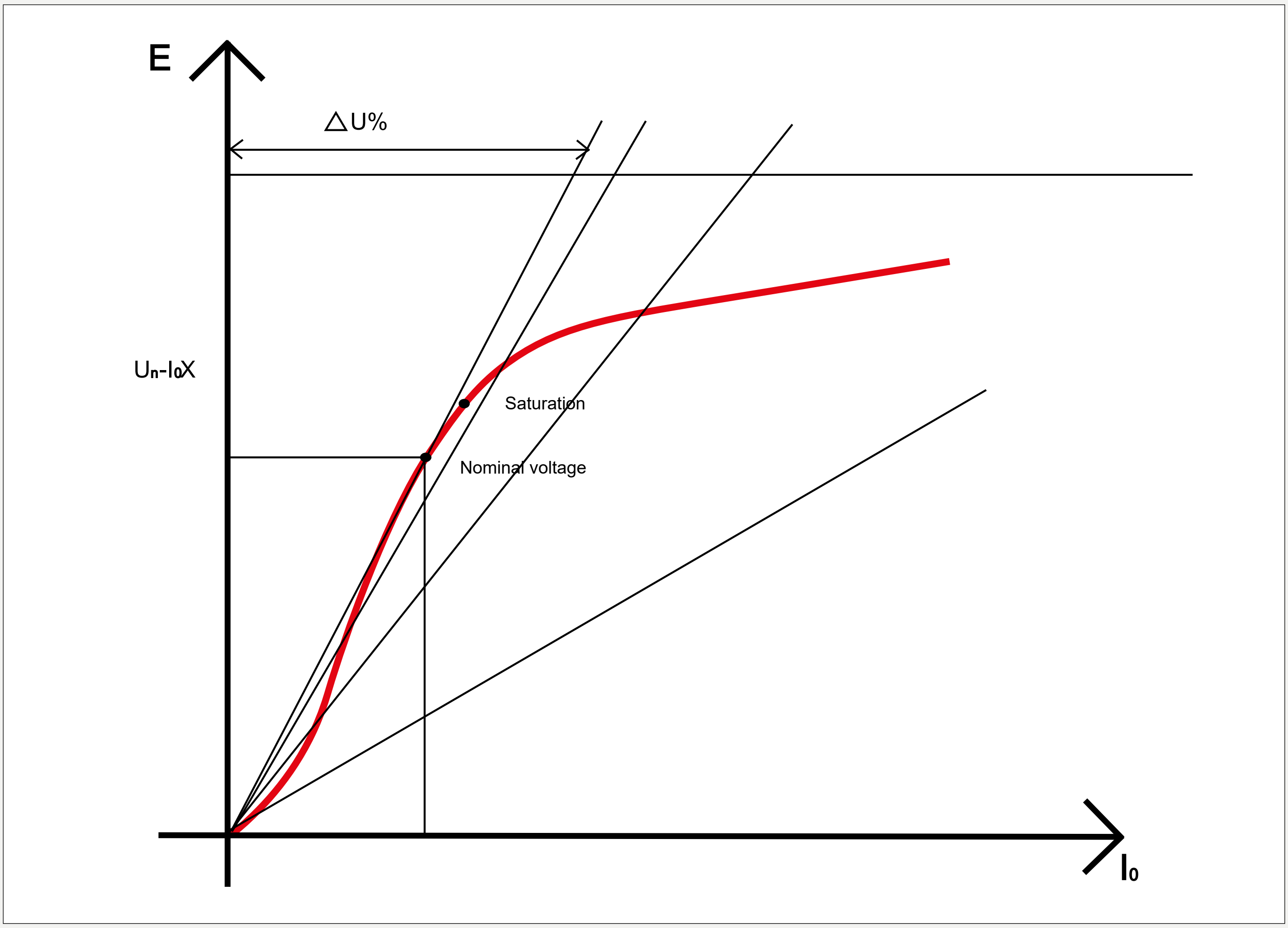


Figure 3. Transformer saturation curve dependent on the no-load current is not linearly decreasing with the voltage decreasing

The presented results for the turns ratio test indicate that the turns ratio deviation is not equal when the test is performed with different test voltages

segment ΔU % is insignificantly increasing. However, at the beginning of the transformer B(H) curve, the segment ΔU % is significantly increased.

According to [5], if the test voltages are decreased up to approx. 5-10 % of transformer nominal voltage, they will not involve a significant measurement error. The test voltages decreased up to approx. 1 % of transformer nominal voltage usually do not involve the measurement error higher than 0.3 %. With the lower voltages, the measurement error is significantly increased. It should be noted that the mentioned values are not general, and they are not equal for all types of transformers. The values are influenced by transformer design, construction, and its hysteresis loop.

4. Case study

The paper will present an interesting case study where the turns ratio issue was experienced during transformer commissioning. Turns ratio test showed unacceptably high turns ratio deviation (approximately 0.68 %). The measurement has been performed with the different test devices to eliminate the suspect that the test instrument was the root cause of the issue. Both test devices have shown a similar turns ratio deviation, which was higher than the standard allows. The test was performed with the same test voltages of 100 V. The idea was to perform the test with a higher test voltage. At that moment, the highest available test voltage was 250 V. The presented results indicate that the turns ratio deviation is not equal when the test is performed with different test voltages. The turn ratio deviation is lower when the test is performed with higher test voltages. This proves the analysis and explanation given above. Higher test voltage provides lower measurement error and gives more accurate results.

Table 1. Transformer nominal parameters

MVA rating	45
Rated voltages (kV)	275/33
Rated current (A)	94.3/787.3
Vector group	YNd1

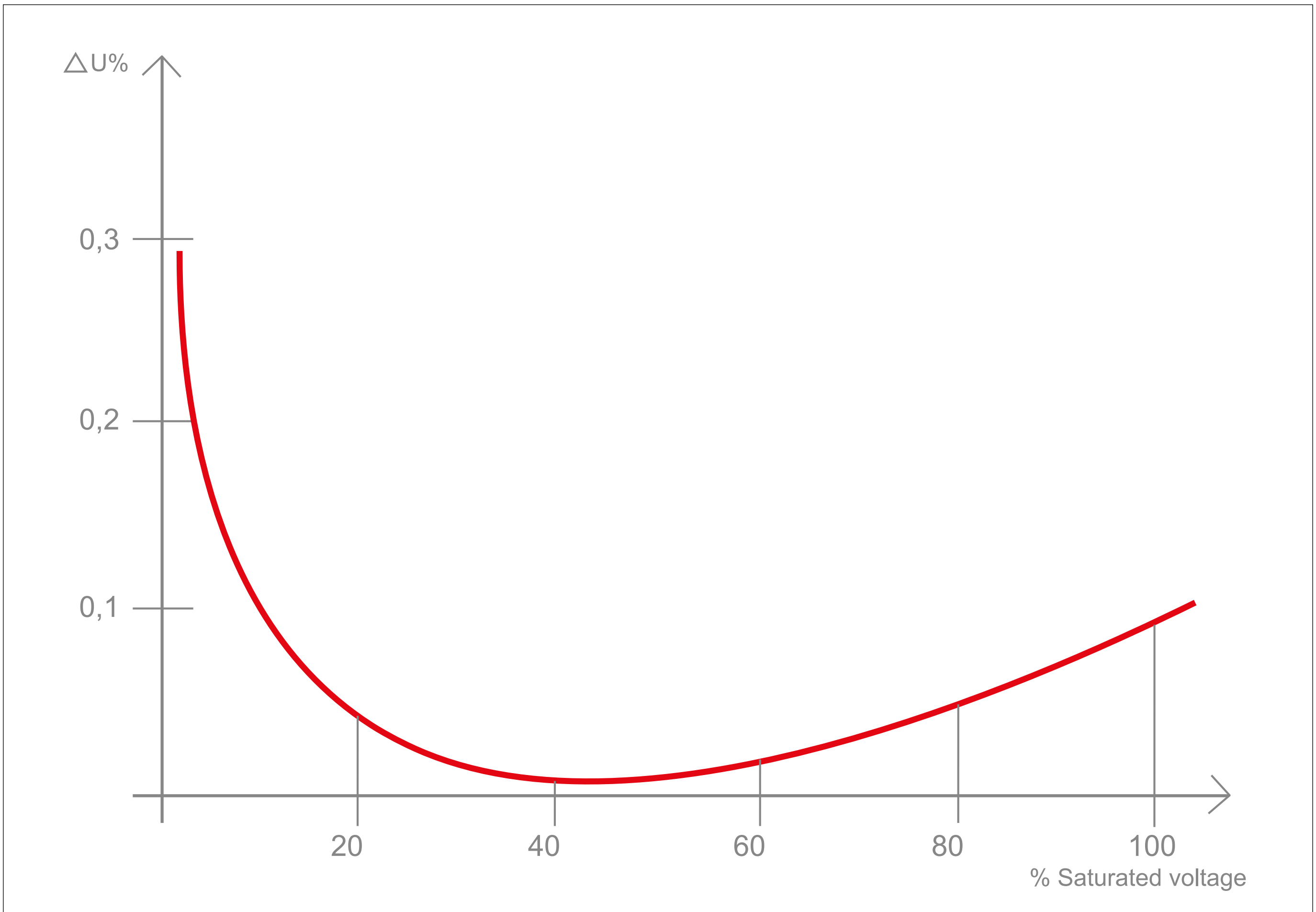


Figure 4. The measurement error vs test voltage curve

Table 2. Turns ratio measurement results - a test performed by using a test voltage of 100 V

Nameplate ratio HV/LV	Tap position	Test voltage	Turns ratio phase A	Turns ratio phase B	Turns ratio phase C	Ratio deviation phase A	Ratio deviation phase B	Ratio deviation phase C	Turns ratio pass/fail
302500 / 33000	1	100	5.3117	5.3031	5.31	0.36	0.2	0.33	Pass
299062.5 / 33000	2	100	5.2519	5.2436	5.2502	0.38	0.22	0.34	Pass
295625 / 33000	3	100	5.1923	5.184	5.1905	0.39	0.23	0.36	Pass
292187.5 / 33000	4	100	5.1326	5.1247	5.1308	0.4	0.25	0.37	Pass
288750 / 33000	5	100	5.073	5.0654	5.0713	0.42	0.27	0.39	Pass
285312.5 / 33000	6	100	5.0135	5.0062	5.0118	0.44	0.29	0.4	Pass
281875 / 33000	7	100	4.954	4.9469	4.9522	0.46	0.31	0.42	Pass
278437.5 / 33000	8	100	4.8945	4.8876	4.8927	0.47	0.33	0.44	Pass
275000 / 33000	9	100	4.835	4.8283	4.8333	0.49	0.35	0.46	Pass
271562.5 / 33000	10	100	4.7755	4.7691	4.7737	0.51	0.38	0.48	Fail
268125 / 33000	11	100	4.716	4.7097	4.7142	0.53	0.4	0.5	Fail
264687.5 / 33000	12	100	4.6564	4.6504	4.6547	0.55	0.42	0.52	Fail
261250 / 33000	13	100	4.5969	4.5911	4.5952	0.57	0.45	0.54	Fail
257812.5 / 33000	14	100	4.5374	4.5317	4.5358	0.6	0.47	0.56	Fail
254375 / 33000	15	100	4.4779	4.4724	4.4763	0.62	0.49	0.58	Fail
250937.5 / 33000	16	100	4.4184	4.4132	4.4168	0.64	0.52	0.6	Fail
247500 / 33000	17	100	4.359	4.3539	4.3574	0.67	0.55	0.63	Fail

Figure 5. Turns ratio deviation vs. tap positions graph. The green area is a "pass zone" within ± 0.5 %

Table 3. Turns ratio measurement results - a test performed by using a test voltage of 250 V

Nameplate ratio HV/LV	Tap position	Test voltage	Turns ratio phase A	Turns ratio phase B	Turns ratio phase C	Ratio deviation phase A	Ratio deviation phase B	Ratio deviation phase C	Turns ratio pass/fail
302500 / 33000	1	250	5.3044	5.2981	5.3043	0.23	0.11	0.22	Pass
299062.5 / 33000	2	250	5.2451	5.239	5.2451	0.25	0.13	0.25	Pass
295625 / 33000	3	250	5.1857	5.1798	5.1856	0.26	0.15	0.26	Pass
292187.5 / 33000	4	250	5.1262	5.1206	5.1262	0.28	0.17	0.28	Pass
288750 / 33000	5	250	5.0668	5.0613	5.0667	0.3	0.19	0.29	Pass
285312.5 / 33000	6	250	5.0074	5.0021	5.0073	0.32	0.21	0.31	Pass
281875 / 33000	7	250	4.9479	4.9428	4.9479	0.33	0.23	0.33	Pass
278437.5 / 33000	8	250	4.8886	4.8836	4.8884	0.35	0.25	0.35	Pass
275000 / 33000	9	250	4.8291	4.8243	4.829	0.37	0.27	0.37	Pass
271562.5 / 33000	10	250	4.7697	4.765	4.7695	0.39	0.29	0.39	Pass
268125 / 33000	11	250	4.7102	4.7057	4.71	0.41	0.31	0.41	Pass
264687.5 / 33000	12	250	4.6508	4.6464	4.6506	0.43	0.34	0.43	Pass
261250 / 33000	13	250	4.5914	4.5871	4.5912	0.45	0.36	0.45	Pass
257812.5 / 33000	14	250	4.532	4.5279	4.5317	0.48	0.38	0.47	Pass
254375 / 33000	15	250	4.4726	4.4685	4.4723	0.5	0.41	0.49	Pass
250937.5 / 33000	16	250	4.4131	4.4092	4.4129	0.52	0.43	0.51	Fail
247500 / 33000	17	250	4.3537	4.3499	4.3535	0.55	0.46	0.54	Fail

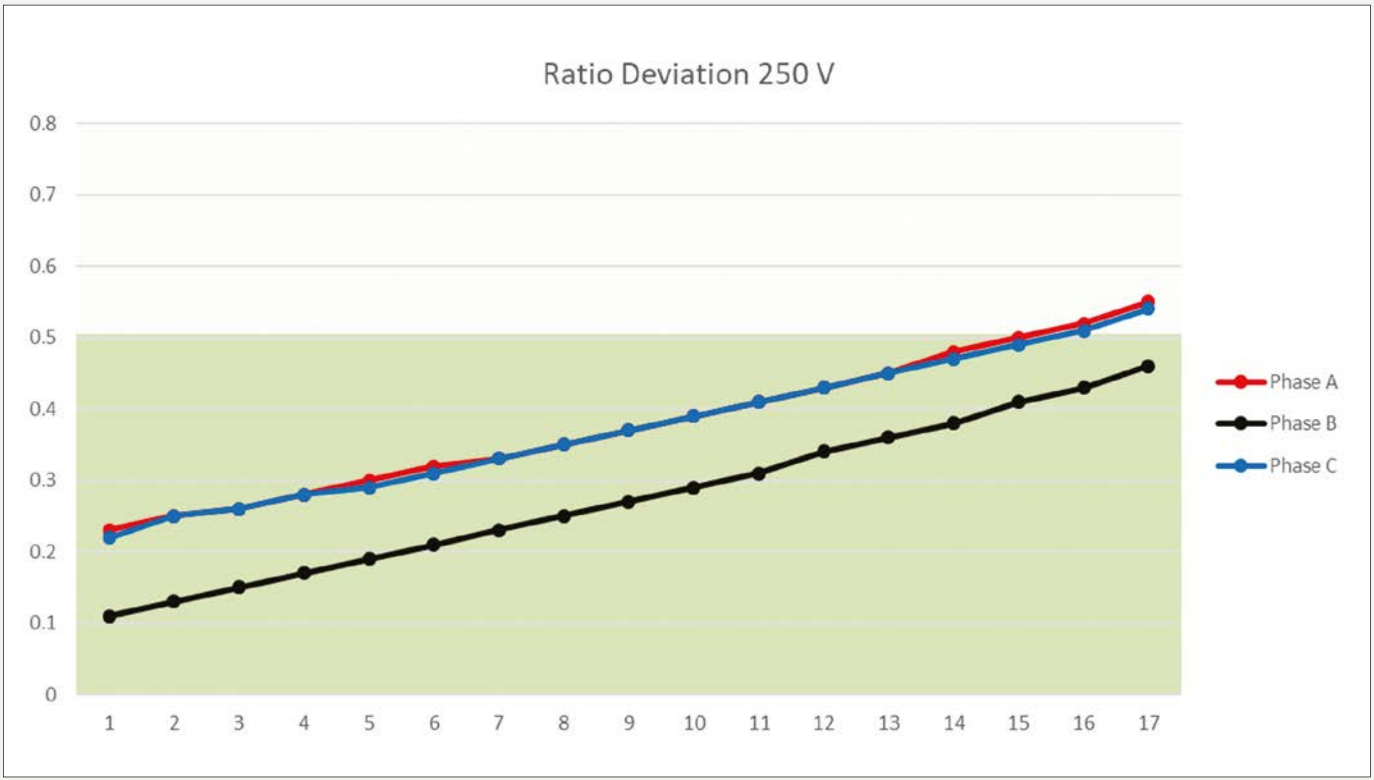


Figure 6. Turns ratio deviation vs. tap positions graph. The green area is a "pass zone" within ± 0.5 %

According to the experience, our preliminary advice is to use a higher test voltage (> 250 V, < 1 kV), as it seems effective and safe

From the previous results, it is noticeable that the turns ratio deviation has quite higher values when the test voltage of 100 V is used. Eight tap positions indicate that turns ratio deviation is outside the green pass zone with turns ratio deviation value up to 0.67 %. When the test voltage of 250 V has been used, only two-tap changer positions indicate a slight deviation from the "pass zone". The maximum turns ratio deviation is 0.55 %.

This case study is very representative to elaborate on the importance of the higher test voltage. Nowadays, modern test devices provide high measurement accuracy. The influence of the test voltage value on the accuracy is not prominent when the turns ratio deviation is very low, e.g., 0.03 %. It is not such important if the device measures 0.02 % or 0.04 %. Both results are deep in the green pass zone. However, when the transformer turns ratio deviation values are on the border to be pass or fail, the test voltage value can be deciding.

Even in this case, it is recommended to pay more attention to this transformer and monitor whether the turns ratio deviation stagnates or increases.

5. Conclusion

The previously presented theory about the impact of the test voltage value on the turns ratio results is confirmed by testing in the field and real case studies. The case study initiates the need for a higher test voltage value than 100 V, which is usually the maximum test voltage value of the many test devices. However, it also should be considered what would be a suitable maximum test voltage value. Too high test voltage (tens of kV) can cause arc and conceal short open circuits. We are conducting further research to establish the optimum voltage level for specific transformer types. According to the experience, our preliminary advice is to use a higher test voltage (> 250 V, < 1 kV), as it seems effective and safe. However, this observation has been the trigger for the development of a new generation of portable turns ratio tester with test voltage up to 500 V [6].

Bibliography

[1] IEC 60076-1 CE1 IEC 60076-1 Edition 2.1 2000-04

[2] IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers (IEEE Std C57.12.90™-2015)

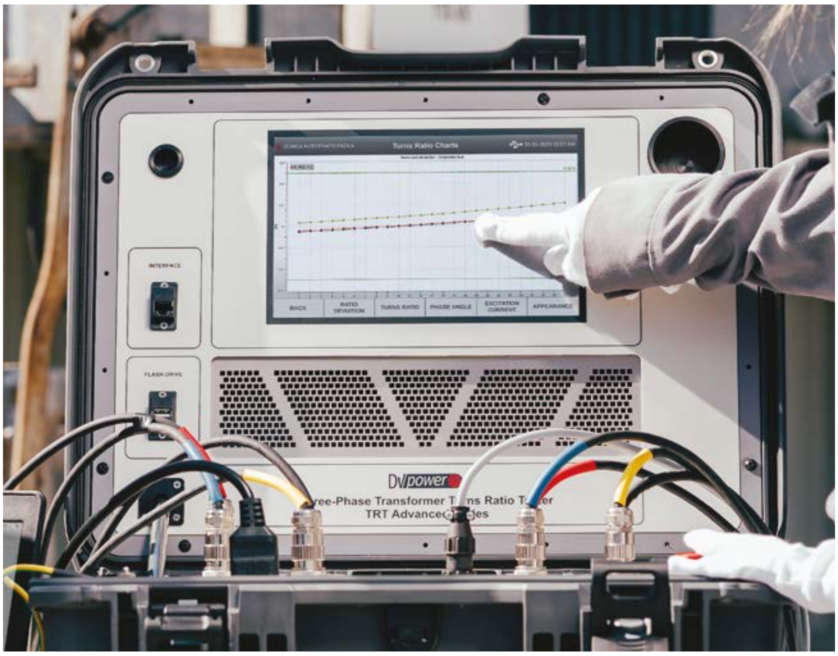
[3] DV Power Application Note How to Measure a Transformer Turns Ratio Using TRT Instruments, A-TRF102-201-EN

[4] DV Power Application Note Differences Between Sequential 3~ and Simultaneous 3~ Turns Ratio Tests, A-TRF121-201-EN

[5] Dr. Radenko Wolf, *Testing the electric machines - Part I*, Faculty of Electrical Engineering University of Zagreb, 1970.

[6] DV Power Manual TRT Advanced Series ver. M-TADVNN-307-EN https://www.dv-power.com/product/transformer-turns-ratio-testers/turns-ratio-tester-advanced/

[7] CIGRE Guide for Transformer Maintenance 445



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Edis Osmanbasic has been working at DV Power since 2010, and his current position is Head of Testing, Training and Education Services. Previously he has been a transformer lead test engineer. His work involves transformer field testing, interpretation of the results, transformer condition assessment and creating professional test reports. He is responsible for the analysis and development of test methods for condition assessment of transformers, and he published numerous papers on DRM OLTC testing methodology and transformer diagnostic methods as well. He is also a member of AM Forum working group for OLTC testing methods. He holds an MSc degree in electrical engineering.