Impact of external influences on the frequency dependent transfer ratio of resin cast MV voltage instrument transformers

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Abstract—**Inductive voltage transformers are widely used in medium voltage networks to measure harmonic voltages. The accuracy of these voltage transformers at frequencies other than nominal frequency (50Hz/60Hz) is not yet defined by standards, but can have a significant impact on the overall accuracy of voltage harmonic measurements. Consequently, the accurate assessment of harmonic voltage levels, e.g. for verifying compliance with compatibility levels, planning levels or emission limits, requires knowledge about the frequency-dependent transfer characteristic of the used voltage transformers. This transfer characteristic of a voltage transformer is not constant, but depends on a complex set of influence factors, like temperature, burden, etc. Therefore, within the EMPIR project 19NRM05 IT4PQ, the effects of different external factors on the accuracy of inductive voltage transformers is systematically investigated. This paper shows the influence of selected external factors (temperature, burden and primary voltage) on the frequency-dependent transfer characteristic of resin cast medium voltage instrument transformers.**

Index Terms: **voltage instrument transformer, harmonics, power quality measurement, measurement uncertainty.**

I. INTRODUCTION

The growing penetration of nonlinear components and power electronics in electrical grids leads to an increasing relevance of power quality (PQ) measurements, e.g. to verify the compliance of voltage disturbance levels with compatibility levels, planning levels or emission limits. As part of the measurement chain, the performance and accuracy of the instrument transformers (IT), which are used in all voltage levels above low voltage, can have a significant impact on the overall accuracy of the measurement chain. In many cases, existing inductive voltage transformers (IVTs) are used for PQ measurements. While the accuracy of the measurement instruments is well defined in IEC 61000-4-30 [1], no normative requirements for the accuracy of IVTs do presently exist for the frequency range required for PQ measurements. Therefore, up to now IVTs are usually designed to measure accurately at nominal frequency and can introduce significant errors due to their frequency response, e.g. for voltage harmonic measurements. Consequently, revisions of the relevant standards are urgently required and already in progress. The EMPIR project 19NRM05 IT4PQ support the respective IEC committee TC 38 in the development of respective methods for the traceable characterization of medium voltage (MV) IVTs for PQ measurements [2]. The frequency-dependent transfer characteristic (frequency response) of an IVT and hence the accuracy of PQ measurements can vary in large ranges depending on a complex set of influence factors.

Despite some research on the frequency response for MV IVTs already exists, a systematic and comprehensive evaluation of the frequency response of MV IVTs, especially regarding the impact of external influence factors like temperature or burden, is still missing. Therefore, the systematic and comprehensive analysis of such influence factors and their importance for accurate PQ measurements are an integral part of the EMPIR project. As part of this research activity, this paper presents the results of extensive measurements studying the impact of selected influence factors on the frequency response of resin cast MV IVTs with rated primary voltages in the range of 10 kV to 35 kV.

The paper starts with a short systematization of possible influence factors. Section III describes the measurement system, while sections IV and V present the respective measurement results. The paper finishes with a summary and still open aspects for future work.

II. CLASSIFICATION OF INFLUENCE FACTORS

Previous research of the authors has shown that the frequency response of MV IVTs can be considerably affected by a large set of influence factors, which can be classified depending on their origin into constructional, ambient and operational influence factors [3]. While constructional factors are related to the physical design of the IVT, ambient factors describe the impact of the surrounding conditions of the IVT. The specific electrical conditions on primary and secondary side of the IVT are attributed to the operational factors, which are of particular importance for the development of simplified setups (e.g. the use of significantly lower voltage magnitudes for testing) for the measurement of the frequency response of IVTs.

1. Constructional influence factors
    - Rated primary voltage
    - Design (windings, iron core, …)
    - Manufacturing tolerances
2. Ambient influence factors
    - Temperature
    - Distance to metallic parts
    - Electric and magnetic field
    - Vibration
3. Operational influence factors
    - Burden
    - Primary voltage
        - Frequency of fundamental component
        - Magnitude of fundamental component

While constructional factors are considered as "internal" influences, ambient and operational factors belong to "external" influences, which is the focus of this paper. Further details on internal influence factors can be found e.g. in [3]. It should be noted that the list of influence factors is not ultimate and might be further extended in the future. The analysis of all external influence factors individually and in combination is a complex and extensive task. Therefore, this paper presents the results of the individual influence of temperature, burden and primary voltage, which are, based on experiences, expected to have the greatest impact on the frequency response of IVTs.

The analysis is performed based on laboratory measurements of four selected resin cast MV IVTs representing the most commonly used rated primary voltages (1x 10 kV, 2x 20 kV and 1x 35 kV) and technology. As all measured IVTs show a similar behavior, the results are presented exemplarily only for the 35 kV IVT.

III. Measurement System

Depending on the required magnitude of the primary voltage, two different measurement setups, namely a low voltage (LV) setup and a high voltage (HV) setup, are used for the study. The principle schemes of both setups are shown in Fig 1. In the LV setup, the IVT is excited directly by a power amplifier with a mixture of the fundamental at rated frequency and a frequency-variable higher frequency (HF) component. Voltages up to an RMS value of 270 V can be generated using this setup. In the HV setup, the fundamental and the frequency-variable HF component are generated separately and superimposed by two special step-up transformers. Voltages with RMS values of up to 24 kV can be generated with this setup. Existing radiated or conducted disturbances, which most likely occur at mains frequency and its harmonics, as well as the distortion generated by the nonlinear characteristic of the IVT itself (iron core) can affect the measurement of the frequency response. Therefore, unless marked differently, HF components have been intentionally selected at interharmonic frequencies 5 Hz above the intended frequency (i.e. 155 Hz instead of 150 Hz, etc.). Further background on this aspect is given in section V.B).

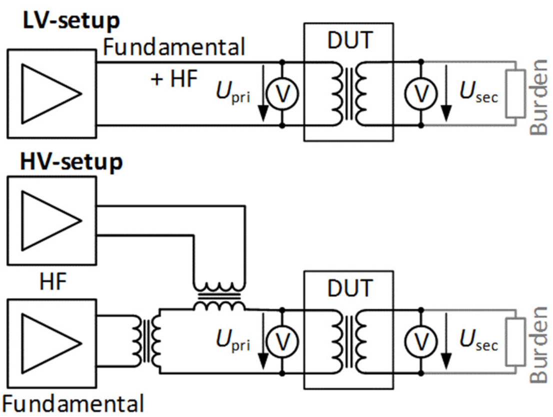

Figure 1 Principal scheme of the measurement setups (above: low voltage (LV) setup, below: high voltage (HV) setup

In the LV setup, the primary and secondary voltages are measured directly with signal conditioning modules, while in the HV setup the primary voltage is measured with a capacitive divider, which has been calibrated before the measurement. Primary and secondary voltages are sampled with a data acquisition system at 1 MS/s and transferred into the frequency domain. Finally, the frequency-dependent ratio error for all applied HF components is calculated. The frequency-dependent phase displacement is not considered in this paper due to space reasons and its lower importance in standardization.

IV. Ambient Influence Factors - Temperature

The ambient *temperature* can affect the ratio error of an IVT in a wide range, depending on where the IVT is located. Therefore, IEC 60721-3-3 [5] introduces different temperature classes depending on the application. MV IVTs are mostly installed in indoor switchgears, but can be in some cases also installed outdoors. Consequently, for this study the temperature range corresponding to class 3K24 (places without temperature control) according to IEC 60721-3-3 has been applied, which is defined as -25°C .. 55°C.

All measurements were performed without burden in order to avoid in the first stage a mix of multiple influence factors. The LV setup was used for the measurement, since the climatic chamber is not designed for applying high voltages inside. The frequency response of the IVTs was measured in 10 K steps from -30°C to 50°C. After each temperature change, 20 hours (about ten times the thermal time constant of the IVT) are given to the IVT to settle in a thermally steady state before the measurements have been performed.

Figure 2 shows the effect of temperature on the 35 kV IVT. The change in temperature shifts the resonance frequencies (around 3 kHz and 6 kHz) as the winding geometry changes. As the temperature rises, the IVT expands, increasing the distance between the winding layers and thus reducing the stray capacitances. As a result, the resonance frequency decreases with rising temperature.

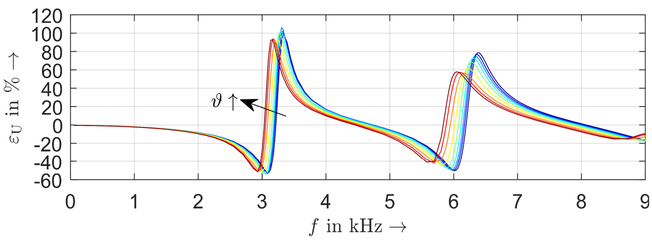

Figure 2 Influence of temperature in the range from -30°C to 50°C in 10 K steps.

Figure 3 shows the change of the ratio error due to the change of the temperature for the first resonance. The frequency response at 20°C is selected as reference, and the difference between the frequency responses at other temperatures and the frequency response at 20°C is presented. Little change is observed at frequencies below the first resonance frequency (upper part of Figure 3). At rated frequency no measurable change due to temperature is observed, while the ratio error at 2.5 kHz slightly changes by ±3 %. In contrast, very large changes are present in the frequency range around the first resonance (lower part of Figure 3). Depending on the frequency, the ratio error can change by more than 100 % between minimum and maximum temperature (e.g. at 3.1 kHz from $\varepsilon_{\mathrm{U}}(\vartheta = -30°C) = -38$ % to $\varepsilon_{\mathrm{U}}(\vartheta = 50°C) = +92$ %).

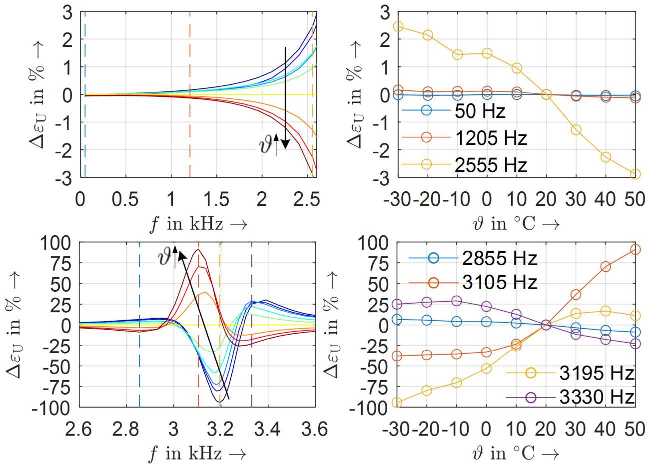

Figure 3 Change of the ratio error as the temperature ranges from -30°C to 50°C in 10 K steps (ratio error at 20°C is selected as reference).

V. Operational Influence Factors

A. Burden

The rated burden of an IVT is defined in IEC 61869-3 [6] for $\cos(\varphi) = 0.8$ (inductive). However, realistic burden values largely vary in terms of impedance magnitude and phase angle (i.e. the combination of resistance, inductance and capacitance). Especially in case of longer connection cables on the secondary side, it can contain a significant capacitive part. If the burden contains inductive and/or capacitive parts, the resulting burden impedance depends significantly on the frequency. A series combination of resistance and inductance, as defined in the standard, increases its impedance and consequently approaches the case without burden for higher frequencies. Therefore, for this study the impact of pure resistive, pure capacitive and resistive/capacitive burden is analyzed. The measurements were performed on the same four MV IVTs as for the ambient temperature analysis (cf. section IV). As all measured IVTs show a similar behavior, only the results for the 35 kV IVT are presented.

1) *Resistive burden*

Figure 4 shows the influence of a variable resistive burden on the frequency response of the 35 kV IVT. The burden was varied in seven steps from 0 % to 100 % of the rated burden. The measurements were performed in an air-conditioned room to minimize the influence of a changing ambient temperature. It can be seen that the burden has an influence on the entire frequency range. With increasing burden (decreasing impedance), the frequency response shifts in the direction of negative ratio errors.

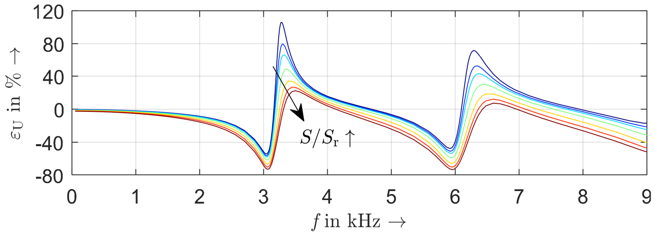

Figure 4 Influence of a resistive burden in the range from 0 % to 100 % of the rated burden (S_{r} = 50 VA).

Figure 5 shows the change of the ratio error due to the change of the burden using the case without burden ($S/S_{\mathrm{r}} = 0$) as reference. The largest change is observed in the range of the resonance, which is damped by the burden. Depending on the frequency, the ratio error changes by up to 120 %. But unlike to the temperature influence, the change is also clearly visible at frequencies well below the first resonance, with the ratio error at rated frequency changing by up to 2 %.

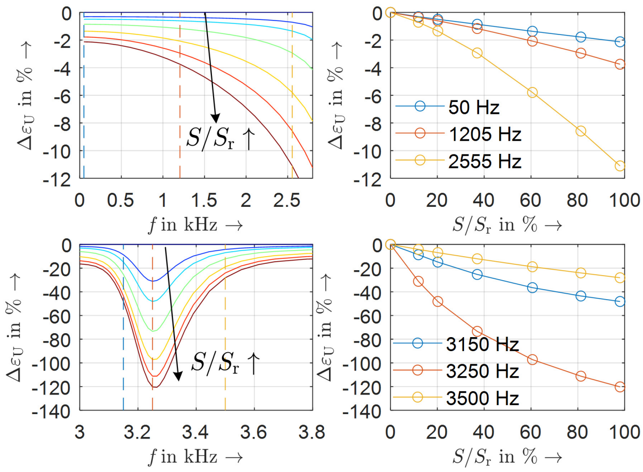

Figure 5 Change of the ratio error by the burden (frequency response without burden (S/S_{r} = 0 %) is selected as reference).

2) *Capacitive and resistive/capacitive burden*

A case that has not yet been considered in the standardization is the possibility of capacitive burden. The voltage inputs of modern measurement instruments have usually input impedances in the range up to 10 MΩ (at power frequency) with resistive/capacitive characteristics. Consequently, the capacitance of the voltage measurement inputs together with the capacitance of the secondary connection cable can be a significant part of the burden, especially at higher frequencies. To estimate the possible capacitance of the burden, the impedance of the voltage measurement inputs of nine PQ measurement instruments was measured, resulting in a capacitance of up to 3.5 nF. The length of the secondary connection cable of the IVT in MV switchgears is typically up to 5 m, sometimes up to 20 m, but can reach in rare cases up to 50 m. With a typical capacitance of 0.14 nF/m, this results in a maximum cable capacitance of 7 nF. Therefore, as worst case including a margin of about 20 %, a capacitance of 12 nF may be expected as burden.

Figure 6 shows an example of the influence of an additional capacitance of 12 nF in parallel to a resistive burden of 0 % and 20 % of the rated burden. The additional capacitance has an influence on the ratio error, which increases with the frequency. Figure 7 shows the change of the ratio error due to the added capacitance. The reference for both curves is the frequency response with the same resistive burden but without capacitance. Two phenomena are visible: On the one hand, the additional capacitance dampens the resonances. In the resonance minima, the ratio error is shifted to the positive and in the resonance maximum to the negative. Consequently, the capacitance can reduce the absolute ratio error in the range of resonances, but at a low level. As expected, outside the resonance areas the impact of a capacitance increases with the frequency. Comparing the cases without resistive and 20 % resistive part, the additional capacitance has a lower influence at the higher resistive burden part.

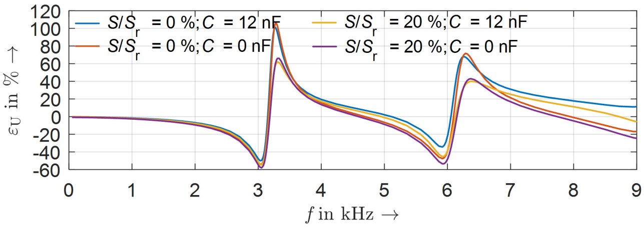

Figure 6 Influence of a capacitive part in the burden.

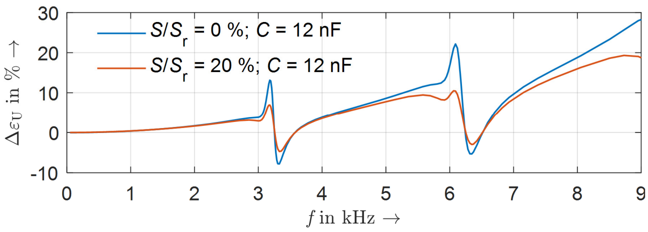

Figure 7 Change of the ratio error by a capacitive part of the burden. The respective case with the same resistive burden but without capacitive part is selected as reference.

B. *Primary Voltage*

The influence of the primary voltage on the measurement uncertainty of an IVT is not only relevant for the normal grid operation, but also for the setups to measure the frequency response as accurate as possible compared to the frequency response under realistic operating conditions. A measurement setup that reproduces realistic operating conditions with a fundamental voltage component at the IVT's rated frequency and magnitude plus a frequency-variable harmonic is complicated and expensive [7]. Therefore, as part of the EMPIR project, possibilities to simplify the measurement setup while maintaining a frequency response comparable to the one under realistic operating conditions, are studied. Consequently, the following subsections study the impact of different features of the primary voltage not only in the characteristic variation ranges for typical operating conditions, but also for considerably extended ranges. As in the sections before, the results for the 35 kV IVT are exemplarily presented. The results of the other measured MV-IVTs are qualitatively comparable.

1) *Frequency of fundamental component*

The possible variation range of the mains frequency can be determined from standards. For example, EN 50160 [8] specifies a range from 48 Hz to 52 Hz for synchronous (interconnected) grids and a range from 42.5 Hz to 57.5 Hz for asynchronous grids (i.e. on islands). Realistic variation ranges of the mains frequency based on world-wide long-term measurements are presented in [9]. A maximum standard deviation of 0.15 Hz has been found, which corresponds to a variation range between 49.1 Hz and 50.9 Hz, if an expanded uncertainty factor of 6 is considered.

In order to observe the principle effect of a frequency variation, the frequency of the fundamental was varied over an extended range from 5 Hz to 50 Hz. Figure 8 shows the change in the ratio error. The variation of the fundamental frequency has a small effect on the ratio error. The largest change is visible in the range of the resonance frequency with up to 3 %, which may not be significant. The measurements were performed in an air-conditioned room and not in a climatic chamber, where the ambient temperature is kept exactly constant. Therefore and based on the results of the temperature measurements in IV, this change of the ratio error could be also caused by a temperature change of 0.8 K. Thus, it cannot be said for certain that the change of the ratio error at the resonance frequency was caused by the frequency change.

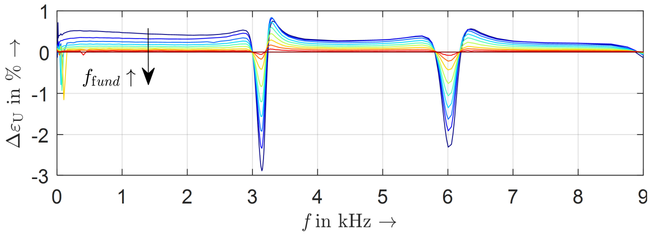

Figure 8 Change of the ratio error by variation of the fundamental frequency from 5 Hz to 50 Hz in 5 Hz steps. Measurement with 50 Hz fundamental is selected as reference.

Figure 9 shows the change of the ratio error for selected frequencies outside the resonances, where a possible influence of the temperature is negligible. It can be seen that the influence of the fundamental frequency is approximately the same for all selected frequencies. Reducing the fundamental frequency to 5 Hz increases the ratio error by almost 0.5 %. In the realistic frequency range down to 42.5 Hz, the change is less than 0.05 % and thus in principle negligible.

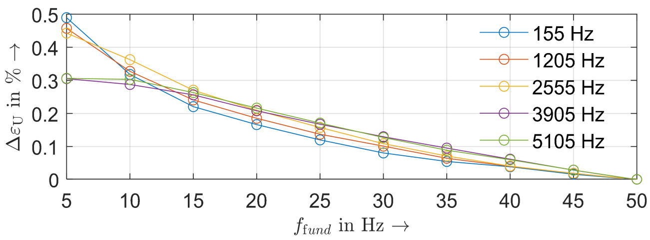

Figure 9 Change of the ratio error by variation of the fundamental frequency for selected frequencies. Measurement with 50 Hz fundamental is selected as reference.

2) *Magnitude of fundamental component*

The possible variation range of the magnitude of the primary voltage, which is almost solely determined by the fundamental component, can also be taken from standards. For example, according to EN 50160 [8], at the supply points of MV customers, the supply voltage magnitude shall be in the range ±15 % of the declared voltage for 100 % of the time.

IEC 61869-3 specifies that IVTs must achieve their accuracy in the range of ±20 % of the nominal voltage [6].

In order to evaluate the representativeness of simplified measurement setups using a significantly reduced fundamental, the variation range has been extended to cover a range from 0.1 % to 100 % of the rated primary voltage of the IVTs. For the 35 kV IVT used as an example, this means that the fundamental voltage magnitudes range from 20.2 V (0.1 %) to 20.2 kV (100 %). The superimposed frequency-variable component has always a magnitude of 5 % of the fundamental.

Figure 10 shows the variation of the ratio error caused by the variation of the fundamental magnitude. A significant variation of the ratio error is visible, especially in the area of resonances. As the measurements could not be carried out in an air-conditioned room or a climatic chamber with controlled ambient temperature, the areas of the frequency responses close to resonances (3.1 kHz and 6 kHz) are most likely affected by the temperature and should not be analyzed. Nevertheless, the frequency range up to 2.5 kHz can be evaluated.

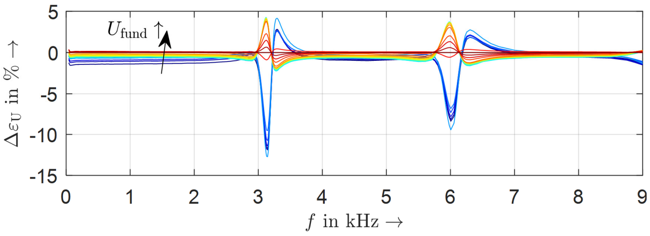

Figure 10 Change of the ratio error by variation of the fundamental magnitude from 0.1 % up to 100 % of the IVT's rated voltage. Measurement with rated voltage is selected as reference.

Figure 11 shows the change of the ratio error for selected frequencies below the first resonance point as a function of the fundamental magnitude. A very small voltage fundamental causes a ratio error deviation of up to 1.6 % compared to the ratio error at rated voltage. The ratio error behaves highly nonlinear, but similar for all frequencies. These findings justify the use of a reduced fundamental voltage of about 1 % to 5 % of the rated voltage, if an influence of around 0.5 % on the ratio error is acceptable. Within the variation range, which is realistic for typical operating conditions, the change of the ratio error reaches a maximum value of 0.07 % at 80 % of the rated voltage and is therefore virtually negligible.

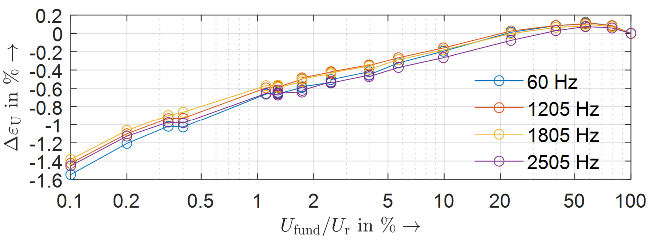

Figure 11 Change of the ratio error caused by the variation of the fundamental magnitude for selected frequencies. Measurement with rated voltage is selected as reference.

3) Nonlinearity of the iron core

Regarding laboratory measurements, interharmonic frequencies are used to determine the ratio error (cf. section II). The ratio error at harmonic frequencies is interpolated using the ratio errors at the respective neighboring interharmonic frequencies. This avoids interferences of the mains frequency with the measurement setup, but also the unwanted impact of any distortion generated by the IVT due to the nonlinear characteristic of its iron core, which is expected to be present at low order odd harmonics. However, under realistic operating conditions, especially low order odd harmonic voltages appear and have to be measured in MV networks. Consequently, the possible impact of the nonlinear characteristic of the iron core has to be analyzed in detail.

Therefore, up to the 11th harmonic (i.e. 550 Hz), the ratio error for different fundamental magnitudes has been measured both at the interharmonic frequencies (h·50 Hz + 5 Hz) and at the respective harmonic frequencies (h·50 Hz). Figure 12 shows that the magnitude of the fundamental has a clear effect on the ratio error for the low order odd harmonics. This effect is strongest at the 3rd harmonic (150 Hz), significant for the 5th harmonic (250 Hz), still visible for the 9th and almost negligible for the 11th order.

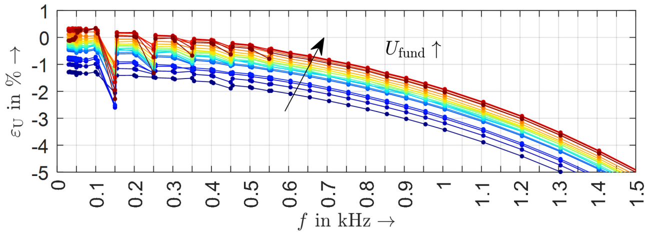

Figure 12 Influence of the fundamental magnitude on low order odd harmonics, variation of the fundamental magnitude from 0.1 % up to 100 % of the rated voltage, HF component with 5 % of fundamental

This influence can be explained using the simplified transformer equivalent circuit shown in Figure 13. The magnetizing current of the IVT $\underline{I}_m$ is nonlinear. Due to the half-cycle symmetry of the magnetization curve, it contains only odd harmonics, which depend on the level of excitation of the iron core and decrease with increasing harmonic order. The current leads to a voltage drop $\underline{U}_z$ across the primary impedance, which superimposes with the existing primary harmonic voltage $\underline{U}_p^{(h)}$ to the resulting secondary harmonic voltage $\underline{U}_s'^{(h)}$. In simple terms, the IVT generates voltage harmonics on the secondary side, which are not present on the primary side.

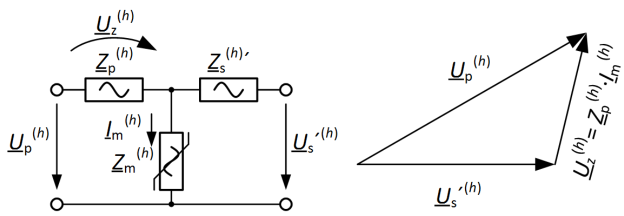

Figure 13 Simplified transformer equivalent circuit as explanation for the influence of the fundamental on the ratio error of low order odd harmonics

To verify this hypothesis, an additional series of measurements was carried out. A constant fundamental of 260 V was used and the HF component at harmonic and interharmonic frequencies was varied from 0.5 % to 5 % of the fundamental (from 1.3 V to 13 V).

Figure 14 shows the measured HF component of the secondary voltage referred to the primary side for the 3rd and 5th harmonic order (150 Hz and 250 Hz) and the respective interharmonic frequencies (155 Hz, 255 Hz). Assuming that the complex transfer ratio is approximately the same for 150 Hz and 155 Hz as well as for 250 Hz and 255 Hz, the curves for harmonics and respective interharmonics are shifted by a constant value in the complex plane. This shift corresponds to the additional voltage introduced by the respective harmonic of the magnetizing current on the secondary side that depends on the fundamental. For the fundamental used in this example, the additional voltage is $(-0.17 + i{\cdot}0.11)$ V for 150 Hz and $(-0.08 + i{\cdot}0.07)$ V for 250 Hz.

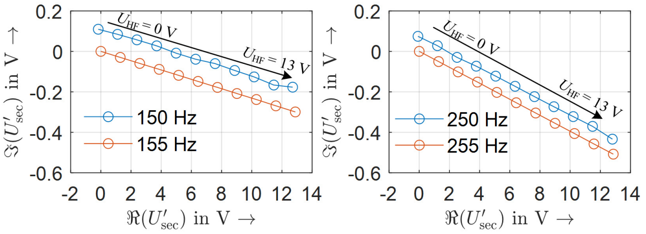

Figure 14 Nyquist plot of measured secondary HF component (referred to primary side) when varying the primary HF component from 0 V to 13 V at constant primary fundamental of 260 V.

Since the harmonic voltage caused by the magnetizing current and the primary harmonic voltage are complex phasors, the impact on the ratio error depends on the magnitude and the phase angle of both voltages (cf. Figure 13). At lower magnitudes of the HF component, a large error is expected since the harmonic voltage drop caused by the magnetizing current dominates the secondary voltage. At higher magnitudes of the HF component, the impact on the ratio error becomes smaller. This is confirmed by Figure 15. It shows that for lower odd harmonics the ratio error reduces with increasing magnitude of the HF component. On the other hand, the plot also confirms that the magnitude of the HF component has no influence at frequencies of interharmonics and even harmonics.

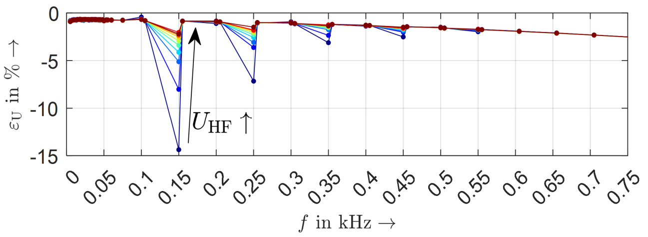

Figure 15 Influence of the magnitude of the HF component varying from 0.5 % to 5 % of the constant fundamental on the ratio error

Since these measurements were performed only with the LV setup, further research must determine, if and how this influence is relevant under realistic excitation conditions (HV setup).

VI. SUMMARY

The frequency response of inductive voltage transformers (IVTs) can be influenced by many constructional, ambient and operational factors. The influence is different in intensity and affected frequency ranges. The ambient temperature shifts the resonance points of IVTs and therefore it significantly affects the ratio error around the resonance frequencies in particular. In contrast, the burden, especially in case of dominating resistive and/or capacitive parts, has an influence on the entire frequency range, whereby the influence around the resonance frequencies is again strongest, but the influence at lower frequencies cannot be neglected. The primary voltage can also have an influence on the frequency response of an IVT. The influence of frequency and magnitude of the fundamental component can be neglected under typical operating conditions. However, very low voltage magnitudes have a non-negligible influence, which has to be considered, when simplified measurement setups are developed. Furthermore, the low order odd harmonics caused by the magnetizing current of the IVT can affect the ratio error. The impact depends on the magnitude of the fundamental, the magnitude and phase angle of the primary harmonic voltage, which is to be measured, as well as the impedance of the primary winding. It is not yet clear, how this phenomenon should be handled and further studies are required.

Future activities within the project include the analysis of the not yet considered influence factors and the extension of existing measurements, particularly with respect to a realistic variation range of the influencing factors. Finally, the superposition characteristic of combined influence factors is to be studied.

The results contribute to the development of traceable and simple methods for the determination of the frequency response characteristics of IVTs, which supports IEC in the revision of the respective standards including requirements on the accuracy of IVTs at frequencies other than the rated frequency.

ACKNOWLEDGMENT

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