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On the limitations of harmonic modeling with measured inputs – a case study

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Abstract—**This paper proposes a method for determining the limitations of harmonic modeling based on measured emissions and standard harmonic impedance models using synchronized spectrum measurements. It was found that the calculation method performs very well for the fundamental frequency and reasonably well for some harmonic orders. The limiting factors based on measurement uncertainty are discussed, and some proposals for future studies are given.**

Index Terms--**Power Quality, Power system harmonics, Measurement uncertainty, Phasor measurement units.**

I. INTRODUCTION

One of the important aspects in the control of Power Quality (PQ) phenomena in electrical networks is network observability. To be able to predict the emission and propagation of disturbances, network operators install PQ monitors in a subset of substations, depending on the needs and regulatory requirements – e.g. a representative sample needed to benchmark the quality of supply in the network. The main reason to limit the number of monitoring points is the price, both in terms of equipment and installation efforts.

An additional restriction in PQ monitoring is the number of channels per measurement device. Typically, voltages at substation busbars need to be monitored for regulatory purposes, while current are not obligatory and are installed per needs, where the choice is sometimes made between a number of incoming and outgoing feeders in the substation.

To characterize the propagation of PQ phenomena, disturbance levels at non-monitored locations/feeders often need to be estimated as well, which requires modeling based on limited measurements and network parameters. The modeling of predominantly linear network elements such as transformers, cables, lines and generators is mature knowledge, covered and summarized in many references such as [1]–[3], just to name a few. The validity of these models is sometimes possible to

check in the laboratory, and some studies have shown the deviations from the usually assumed frequency dependent parameters, e.g. [1], [4]. Generalizing these deviations is however difficult, and differences between the laboratory and field conditions – e.g. frequency dependence of parameters, uncertainty of cable length, conductivity of surrounding soil etc., make this task even more difficult. This opens up the question of the accuracy of modelling results if such effects cannot be included.

This paper discusses one possibility for determining the limitations of a calculation based on emission measurement and modelling of harmonic impedances, based on synchronized spectrum measurements. Synchronization of instruments located in different measurement points (not to be confused with matching time-stamps of devices which use individual clocks) is currently uncommon practice in PQ monitoring. However, this functionality is nowadays offered frequently for PQ meters, and PQ functionality is also often included in Phasor Measuring Devices (PMUs), which opens up the possibility to obtain such field data on a larger scale in the future. It should be also noted that PQ analyzers and PMUs use different approaches for defining data windows, as described in the standards [5], [6], which would require alignment if different types of devices are used for this purpose.

The lumped impedance model of a cable is discussed in this paper as an example, using a comparison between the measured harmonic current at one end of the cable and the same current calculated based on the cable parameters and the measurements of other variables in the model, as discussed in the next section. The results are analyzed for low order harmonic orders, which have significant enough excitation levels and give less measurement sensitivity issues.

The influence of measurement uncertainty and sensitivity is also discussed as the limiting factors. It is however concluded that this question requires further studies, due to its high complexity and significant influence on the end results.

II. METHODOLOGY

As mentioned, the aim of this paper is to check the performance of a harmonic model which uses a measured harmonic injection to obtain the disturbance value at another point in the network. The proposed method uses the harmonic impedance model, and a set of measurement values to obtain a variable which is assumed to be unknown. This is done by comparing the calculated value to a reference – a measured value with very low uncertainty. In this study a single π harmonic model of a cable is used; the parameters and variables of this model are shown in Figure 1.
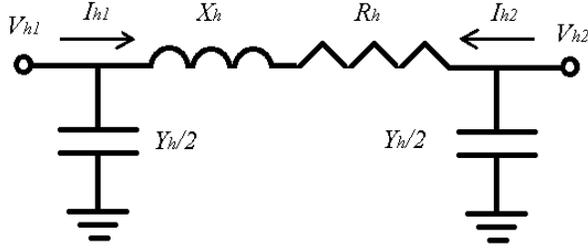

Figure 1. Lumped harmonic model of a cable

In this figure, X_h is the total inductive reactance of the cable, R_h is the resistance, and Y_h is the admittance, all for the observed harmonic order h. The variables which can be either measured or calculated are the harmonic voltages and currents at both ends of the cable – V_{h1}, V_{h2}, I_{h1} and I_{h2}.

If cable parameters are known, and three out of four variables are measured, the fourth one can be calculated as:

$$I_{h1} = \frac{Y_h}{2}(V_{h1} + V_{h2}) - I_{h2} \qquad (1)$$

If all four variables are measured, the calculated value can be compared with the measured one to estimate the uncertainty of the calculation. In this process it is very important to include the measurement uncertainties for each of the four variables, both in terms of magnitude and phase angle.

This comparison can be conclusive only if at least one of the two current transducers has very low uncertainty and that side of the cable is used as a reference. The reasons for this are discussed in [7], and the low sensitivity of the results to the voltage measurements is confirmed in the results section of this paper.

As can be seen in (1), from the cable parameters the only variable that plays a role is the cable capacitance – which consists out of the frequency dependent capacitance per unit length (e.g. as the value of μF/km) and the cable length. It should also be noted that a single π model is valid only in a certain range defined by the maximal frequency of interest and the cable length. For lengths and frequencies above this limit a multiple section or distributed parameter model should be used instead.

III. TEST SYSTEM

As a test system, a 50 kV network of Enduris in the Netherlands is used, with six PMU's installed in five consecutive substations, as explained in [8]. A diagram of the test network is shown in Figure 2.

As mentioned earlier, the used measurement devices include PQ functionality. Next to the standard PMU measurements of single-cycle magnitudes, phase angles and powers, the PMU units used for monitoring also measure some of the PQ parameters, such as the voltage and current spectrums [9], with a time resolution of one second.

The element chosen for the analysis is the cable between substations Oosterland and Tholen, as here PMU measurements are present on both sides of the cable. The accuracy classes of the voltage and current transformers used (CTs and VTs) are given in Table I. It should be noted that these values are validated only for the fundamental component and that higher uncertainties are expected at higher frequencies.

TABLE I. ACCURACY CLASSES OF THE VOLTAGE AND CURRENT TRANSFORMERS USED

	CTs [%]	VTs [%]
Oosterland	0.1	0.5
Tholen	1	1

Regarding the use of a single π model, the length of the cable is approximately 15 km, which is an order of magnitude lower than the wavelength of the highest harmonic order considered (in this case the 11th), which justifies the use of this model.
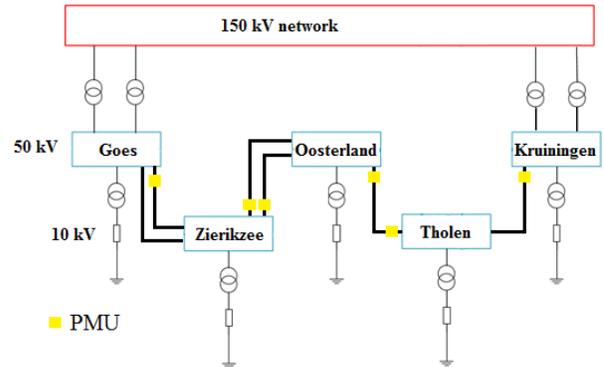

Figure 2. Topology of the test network

IV. RESULTS AND DISCUSSION

The calculation based on (1) gives good results for the fundamental frequency. A histogram of differences between the measured and calculated current of the cable at the Tholen substation is presented in Figure 3. It can be seen that the differences are limited to about 2 % except for rare instances in time.
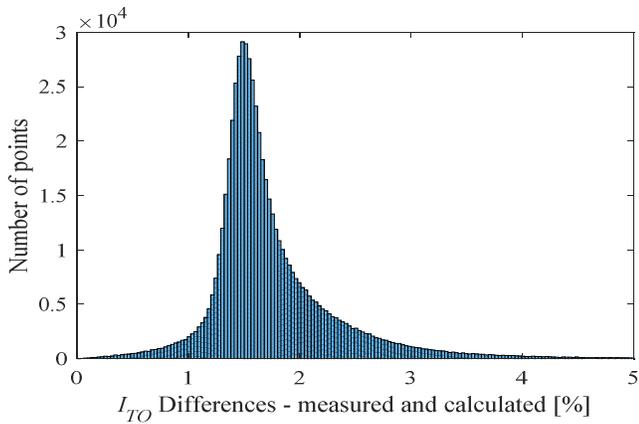
Figure 3. Histogram of differences for the fundamental current component

When the same calculation is repeated for the 5th harmonic, the differences increase, as shown in Figure 4. For sensitivity reasons, the calculations for all harmonics other than the fundamental are applied only to a subset of data samples – time instances with current magnitudes lower than 5 A were excluded from the calculations as the reduced sensitivity might greatly increase the uncertainty (the threshold is set to slightly more than 1 % of the full scale of current transformers, which is 400 A).
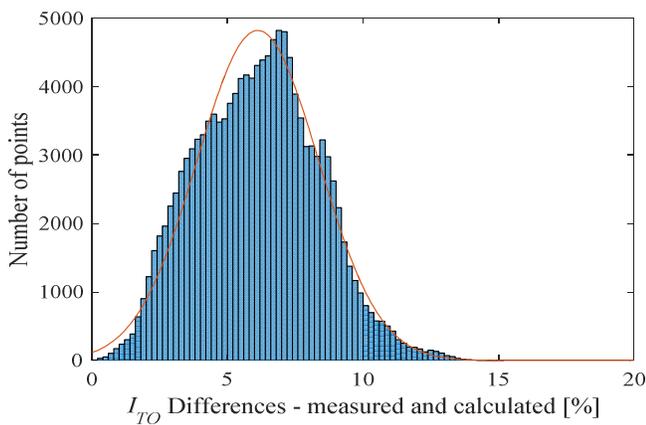

Figure 4. Histogram of differences for the 5th harmonic of the current

One of the aspects affecting accuracy of measurements in the medium and high voltage grids is the utilization of the voltage and current transformers. The impact of these instrument transformers on the measurements performed at power frequency is well described in the literature. Standards [10], [11] describe behavior of such instrument transformers based on the certain accuracy classes.

However, at frequencies other than fundamental the performance of these measurement transformers becomes a source of a larger uncertainty. Having one VT and one CT fixed as reference (with higher accuracy class), the uncertainty of another pair of instrument transformers with lower accuracy class can be reduced by introducing correction factors. This concept is similar to the one presented in [12].

In order to determine these factors, the biases of wide ranges were applied deliberately to the magnitude and phase of the measured values. Furthermore, each single perturbation was followed by computation of the new estimated difference between measured and calculated currents for the end of the cable. The mean values of these differences based on the fitted probability distribution function were then taken as the input for Figure 5, which represents a case for 5th harmonic current calculation considering the bias applied to low accuracy CT.
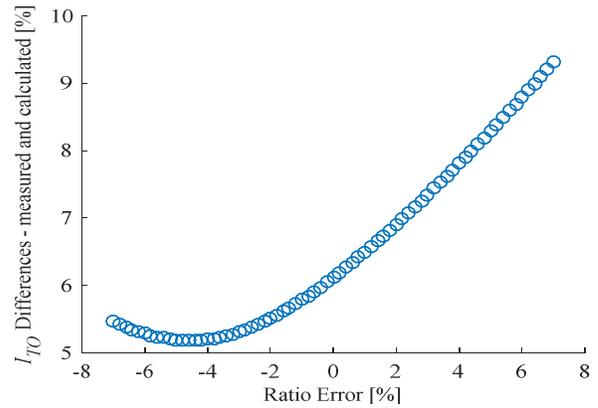

(a)
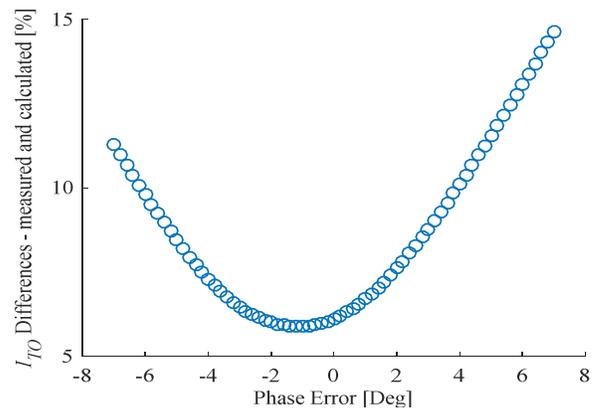
(b)

Figure 5. Estimated current differences based on current transformer bias – 5th harmonic: (a) magnitude, (b) phase angle

As may be seen from the presented graphs the variation of differences related to the ratio error and phase displacement is significant. Further, both of the graphs exhibit a minimum at certain values of applied bias – which can be adopted as a correction factor.

Figure 6 presents dependencies between estimated current differences and biases applied to the measured voltage. It can be inferred that variation of the VT ratio error and phase displacement does not have significant influence on the final result. The later confirms conclusions of [12]. Results of this paper will not consider influence of the voltage transformers any further.
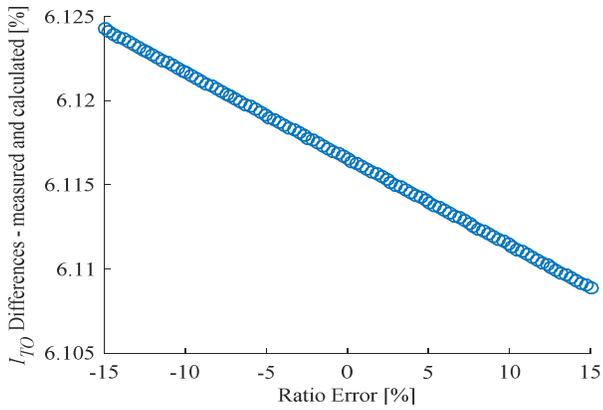
(a)
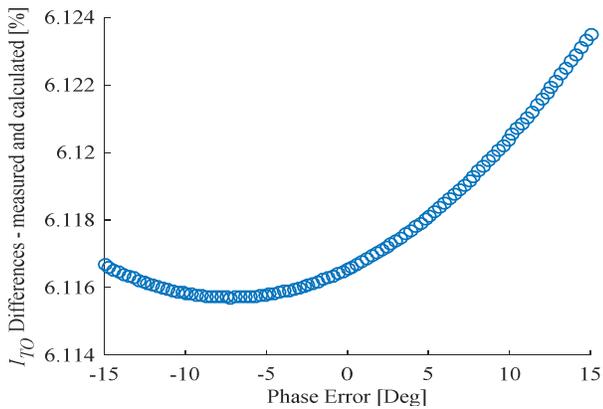
(b)

Figure 6. Estimated current differences based on voltage transformer bias – 5th harmonic: (a) magnitude, (b) phase angle

The way to reduce uncertainty of the measurement is applying biases associated with minimum mean values of current differences to the CT with low accuracy class. The combined effect of that process is demonstrated in Figure 7.
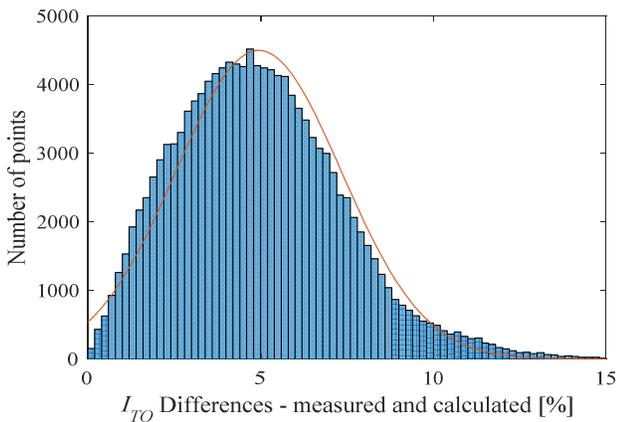

Figure 7. Histogram of differences after correction for 5th Harmonic

The proposed method was further applied to 7th and 11th harmonic order voltages and currents. It is worth mentioning that for these harmonic orders CT ratio error required for correction demonstrated a dramatic increase, since the behavior

of instrument transformers at higher frequencies is not well characterized and shows allegedly a strong distinction from the one at power frequencies. As an example, this phenomena is shown in Figure 8 for 7th harmonic order.
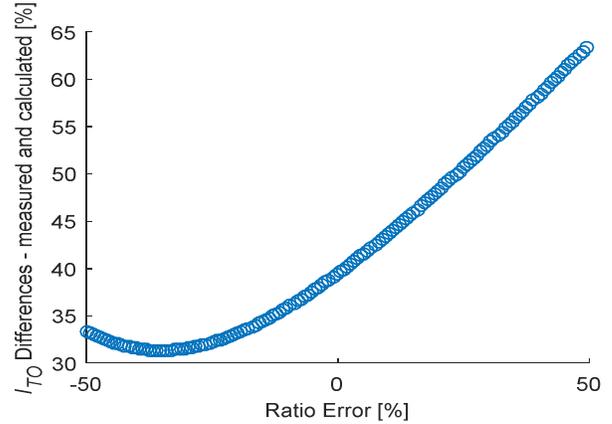

Figure 8. Estimated current differences based on current transformers magnitude bias – 7th harmonic

Figure 9 shows the probability density functions of the diversities between measured and calculated currents both before and after the bias was applied to the CT for 7th harmonic order.
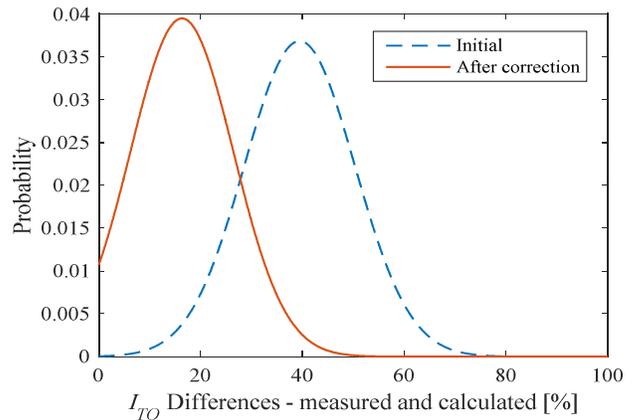

Figure 9. Probability density functions of initial and corrected values of current – 7th harmonic.

The obtained results are summarized in Table II. It is noticeable that the difference between measured and estimated values increases with frequency, where the measurement accuracy plays an important role. Correction of the voltage and current measurements improves the results only partially, given the fact that introduced correction factors include combined uncertainties of the other components of the measurement chain, i.e. control cables and PMUs.

The corrected results in Table II give an indication of the uncertainty introduced by the single π harmonic model of the cable, which could be further analyzed based on the distributed parameter representation, which needs to include also the geometry of the cable. Characterization of the reference current transformer in a broader frequency range would also contribute

significantly to the definition of uncertainties associated with measurement and uncertainties introduced by the model.

h, #	Bias		I_{TO} relative error, %	
	Ratio error, %	Phase error, deg	Initial	Corrected
5	-4.6	-1.2	6.12	4.95
7	-35.3	-16.4	39.46	11.54
11	-79	+16.3	80.47	10.05

V.   CONCLUSIONS

The paper proposes a method for determining the limitations of harmonic modeling based on measured emissions and standard harmonic impedance models using synchronized spectrum measurements. It was found that the calculation performs very well for the fundamental frequency (up to 2 % difference in the case study) and reasonably well for some harmonic orders (between 5 % for the 5th and almost 80 % for the 11th order in this case).

The uncertainty of measurement transducers is found to be very significant, which in the case of the cable model applies only to the current transducers (low impact of the voltage transducers). The broader frequency response of CTs is commonly not known, which limits the capabilities of such propagation studies.

Correction of transducer biases was also analyzed in the paper based on an earlier study aimed at the fundamental frequency. The results of the calculation are improved in this way. These correction factors could be determined for the phase angle and magnitudes for higher frequency components, provided that sensitivity level is satisfactory for certain harmonic orders. However, as it is discussed in section IV, these correction factors comprise uncertainties of the whole measurement chain. This shows potential to use these parameters as an indication for calibration process of instrument transformers, but not as the values for calibration itself. The calibration capabilities are limited for now because the reference CT was not characterized for higher frequencies in the current study. A characterized reference would also help in the determination of measurement and model uncertainties.

The values of differences between measured and calculated currents after the application of corrections potentially indicate the level of the accuracy of utilized lumped impedance model. The results of this study show that starting from 7th harmonic order the uncertainties associated with aforementioned model become very significant. Nevertheless, it was concluded that iteration of calculations in three-dimensional space (both ratio error and phase displacement are changed simultaneously) can shift the conclusions about the model.

The influence of a more detailed impedance model, e.g. distributed parameters representation and influence of three dimensional correction are expected to improve the results. This is left as a follow-up study of this work.

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