Cost-effective Approach for On-line Measurement of Harmonics in Power Systems

J. L. Velásquez, N. Liu, J. Reisbeck, S. Beckler, C. Butterer, S. Wenig

Abstract—**Due to the increase of non-linear loads in distribution networks, but also in transmission networks, there is a corresponding increasing interest on evaluation of the harmonic situation. For such evaluation power quality measurements are carried out, under which the voltage as well as the current harmonics can be assessed. This contribution describes an approach that can be used to measure voltage and current harmonics in a cost-effective way without the need of installing expensive high voltage equipment. The proposed approach is based on an accurate voltage measurement through the measurement tap of power transformer bushings as well as on current measurements using Rogowski-coils. For validation purposes the measurement system was put into operation in a 400 kV power transformer resulting in satisfactory data acquisition which confirms technical feasibility. From the measured data, the proposed "apparent" harmonic impedance of the AC networks can be determined, which is a useful indicator to monitor the harmonic situation.**

Keywords: **harmonics, Rogowski-coil, transformer bushing, coupling unit, harmonic impedance, point of common coupling, PQ-device.**

I. INTRODUCTION

It is well known that the presence of harmonics deteriorates power system stability and reliability. On the one hand, harmonics can lead to additional thermal stress of high voltage equipment [1]. On the other hand, harmonics can lead to harmonic stability problems, particularly in renewable power systems [2]. Due to this reason, network operators put significant effort in a reliable evaluation of the harmonic situation of their networks [3]. In the past, issues related to harmonics were mainly a topic in industrial and distribution networks, where a high level of power electronic devices (i.e. frequency converters, solar inverters) are installed, while harmonic content in transmission networks has been negligible. Nevertheless, in the last years more attention has been given to the evaluation of the harmonic situation of the networks at transmission level. Due to the changes that power systems are facing in some countries, mainly driven by the increasing penetration of renewable energies, the behavior of the harmonic situation in transmission networks has correspondingly changed. It is also expected that the situation will probably worsen when the power electronics penetration is further increasing. The installation of power electronic-based systems, such as HVDC schemes and STATCOMs, are examples of assets which contribute to changes in the harmonic situation of transmission networks. Additionally, in some countries there is also an increasing trend of respective need to install underground high voltage cables. As the impedance of a cable is different compared to the impedance of an overhead transmission line, changes in the natural resonances of power systems are expected. These changes in combination are the key motivation to look for reliable and cost-effective measurement and monitoring possibilities.

In view of the importance of assessing the harmonic situation of a transmission network, a research project has been initiated with the goal of developing a concept for on-line monitoring of the harmonic situation of the transmission network. The following three main requirements have been defined for the project: the bandwidth of the measurement system shall allow an assessment of harmonics at least up to 9 kHz, existing infrastructure shall be used as much as possible, the measurement of the harmonic impedance shall be possible. In order to meet the requirements, a novel measuring system was conceptualized. The main novelty of the proposed method is the fact that the measurements are based on existing substation infrastructure. Only a few sensors had to be installed, allowing a very cost-effective way of performing the measurements in this manner. The paper describes the first experiences obtained from the pilot installation of the measurement system, which has been put into service in a 400 kV substation of German network operator TransnetBW.

Chapter II describes general approaches for harmonic measurements, while Chapter III introduces the specific measurement system used within this project. Chapter IV describes the data analysis using the obtained measurement data. Chapter V analyses the possibility to derive harmonic impedances based on the measured quantities. Finally, Chapter VI concludes the paper.

II. APPROACHES FOR HARMONIC MEASUREMENTS

A typical approach to monitor the harmonic situation in transmission networks is based on harmonic voltage measurements. There are different kinds of power quality devices (PQ-device), which are commercially available for a permanent monitoring of harmonics. The most straightforward approach is to connect the PQ-device to the secondary side of a conventional voltage transformer (normally an inductive

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voltage transformer placed at the busbar of the substation). The main disadvantage of this approach is, especially at transmission levels, that due to the non-linear behavior of the voltage ratio of the voltage transformers measured harmonic levels are erroneous. The reasonances created by the inductances and by stray capacitances of the insulation lead to a non-linear behaviour of the ratio. For more details see referece [4]. A possibility to improve accuracy of the measurement is to use a resistive-capacitive voltage divider [5].

As the harmonic limits at transmission level are only given for the voltage [6], it is common to limit evaluation to this quantity. However, for an extended analysis of the harmonic situation, in which not only the fulfillment of harmonic voltage requirement is of interest but also the harmonic power flows, the harmonic of the current shall be measured. There are different publications dealing with the evaluation of harmonic power to identify the source of harmonic distortion [7]. Some of these methods are even implemented in commercially available PQ-devices. The most common method is the so called "power direction" method. Even though this method is commonly used, it shall be mentioned that according to previous research works, the validity of using the "power direction" method for determining the source of harmonics is questionable [8].

An additional topic of great interest is the possibility of measuring harmonic impedances. The methods for measuring harmonic impedances can be classified as invasive and as noninvasive methods. In the case of invasive methods, the injection of a signal is needed for calculating the harmonic impedances [9,10]. Noninvasive methods are based on voltage and current measurements at the points of common coupling (PCC) between utility and customer, without any external injection of signals. The measured impedance is in this sense based on existing harmonics [11] or on the analysis of the waveforms of voltages and currents measured during switching transients [12]. The main advantage of invasive methods is the possibility of measuring the harmonic impedance in a wide frequency range by a proper excitation of all frequencies of interest. A challenge of invasive methods, especially in high voltage networks, is the way how the excitation signals can be safely injected without disturbing the stable operation of the network. It is for this reason that the use of noninvasive methods is preferred. A common noninvasive approach for determining a harmonic impedance is based on the ratio of harmonic voltage and current increments caused by a load change according to the (1) [10].

$$Z_p(f) = \frac{U_{pcc2}(f) - U_{pcc1}(f)}{I_{pcc1}(f) - I_{pcc2}(f)} = \frac{\Delta U_{pcc}(f)}{\Delta I_{pcc}(f)} \quad (1)$$

This method relies on the measurement of current (I_{pcc}) and voltage (U_{pcc}) at the PCC between the utility and the customer at two different points of time. The indexes 1 and 2 in (1) represent two different power system states, i.e. two different points of time. A Thevenin equivalent circuit of a power system is shown in Figure 1. The impedances Z_p and Z_s represent the harmonic impedances to the left side and to the right side of the PCC, respectively. The voltage sources U_{hp} and U_{hs} represent the background harmonics of the networks to the left side and to the right side of the PCC. An important remark is that the flow of harmonics at a given point of time is affected by the presence of background harmonics from both sides of the PCC. In such a situation, the estimation of a harmonic impedance is not straightforward. That is the reason why the method according to (1) is valid only under the assumption that there is no variability of the utility side parameters U_{hp} and Z_p. This assumption might be valid in certain power systems. Nevertheless, the validity of this assumption is questionable particularly in the case of a meshed network, where a bidirectional harmonic flow takes place.

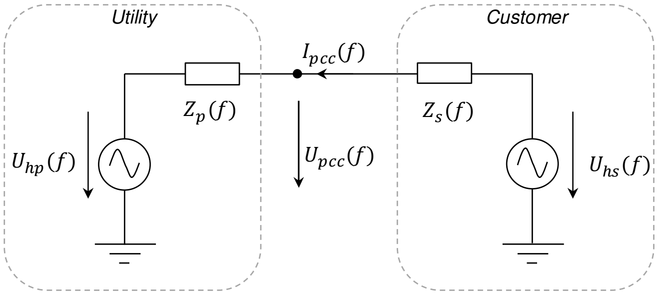

Fig. 1. Thevenin equivalent circuit used for noninvasive harmonic impedance estimation

Another possible approach for nonintrusive measurement is the one based on switching transients of a capacitor bank. This method is described in [10,12]. Recording the voltage and current signals in a time window including the transient allows the assessment of the harmonic impedance as seen at the PCC of the capacitor bank to the network. The main limitation of this method is that the presence of a capacitor bank is necessary.

III. DESCRIPTION OF THE MEASUREMENT SYSTEM

Measurements up to at least 9 kHz impose strong requirements on the bandwidth of voltage and current sensors. As the conventional instrument transformers available in the substation do not offer a sufficient bandwidth for a reliable assessment of harmonics up to 9 kHz, different alternatives have to be evaluated. In literature a measurement system for monitoring transient stresses of distribution transformers using the bushing-embedded capacitive voltage dividers and Rogowski coils is presented [13]. This measurement concept is an attractive option, as it fulfills the requirements on both, bandwidth and utilization of existing infrastructure. Due to these advantages, it has been decided to follow this concept for the measurement of harmonics.

The voltage measurement was carried out through a voltage divider consisting of series connection of the capacitance C_1 of the 400 kV bushing of a 400/110 kV transformer and the capacitance of an OMICRON coupling unit (CPL 843 with an additional accessory), which was connected to the test tap of the bushing. The divider is schematically depicted in Fig. 2. For the current measurement, the Rogowski coil AmpFlex A 130 from manufacturer Chauvin Arnoux was used, where currents going out from the bushing are positive. The polarity of the Rogowski coil was chosen in such a way, that currents going out from the 400 kV side of the transformer are measured as positive. See Fig. 2.

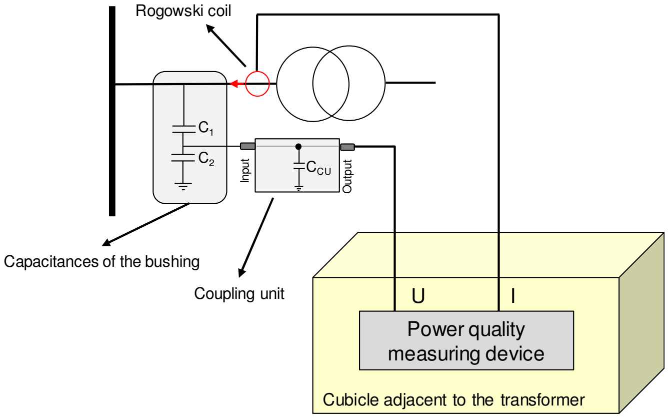

Fig. 2. Schematic view of the measuring system

Fig. 3 shows an overview of the sensor installation on-site, while Fig. 4 shows the cubicle which was installed adjacent to the transformer, where the measuring instrument was placed. As measuring device, the A.Eberle device *PQ Box 150* was used. Additionally, the magnitude and phase angle of the harmonics of the voltages and currents in the ranges from 2 kHz up to 9 kHz according to IEC 61000-4-7 are measured. The setting of the recording intervals is a key setting for the measuring system. As a first attempt, an interval of 10 minutes has been selected. It is part of the pilot project phase to assess a suitable setting for the signal recording.

Fig. 3. View of coupling unit connected to the measurement tap of the bushing for the voltage measurement and view of the rogowski-coil used for current measurement

Fig. 4. View of the cubicle installed closed to the transformer, where the PQ device was installed

The accuracy of the proposed voltage measurement depends mainly on the linearity of the frequency dependence of the capacitances and on the dielectric losses of the capacitances. The effect of the dielectric losses is negligible compared to the effect of the capacitances. Additionally, the capacitance C_2 of the bushing (in the range if pF) is much smaller than the capacitance of coupling unit (usually between 10µ and 1 uF). In this manner the capacitance C_2 can be neglected and the voltage ratio of the divider can be described in a simplified way by (2). An example of a typical frequency dependence of the capacitance C_1 is shown in Fig. 5. Due to polarization effects the capacitance decreases with the increase of the frequency. The capacitance at 9 kHz is approximately only 1 % smaller than the capacitance at 50 Hz. By a proper design of the coupling unit is also possible to get a low frequency dependent capacitance. As a result, the ratio of the divider is not significantly influence by the frequency and it is possible to get a resonance-free and accurate measurement of harmonics. As a next step it is planned to measure the accuracy of the complete measurement system on-site.

$$Ratio = \frac{C_1 + C_{cu}}{C_1} \tag{2}$$

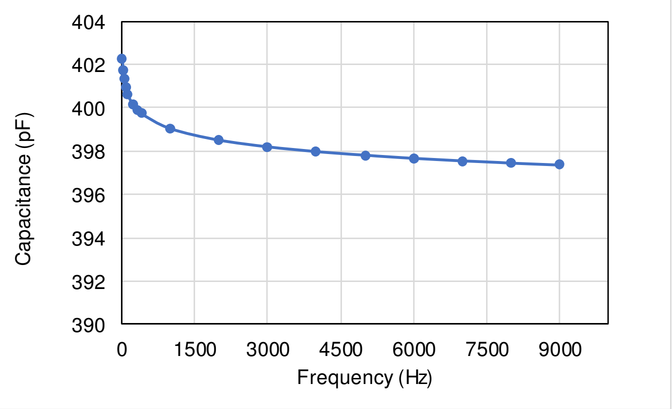

Fig. 5. Example of a typical frequency dependence of the capacitance C1

IV. ANALYSIS OF DATA

For illustration purposes, the data analysis presented in this contribution corresponds only to data measured from 02/10/2018 until 10/10/2018. In a first step, the classical harmonic spectrum of voltages and currents up to 50th order is plotted and analyzed. As an example, Fig. 6 shows the maximum harmonic spectrum of the voltage of the phase L1. The time series of the harmonics has also been analyzed with the aim of observing the presence of a periodical behavior. In Fig. 7, it can be observed that the behavior of the 7th harmonic shows, as expected, a periodical behavior. The harmonic spectrum of the current up to 50th order is shown in Fig. 8. By comparing the spectrums of the voltage and the current, it can be observed that the spectrums are qualitatively similar. In both plots, the 3rd, 5th, 7th, 11th and 13th harmonics are the most significant ones.

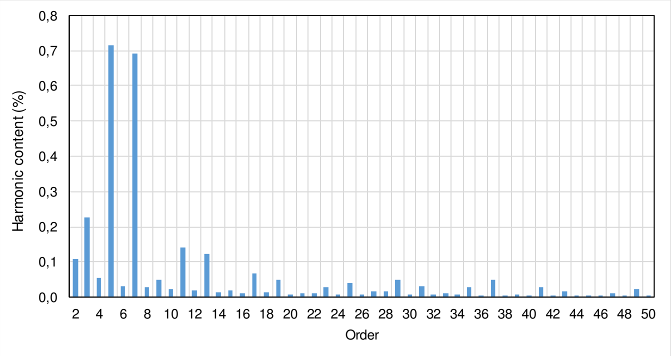

Fig. 6. Harmonic spectrum of the voltage up to 50th order (maximum values)

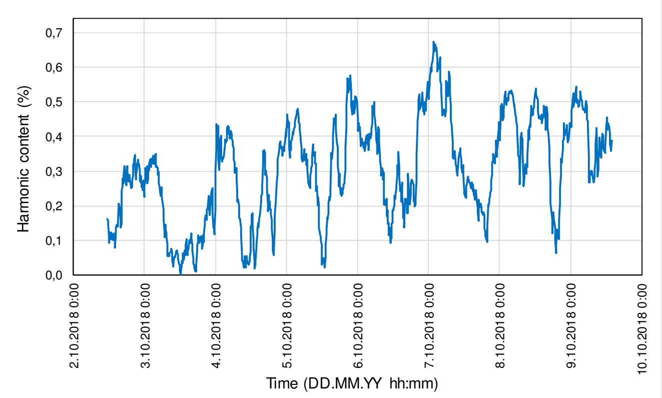

Fig. 7. Time series plot of the 7th harmonic of the voltage

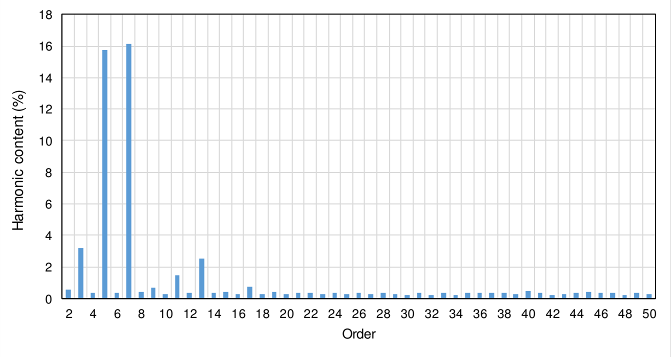

Fig. 8. Harmonic spectrum of the current up to 50th order (maximum values)

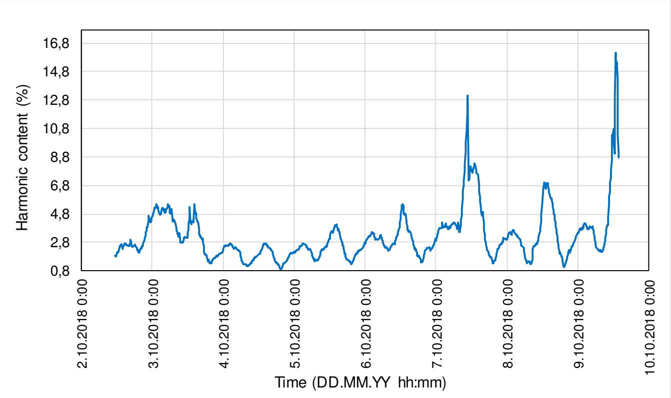

Fig. 9. Time series plot of the 7th harmonic of the current

The harmonics in the range of 2 kHz up to 9 kHz have also been analyzed. In Fig. 10, the resulting harmonic spectrum of the voltage is presented. It can be observed that the harmonic content above 2 kHz is low (below 0.04 %).

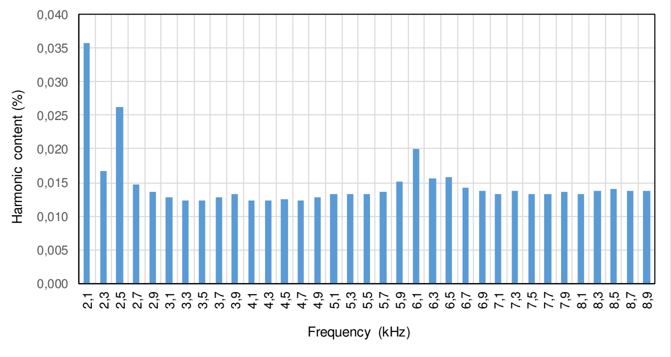

Fig. 10. Harmonic spectrum of the voltage in the range from 2 kHz up to 9 kHz (maximum values)

In addition to the traditional analysis of harmonic spectrums, the simultaneous measurement of voltages and currents allows analysis of harmonic power flows. From the raw data acquired by the PQ-device, the phase angle between the voltages of the harmonic h and the current of the harmonic h (φ_h) are determined. Subsequently, the harmonic active power is calculated according to (3). In a similar way, the reactive power of the harmonics was calculated according to (4), where U_h and I_h are the magnitudes of voltage and current of harmonic h.

$$P_h = U_h I_h \cos\varphi_h \tag{3}$$
$$Q_h = U_h I_h \sin\varphi_h \tag{4}$$

Fig. 10 and 11 show the calculated active and reactive powers for the 3rd (h3), 5th (h5), 7th (h7), 11th (h11) and 13th (h13) harmonic, respectively. Based on the sign of the calculated active and reactive powers some analysis on the predominant source of the harmonics can be carried out, but as already mentioned in Chapter II, it shall be kept in mind that according to previous research works the "power-direction" method might lead to misleading results [8]. According to Fig.

11 the power flows of the relevant harmonics have different patterns. The active power of the 3rd and 13th harmonics appear constant and their magnitudes are, compared to the magnitude of the other relevant harmonics, relatively small (less than 0,3 %). The power flows of the 7th harmonic is changing over time. Bi-directional power flows are also observed. This suggests that during some periods of time the active power of the 7th harmonic is flowing from the 400 kV side of the transformer to the 110 kV side and vice versa. The active power of the 5th harmonic also exhibits an interesting behavior. First, it is observed that the 5th harmonic is flowing from the 110 kV to the 400 kV side most of the time. It is also identified that the pattern is highly dependent on the weekday, which is why a clear difference of the patterns during work days and during public holidays and weekends can be observed. In Germany for example, the 3rd October is a public holiday. In Fig. 11 it can be seen that the active power of the 5th harmonic during the 3rd October is very low. The pattern of the 5th harmonic during the weekends (6/10/18 and 7/10/2018) is similar to the pattern of the 3rd October.

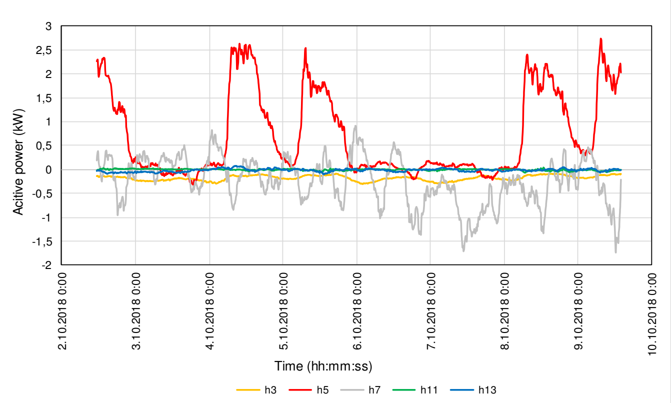

Fig. 11. Calculated power for relevant harmonics

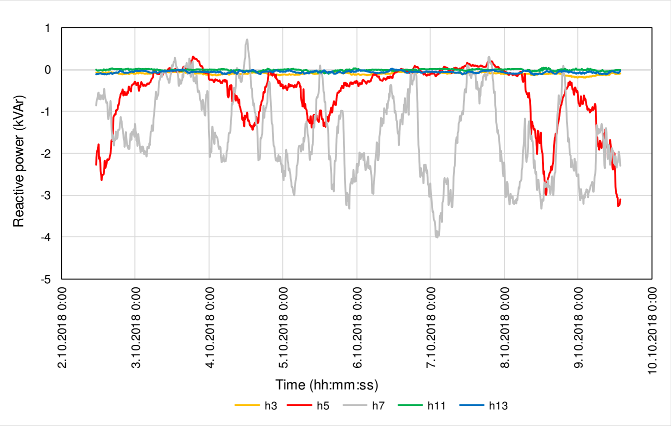

Fig. 12. Calculated reactive power for relevant harmonics

The presence of certain patterns suggests that, following a more thorough data analysis, the behavior patterns of the harmonics can be discovered under consideration of additional information, such as the day of the week and loading conditions (50 Hz currents and voltages). Knowledge about detailed patterns allows at the same time implementation of monitoring systems under which abnormal harmonic situations can be identified. Some ideas about pattern-based evaluation of harmonics are presented in [14].

V. CALCULATION OF HARMONIC IMPEDANCES

In terms of estimation of harmonic impedances, a clear understanding about the impedances, which are measurable at the point of measurement (POM), is needed. Fig. 13 shows the Thevenin equivalent circuit of the power system as seen from the POM. Primary interest is to evaluate the possibility of estimating the harmonic impedance seen from the 400 kV side of the transformer. This impedance corresponds to the impedance Z_p in Fig. 13. Additionally, it would be interesting to identify a methodology to estimate also the impedance Z_s seen from the 110 kV side of the transformer. The harmonic impedance Z_p seen from the 400 kV side can be calculated according to (5). Obviously, for the calculation of Z_p the background harmonics (U_{hp}) seen at the 400 kV side has to be known. Due to the fact that the background harmonics are not known in practice, a direct calculation of the harmonic impedance using (5) is not possible. However, for monitoring purposes the impedance Z'_p calculated according to (6) from the measured voltage U_{Thp} and from the measured current I_{hp} can be used. Here, this impedance is defined as the "apparent" harmonic impedance of the network. If background harmonics are negligible, the apparent harmonic impedance will be very close to the real harmonic impedance of the network. Fig. 14 shows the results of the apparent harmonic impedance calculated from the data of the measurement systems described in Chapter III.

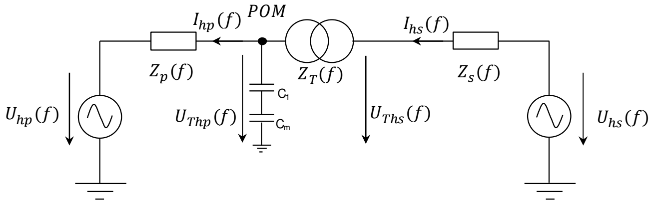

Fig. 13. Thevenin equivalent circuit of the power system as seen from the point of measurement

$$Z_p(f) = \frac{U_{Thp}(f) - U_{hp}(f)}{I_{hp}(f)} \quad (5)$$

$$Z'_p(f) = \frac{U_{Thp}(f)}{I_{hp}(f)} \quad (6)$$

In Fig. 14 the real and imaginary parts of the impedance of the relevant harmonics are shown. The highest variation of R-X-points was observed for the 5th harmonic. In Fig. 14 it can be seen that the resistance has positive and negative values. The meaning of the negative values in Fig. 14 refers to the fact that harmonics are flowing in two directions. The R-X-points of the 3rd and 7th harmonics cannot be appreciated in Fig. 14. This is caused by the high variation of the R-X points of the 5th , 11th and 13th harmonic, which overlap by the R-X-points of the 3rd and 7th harmonics.

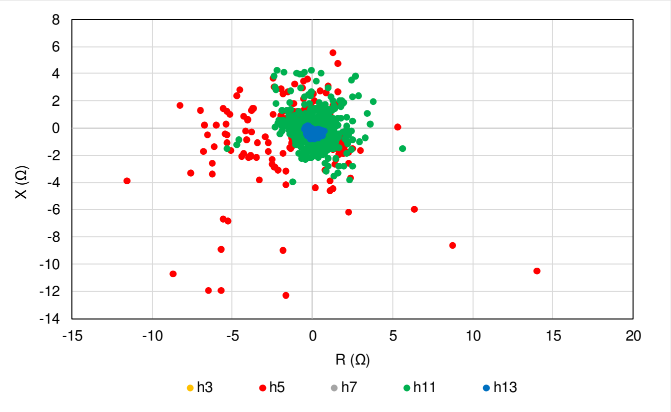

Fig. 14. Apparent harmonic impedance seen from the 400 kV side of the transformer

VI. CONCLUSIONS

The experiences within this project have shown that the harmonic situation at a PCC of a transformer connected to a transmission network can be measured in a very cost-effective way by the measuring system described in Chapter III. The voltage measurement through the test tap of the transformer bushings together with the coupling unit is not only cost-effective, but also an accurate way with a sufficient bandwidth for measuring harmonics up to 9 kHz and even above. The current measurement thought the Rogowski-coils is a method with sufficient bandwidth. From the magnitude and phase angle of the measured voltages and currents, the harmonic situation at the PCC was analyzed. In addition to the classical harmonic spectrums, a deeper analysis has been carried out. The results show that the behavior of the harmonics follow patterns, which depend on the loading conditions as well as on the day of the week (i.e. work day, public holidays or weekends). This suggests that extracting the patterns of such data enables the implementation of sophisticated algorithms for monitoring of the harmonic situation. Furthermore, the data allow for a calculation of an “apparent” harmonic impedance, which is defined within this paper. Even though the apparent harmonic impedance is not completely reflecting the real harmonic impedance of the network, this can be useful for monitoring of the harmonic situation of the network.

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