ALTERNATING VOLTAGE TESTS ON DISTRIBUTION TRANSFORMERS USING STATIC FREQUENCY CONVERTERS

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Abstract: This paper presents experience in performing alternating voltage measurements on distribution transformers using a static frequency converter without particular control scheme. Regarding induced voltage tests, no-load and load measurements, the quality, i.e. the degree of distortion and the symmetrical shape, of the generated test voltage, deviations in measured power and the relation between demand for reactive power and frequency and level of the provided voltage are discussed.

1. INTRODUCTION

Still today the test voltage for the alternating voltage tests on distribution and power transformers is generated using motor-generator sets, providing amplitude- and frequency-variable output voltages for no-load tests, load tests and induced voltage tests. In the recent years strong efforts were made on the qualification of static frequency converters not only to generate test voltages fulfilling the requirements of the applicable standards by using an elaborate control scheme to dynamically generate the pulse pattern driving the power electronic modules [1], but also having a limited impact on the measurement of partial discharge during induced voltage tests. Thus today new or modernized transformer test facilities for factory testing or mobile test applications are often equipped with static frequency converters, as investment and maintenance costs are less. Regarding the routine, design and other tests on distribution transformers, interest is now put on versatile automated test systems supplying satisfying test voltages and sufficient output power. The simplest approach is to employ standard frequency converters designed for drive applications.

This paper discusses the results measured with a laboratory test setup based on a static frequency converter. No-load and load measurements as well as measurements with induced voltage were conducted on different distribution transformers, having the same vector group and voltage ratio but having different rated power and impedance voltage. Regarding the requirements established by international standards, the quality of the output voltage was assessed with respect to the symmetrical shape of the three phases and the degree of voltage distortion in conjunction with deviations of measured no-load losses. For the examined distribution transformers a second focus is put on the demand for reactive power related to frequency and level of the provided voltage.

2. EXPERIMENTAL SETUP

2.1. Test setup

The experimental setup used to produce the results in this paper is shown in Figure 1. A mains transformer is employed to adapt mains voltage to the input voltage of the static frequency converter and to galvanically decouple the following test circuitry from mains network. The output power of the static frequency converter is rated to 250 kVA, the maximum output voltage level is 690 V, adjustable in steps of 0.1 V and the maximum frequency for induced voltage tests is 194 Hz. A L-C sine filter is inserted between the static frequency converter and the following components to convert the pulse-width modulated output voltage to a sinusoidal voltage. A dry-type step-up transformer is used to adapt the output voltage level of the converter to rated voltage of the devices under test (DUT), providing different voltage levels, i.e. 400 V, 800 V, 1250 V and 1600 V for the different tests presented in this article.

The distribution transformers used for investigations feature a vector group of Dyn5 and a voltage ratio of 20 kV / 400 V. The devices under test have a rated power of 250 kVA (DUT1), 400 kVA (DUT2) and 800 kVA (DUT3) and a relative short-circuit impedance of 6 %, 4 % and 4 %.

As a validation of the results obtained in executing no-load measurements with a static frequency converter tests were redone with a mains-operated adjustable transformer and a motor-generator set as voltage source, which were both connected to the DUT without step-up transformer.

2.2. Measurement configuration

Wave shape visualization and recording was done with a digital oscilloscope, a power analyzer was used to determine the characteristics of voltage, current and power. As the described laboratory tests result in comparable low voltages, no voltage transformers were needed except for load losses measurement.

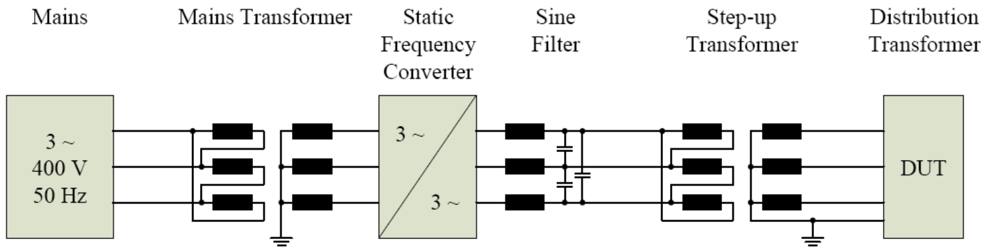

Figure 1: General examination setup

The employed voltage transformers offer a maximum error of 0.15 % and a maximum phase displacement of 1 minute. Currents were measured with current transformers having a maximum error of 0.69 % and a maximum phase displacement of 18 minutes. The maximum error of the power analyzer in the frequency range between 45 Hz and 65 Hz is specified to 0.05 % of the measurement reading and 0.05 % of the measurement range for voltage and for current. The maximum uncertainty of measurement for active power is specified to 0.07 % / 0.08 %. All specifications given by the manufacturer only apply to sinusoidal quantities.

2.3. Applied analysis criteria

The symmetrical shape of the three-phase voltage system at the terminals of the DUT was assessed not only by calculating

$$\left|\frac{U-\bar{U}}{\bar{U}}\right| \tag{1}$$

but also by evaluating the more strict criterion of

$$\left|\frac{U_{\max}-U_{\min}}{U_{\min}}\right| \tag{2}$$

for the crest value, the rms value and the rectified mean value of the voltage. According to particular national standards the value of Equation 1 shall always be less than 3 % for no-load measurements.

The analysis criteria for the degree of distortion were chosen according to [2]: The relation between crest value and rms value

$$\left|\frac{\hat{U}-\sqrt{2}U_{\mathrm{rms}}}{\sqrt{2}U_{\mathrm{rms}}}\right| \tag{3}$$

must be less than 5 % and the factor of total harmonic distortion

$$THD=\frac{\sqrt{\sum_{n=2}^{m}U_{n,rms}^{2}}}{U_{1,rms}} \tag{4}$$

must not exceed a level of 5 %.

Additionally [3] requires the factor

$$\left|d\right|=\left|\frac{U'-U_{rms}}{U'}\right| \tag{5}$$

to be less than 3 % for no-load measurements, employing the corrected rectified mean value

$$U'=1{,}1107\cdot U_{rect}\,. \tag{6}$$

The measured values P_{m} of the no load losses were corrected to P_{c} as proposed by [4] and [5], using the rms value and the corrected rectified mean value of the measured voltage:

$$P_{c,IEEE}(T_m)=\frac{P_m}{P_1+\left(\frac{U_{rms}}{U'}\right)^2 P_2}\,. \tag{7}$$

P_1 and P_2 were assigned to 0.5 as the actual per-unit values of eddy current and hysteresis losses could not be identified. T_{m} is the average oil temperature at time of test. Additionally the measured results were corrected by applying the proposed waveform correction formulated in [3]:

$$P_{c,IEC}=P_m(1+d)\,. \tag{8}$$

3. MEASUREMENT RESULTS

3.1. No-load measurements

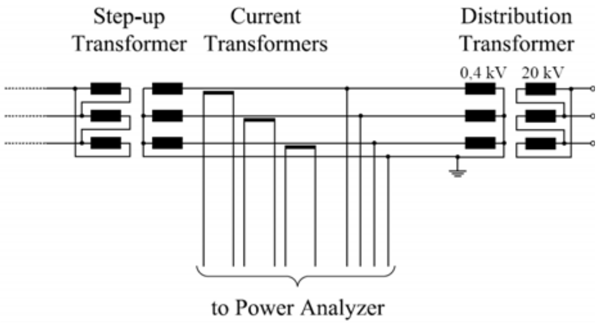

Figure 2: Setup for no-load measurements with static frequency converter

The setup for the no-load measurements was arranged as shown in Figure 2. By adjusting the static frequency inverter the corrected rectified mean value of the applied phase-to-neutral voltage was set to 100 % of rated voltage at rated frequency of the DUT.

Table 1 shows the maximum values for both expressions of asymmetry measured for each DUT. Different taps of the step-up transformers were used for static frequency converter operation; the rotary converter and the adjustable transformer were connected to the DUT without step-up transformer.

Table 1: Assessment of voltage asymmetry for no-load measurements

Criterion	DUT1	DUT2	DUT3
$\left\lvert\frac{U-\bar{U}}{\bar{U}}\right\rvert$	≤ 1.14 %	≤ 1.18 %	≤ 1.98 %
$\left\lvert\frac{U_{\max}-U_{\min}}{U_{\min}}\right\rvert$	≤ 1.88 %	≤ 2.38 %	≤ 3.24 %

With increasing rated power of the distribution transformers the maximum values of asymmetry increase. For each DUT regarded separately there is no definite relation between asymmetry and chosen tap of the step-up transformer. Least values of asymmetry could be obtained with the adjustable transformer, the rotating converter and the static frequency converter operated with the step-up transformer set to the 400-V-tap.

Table 2 shows the results for the waveform-corrected no-load losses; both correction rules, according to IEEE and according to IEC standard, produce the same results with negligible differences. The deviation between maximum and minimum value of the no-load losses increases for rising rated power of the examined transformers. Table 3, Table 4, and Table 5 show the degree of distortion for the different DUT, each tested with different tap positions of the step-up transformer during static frequency converter operation and additionally energized by the adjustable transformer and the rotary converter. This assessment reveals that distortion worsens with augmented voltage ratio of the step-up transformer and increasing current flowing at rated voltage. Both phenomena indicate the influence of a non-sinusoidal voltage drop over the effective series reactance in the circuit. Furthermore the results point out, that different criteria of distortion can lead to different statements concerning acceptability of the voltage wave shape. The requirements of the standards concerning quality of the test voltage can only be fulfilled for static frequency converters without particular control scheme, if the step-up transformer is adjusted appropriately. The quality of the voltage could not be surpassed significantly by the mains-operated adjustable transformer and the motor-generator set.

Table 2: Waveform corrected no-load losses

Tap	DUT1	DUT2	DUT3
400 V	568.48 W	634.48 W	1395.49 W
800 V	565.83 W	640.93 W	1349.56 W
1250 V	566.60 W	645.46 W	1277.45 W
1600 V	571.09 W	625.50 W	1294.99 W
Adj. transformer	563.19 W	636.92 W	1418.22 W
Rot. converter	561.34 W	634.52 W	1418.53 W
$\frac{P_{\mathrm{c,max}}-P_{\mathrm{c,min}}}{P_{\mathrm{c,min}}}$	1.74 %	3.19 %	11.04 %

As all tests were done with equivalent ambient conditions; in accordance to [4] temperature correction was not carried out for the no-load losses.

Table 3: Assessment of voltage distortion for DUT1

Tap	THD$_{\max}$	$\lvert d\rvert_{\max}$	$\left\lvert\frac{\hat{U}-\sqrt{2}U_{\mathrm{rms}}}{\sqrt{2}U_{\mathrm{rms}}}\right\rvert_{\max}$
400 V	1.92 %	0.32 %	1.37 %
800 V	2.86 %	0.37 %	6.47 %
1250 V	3.97 %	0.78 %	7.05 %
1600 V	4.51 %	0.87 %	7.96 %
Adj. transformer	1.44 %	0.23 %	0.86 %
Rot. converter	0.66 %	0.13 %	0.33 %

Table 4: Assessment of voltage distortion for DUT2

Tap	THD$_{\max}$	$\lvert d\rvert_{\max}$	$\left\lvert\frac{\hat{U}-\sqrt{2}U_{\mathrm{rms}}}{\sqrt{2}U_{\mathrm{rms}}}\right\rvert_{\max}$
400 V	1.48 %	0.29 %	0.61 %
800 V	6.52 %	0.78 %	20.24 %
1250 V	4.99 %	1.01 %	12.62 %
1600 V	9.97 %	1.62 %	24.76 %
Adj. transformer	1.21 %	0.08 %	0.89
Rot. converter	0.61 %	0.15 %	0.24

Table 5: Assessment of voltage distortion for DUT3

Tap	THD$_{\max}$	$\lvert d\rvert_{\max}$	$\left\lvert\frac{\hat{U}-\sqrt{2}U_{\mathrm{rms}}}{\sqrt{2}U_{\mathrm{rms}}}\right\rvert_{\max}$
400 V	2.29 %	0.59 %	0.7 %
800 V	9.27 %	1.97 %	2.23 %
1250 V	11.52 %	3.49 %	11.56 %
1600 V	13.27 %	4.16 %	20.46 %
Adj. transformer	2.76 %	0.91 %	2.01 %
Rot. converter	2.88 %	1.01 %	2.11

For the 800-kVA-transformer the best and the worst wave shape of voltage and current are plotted in Figure 3 and Figure 4.

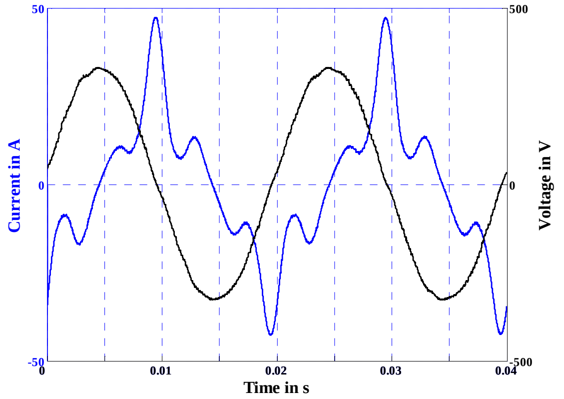

Figure 3: No-load measurement, DUT3, 400-V-tap

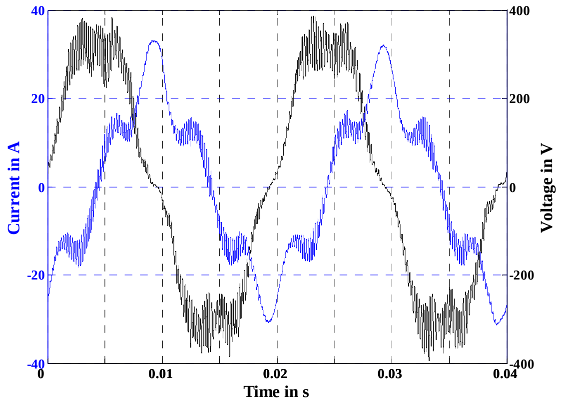

Figure 4: No-load measurement, DUT3, 1600-V-tap

3.2. Load-Measurement

The setup for the load measurements was arranged as shown in Figure 5.

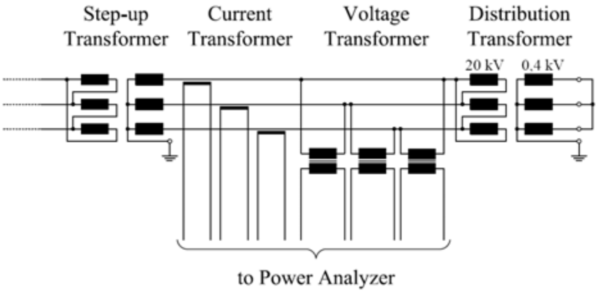

Figure 5: Setup for load measurements with static frequency converter

The current flowing into the DUT was adjusted to rated current at rated frequency. Again the voltage system shows a sufficient symmetry: The maximum deviation for average, crest and rms value of the three phases according to Equation 1 is 0.64 % and 1.03 % according to Equation 2; both values were measured for DUT2.

The results for the relative short-circuit impedances satisfactorily match the data on the nameplate of each DUT. For increasing rated power of the DUT the differences between the measured load losses for different tap positions of the step-up transformer increases; the maximum deviation for all examined distribution transformers is 0.84 %. The assessment of voltage distortion in Table 6, points out that an acceptable degree of distortion can again only be accomplished by adjusting the step-up transformer to the lowest possible voltage ratio. Due to a sinusoidal wave shape of the current the resulting values for $|d|$ are very little; thus $|d|$ is not suitable to assess voltage distortion in case of load measurements and therefore not considered in Table 6.

Table 6: Assessment of voltage distortion for load measurement

	Tap	THD_{max}	$\left\lvert\frac{\hat{U}-\sqrt{2}U_{\text{rms}}}{\sqrt{2}U_{\text{rms}}}\right\rvert_{\text{max}}$
DUT1	800 V	1.22 %	2.74 %
	1250 V	1.22 %	5.95 %
DUT2	800 V	0.88 %	2.58 %
	1250 V	2.23 %	7.21 %
DUT3	1250 V	1.3 %	2.11 %
	1600 V	1.8%	5.04 %

3.3. Measurement with induced voltage

Measurements with induced voltage were conducted on basis of the measurement setup illustrated in Figure 6. As demanded by the standards frequency was increased to reduce the magnetization current.

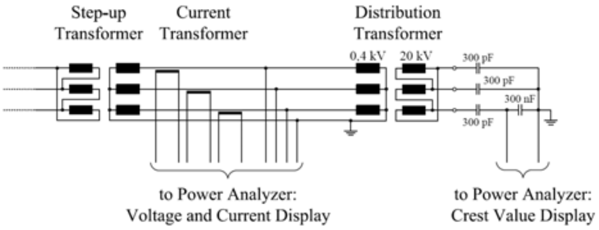

Figure 6: Setup for the measurement with induced voltage

As seen in Figure 6 the voltage was measured between the terminals of the high voltage winding and an artificial neutral point. Voltage was raised to 150 % of the rated voltage; frequency was swept from 100 Hz to 150 Hz in steps of 5 Hz. The effective voltage level was determined according to crest value divided by $\sqrt{2}$. Compared to load measurement symmetry has worsened: The maximum deviation for average, crest and rms value of the three phases is 2.03 % according

Table 7: Assessment of voltage distortion for measurement with induced voltage

	Tap	$\mathrm{THD}_{\max}$	$\lvert d\rvert_{\max}$	$\left\lvert\dfrac{\hat{U}-\sqrt{2}U_{\mathrm{rms}}}{\sqrt{2}U_{\mathrm{rms}}}\right\rvert_{\max}$
DUT1	800 V	2.49 % - 6.25 %	0.02 % - 1.01 %	0.02 % - 5.6 %
	1250 V	2.13 % - 5.78 %	0.02 % - 0.62 %	0.03 % - 5.89 %
DUT2	800 V	3.10 % - 7.86 %	0.00 % - 0.91 %	6.11 % - 12.8 %
	1250 V	2.91 % - 4.62 %	0.01 % - 0.56 %	6.71 % - 11.19 %
DUT3	800 V	4.07 % - 7.29 %	0.01 % - 1.07 %	8.27 % - 13.31 %
	1250 V	2.85 % - 5.82 %	0.01 % - 0.67 %	6.18 % - 9.85 %

to Equation 1 and 2.8 % according to Equation 2. Both values were measured for DUT2. Table 7 shows the measured values for the different criteria for voltage distortion, although |*d*| normally is not applied for induced voltage tests. For every DUT there was no tap position of the step-up transformer, for which every criterion, except |*d*|, would have been fulfilled for every frequency. Neither the rated power of the DUT nor the chosen voltage ratio of the step-up transformer could furthermore be related to the degree of distortion in this case.

4. REACTIVE POWER ANALYSIS

Regarding induced voltage tests, interest is focused on the quest for the frequency of test voltage, with which the reactive power consumed by the DUT is minimal, in order to limit the needed compensation equipment and increase the usable output power. Frequency sweeps have been accomplished to experimentally assess the dependency of the demand for reactive power of the examined distribution transformers on frequency and voltage level. In Figure 7, Figure 8 and Figure 9 the needed reactive power is plotted over the frequency for different voltage levels applied to the DUT. Tests showed that examinations with voltage levels less than rated voltage could not produce a significant behavior and explicit minima due to too little changes in the measured values of reactive power. Figure 7 shows a narrow frequency range with minimum values for reactive power absorbed by DUT1 at rated voltage, 125 % of rated voltage and 150 % of rated voltage. The frequency of the detected minima is between 65 Hz and 85 Hz and it increases with increasing voltage level. Regarding the reactive power characteristics of the 400-kVA-transformer, the minima of the absorbed reactive power are located between 110 Hz and 130 Hz; in comparison with DUT1 the absorbed reactive power does not vary significantly with respect to the voltage level. The 800-kVA-transformer shows a clear trend: for all applied voltage levels the reactive power decreases steadily with increasing frequency; the entire frequency range between 150 Hz and 190 Hz appears as region of least reactive power, yet an explicit minimum or a narrow frequency band related to minimal reactive power can not be identified. Due to the limited properties of the static frequency converter and the lack of an appropriate motor-generator set, assessment could not be extended to frequencies exceeding 194 Hz. As a further step reactive power analysis has been conducted on a power transformer having a voltage ratio of 220 kV / 110 kV / 10.5 kV, rated power of 180 MVA and a vector group of YNyn0d5 on-site. As the laboratory test system could not provide sufficient power to reach rated voltage, examination was done with 50 % of rated voltage and levels below. In Figure 10 again the absorbed reactive power is plotted over the frequency for different voltage levels applied to tertiary winding: For $U = 2$ kV 70 Hz to 90 Hz is the frequency range of minimal reactive power. Doubling the voltage level now shifts this range to 60 Hz to 70 Hz. Applying 50 % of the rated voltage the range of minimal reactive power does not change significantly.

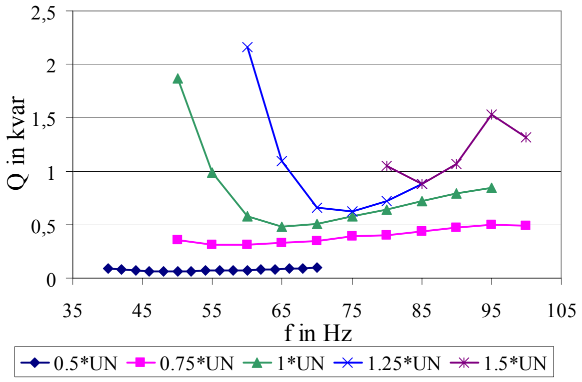

Figure 7: Reactive power analysis for DUT1

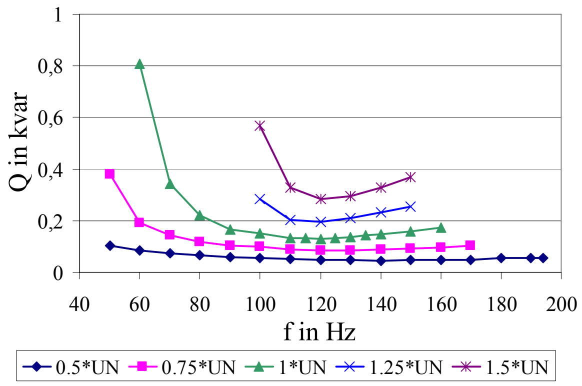

Figure 8: Reactive power analysis for DUT2

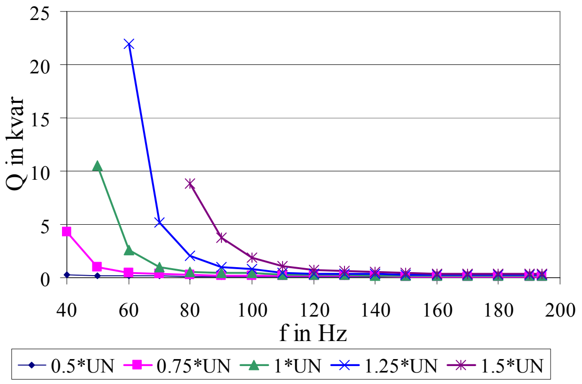

Figure 9: Reactive power analysis for DUT3

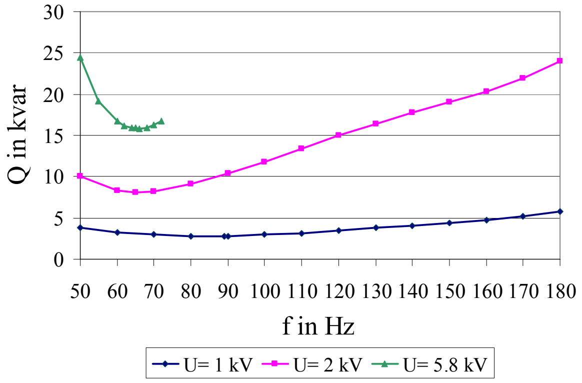

Figure 10: Reactive power analysis for a power transformer

5. CONCLUSION

Regarding the evaluation of the applied criteria the symmetrical shape of the three-phase-system generated by the static frequency converter has proved to be acceptable for measurements with induced voltage, no-load and load measurements.

In the laboratory tests the distortion of the test voltage is strongly depending on the resulting series reactance in the circuit especially for no-load tests. Voltage distortion rises with increasing rated power of the DUT and thus increasing current flowing in the test circuit. For the same DUT voltage distortion is depending on the chosen tap of the step-up transformer: Stepping up the adjusted voltage ratio worsens the resulting voltage distortion, as series reactance is increased and output voltage of the static frequency converter is reduced. For the different testing procedures, DUT and tap positions of the step-up transformer the degree of distortion has been assessed with different criteria established by international standards. Conducting no-load measurements with the static frequency converter as voltage source, satisfying results could only be obtained adjusting the lowest possible voltage ratio. Unless using the ideal tap, at least one criterion can not be fulfilled. Tests were repeated employing a mains-operated adjustable transformer and a rotary converter to compare not only the results for the voltage distortion but also to evaluate the deviation of the no-load losses: Voltage distortion could not be improved significantly; in the case of the 800-kVA-distribution transformer the static frequency converter could produce a test voltage with even less distortion. The maximum deviation among the results for the no-load losses for a specific DUT increases with the rated power. The measured values turned out to be different for static frequency converter operation, for adjustable transformer operation and for employment of the rotary converter and proved to be dependent on the settings of the step-up transformer.

Due to a sinusoidal wave shape of the current the quality of the test voltage during load measurements has significantly improved compared to no-load measurement. Nevertheless, the criterion relating crest value to rms value of the voltage can only be fulfilled for the step-up transformer being set to the lowest possible voltage ratio. In this case changing the voltage ratio of the step-up transformer only has limited impact on measured load losses and short-circuit impedances. Examining the distortion of the voltage wave shape during measurements with induced voltage, at least one criterion, except |*d*|, could not be fulfilled for all tested frequencies.

An analysis of the dependency of the demand for reactive power on voltage level and frequency shows, that there is always absorption of reactive power, although each of the examined transformers shows a frequency range, in which the absorbed reactive power is minimal. Position and width of this frequency range, as well as the dependency on the applied voltage level and the absolute value of reactive power is different for the various DUT and cannot be pre-estimated at the current point of research.

6. REFERENCES

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