Future Work on harmonics – Some Expert Opinions Part II – Supraharmonics, Standards and Measurements

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***Abstract*—A workshop on power system harmonics was organized in Stockholm in January 2014. On the agenda was among others a discussion on what are the main issues on harmonics at the moment and in the near future. Some of the issues discussed at that workshop are presented in this paper and its companion paper. In this paper the following issues will be addressed: the appearance of emission at higher frequencies (supraharmonics); the need for new and improved standards; measurement issues and data analysis.**

***Index Terms*—electric power systems, power quality, harmonics, wind power, solar power, suprharmonics, EMC standards.**

I. INTRODUCTION

A workshop on power-system harmonics was held in Stockholm on 21 January 2014, organized by Luleå University of Technology and Elforsk (Swedish Electrical Utilities' R & D Company). Participants were representatives from industry and academia from a number of European countries where Sweden as a host was taking the lead. The participants agreed on future common cooperation and perhaps new harmonic-related workshops. The aim of the workshop and a summary of the harmonic-related issues are presented in a companion paper (Part I). Some of the issues are discussed in more detail in Section II through V of this paper.

II. SUPRAHARMONICS

The presence of waveform distortion in the frequency range 2 to 150 kHz ("supraharmonics") has long been discussed, but the lack of standards (above 2 kHz and below 150 kHz) also resulted in a lack of research. Research on this subject seriously started a few years ago [1][2][3][8]. There is now a general acceptance of the need for research to understand origin, spread and consequences of emission in this frequency range. This research was partly triggered by the use of this frequency band for power-line communication and partly by the proliferation of equipment using switching frequencies in this range. An overview of interference cases was created by a CENELEC working group [4]. More documented and studied cases of interference are needed to direct the further research on supraharmonics. Future research is needed to model and study the emission, propagation and impact of supraharmonics. Two specific issues are discussed below.

A. Primary and secondary emission

The harmonic current at the interface of a device (or a complete installation, the basic principles are the same) and the grid depends on sources inside and outside of the device. In [11] a distinction is made between primary and secondary emission to explain observed behavior in an installation with a large number of lamps. With reference to Fig. 1, the primary emission is driven by I_1, i.e. by sources inside of the device, whereas E_2 is what drives the secondary emission. The measured current at the interface between the device and the grid, I, is the sum of primary and secondary emission.

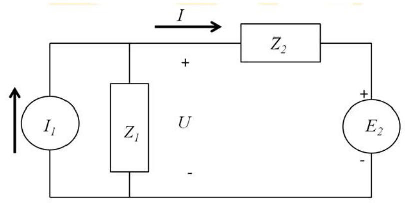

Fig. 1. Primary emission (I_1) and secondary emission (E_2).

In the frequency range above 2 kHz, the secondary emission plays an important part and is often the dominant contribution. One of the consequences of this is that the (total) emission is strongly location dependent, as is shown in Fig. 2. Methods are needed to estimate the primary emission from measurements in the field.

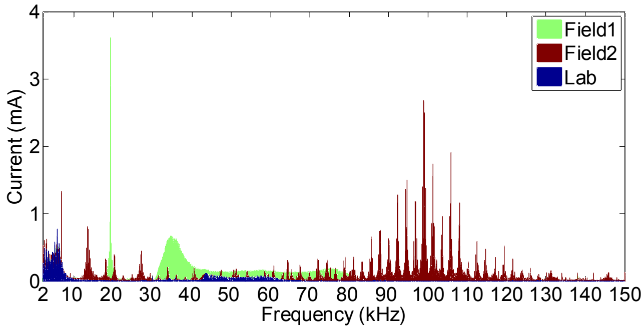

Fig. 2. Emission, 2 to 150 kHz, measured in a laboratory environment (blue) and at two locations in the field (red, green).

B. Power-line communication

The interest in supraharmonics is triggered among others by the use of large parts of this frequency band for power-line communication (PLC). As shown in [12], secondary emission, driven by the PLC transmitter, plays an important role in the interaction between PLC and end-user equipment. An example is shown in Fig. 3. Reducing the secondary emission, without increasing the primary emission, is one of the big challenges.

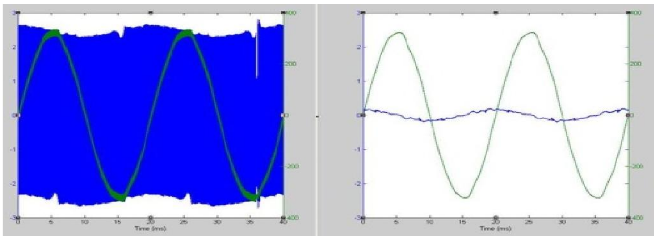

Fig. 3. Total emission of a TV in stand-by, with power-line communication (left) and without power-line communication (right), measured during a 40-ms window; voltage (green) and current (blue).

III. Standardization

The need for new standards and improved versions of existing standards was mentioned by several speakers at the workshop. Some examples are given below. Further standard development is also needed in the frequency range 2-150 kHz.

A. IEC 61000-3-2

About 20 years ago a major driver behind the emission limits in IEC 61000-3-2 was the utilization of cancellation effects between different equipment technologies. Nowadays more and more equipment, like computer power supplies, EV chargers or small PV inverters implement technologies based on switching at higher frequencies (self-commutating inverters, active PFC). The harmonic emission of this new equipment under sinusoidal conditions (as required for testing according to IEC 61000-3-2) is negligible small and it usually complies with the given limits.

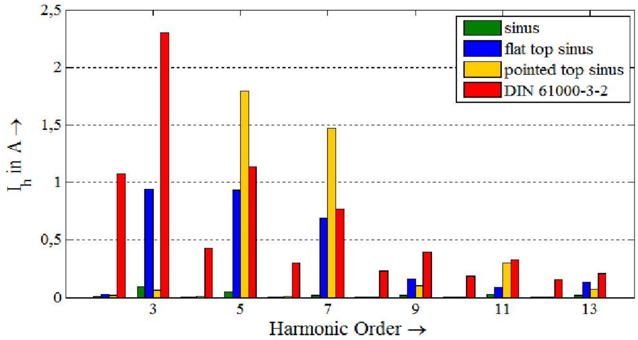

Fig. 4. Spectrum of PV inverter for different voltage distortions compared with IEC 61000-3-2 class A limits.

In case of voltage distortions that are typical for public or industrial grids (flat top / pointed top form) the harmonic emission can increase considerably and may even exceed the specified limits (Fig. 4). Research is needed to analyze the impact of this technology change to the harmonic situation (in particular the efficiency of cancellation) in the LV grids and if IEC 61000-3-2 may have to be changed or extended [9].

Not only the background distortion, also the source impedance at the equipment terminals can impact the emission, as is for example shown in Fig. 5 for a load with a diode rectifier and a capacitive load. Two different source impedances and two distorted waveforms (V_2 and V_3) next to a clean waveform have been compared. The voltage distortion used was small (THD about 1%) but the phase angle of the third harmonic was opposite for V_2 and V_3. Above harmonic 10 the impact is big and the standard test cannot be considered as repeatable.

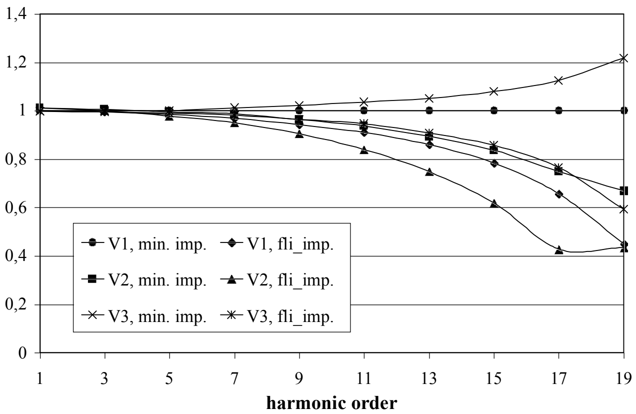

Fig. 5. Influence of background voltage distortion and source impedance during compliance test with respect to standard requirements for supply voltages and impedances.

Another example of the impact of background voltage distortion is shown in Fig. 6. Relatively minor differences in voltage waveform cause a large difference in current waveform. The distortion as obtained from the standardized test may thus not be a good indication of the distortion as it will occur in the real application.

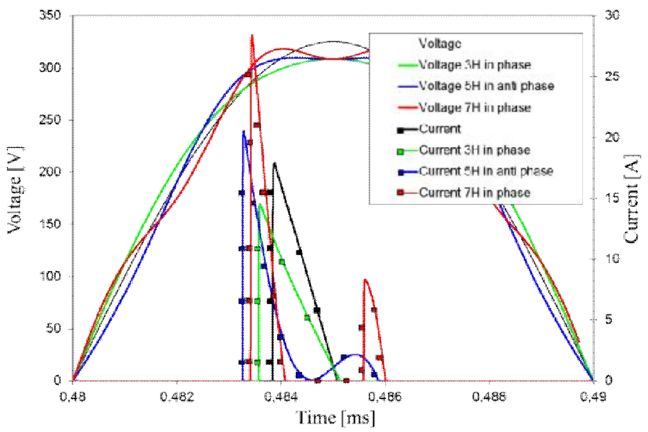

Fig. 6. Simulation of the influence of background distortion on the harmonic current content of a non-linear load

B. IEC 61400-21

The IEC 61400-21 standard on wind turbine power quality exists more than 10 years and the third edition is under development. The standard is well recognized and accepted in the industry, e.g. TSOs, DNOs, wind turbine manufacturers, developers, certification bodies, etc. The idea of the standard is to analyse the impact of wind turbines and wind power plants on the grid with respect to the electrical performance.

In the light of the rapid development of the wind power industry and experience with the existing 2nd edition of IEC 61400-21, a new revision was proposed. The new revision is expected to define extended and more sophisticated measurement procedures [5].

It is worth to emphasize that due to the modern power converters complexity there is a high necessity to perform careful power quality evaluation including harmonic measurements, data processing, data analysis, and harmonic modelling of wind turbines.

Measurements are an important part in the wind power plant and wind turbine evaluation process. In order to validate theoretical analysis and numerical simulations measurements are required. Appropriate measurements as well as data processing are crucial in wind turbine analysis and comparison with expected theoretically assumptions.

The appropriate harmonic assessment can be divided in the following stages:

- harmonic measurements,
- data processing,
- data analysis,
- possible model development.

Each of the stages is equally important in appropriate and trustful harmonic evaluation in wind turbines and wind power plants. Of course each of the stages introduces uncertainties which should also be evaluated carefully [6].

The measurement procedure and assessment of harmonics has been reported by the industry to be very inaccurate in the 2nd edition causing costly oversizing of passive filters. This is mainly due to the fact that the existing IEC 61400-21 assumes wind turbines to be an ideal harmonic current source neglecting the internal impedance. This approach also neglects any grid impedance impact on the generated harmonic currents [7]. More accurate measurement and assessment procedures are therefore specified in the new revision.

Harmonic current emission from the wind turbine is strongly dependent on the wind turbine internal impedance as well as the external network frequency-dependent short circuit impedance (See Section II.A). In Fig. 7 (a) one can see how such harmonic current can affect voltage distortion at the LV side of the wind turbine transformer and in Fig. 7 (b) how the infuence by the background distortion can be excluded by harmonic modelling. The figure shows the variation of the 5th harmonic component vs. percentage loading of the wind turbine. To be able to get more accurate assessment procedure, the new revision specifies besides the harmonic currents also the harmonic voltage measurement procedures including phase angle information and aggregation techniques. Furthermore it also addresses the evaluation of uncertainties of the measurements and the data analysis. The new edition also provides guidelines how to detect which harmonics currents are affected by the background harmonic distortion.

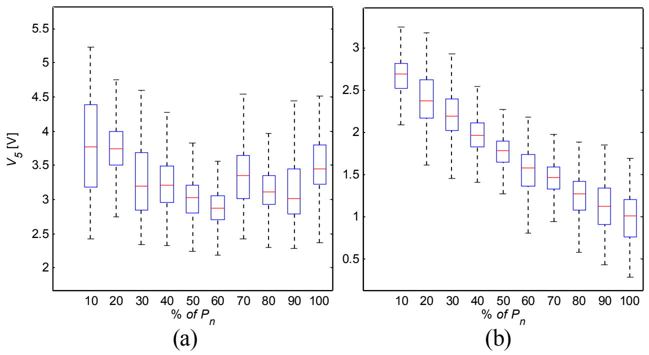

Fig. 7. Harmonic voltage distortion (a) measured at the LV side of the wind turbine transformer, (b) of the harmonic model; shown as a box plot with median, 25 and 75 percentiles

The wind turbine harmonic assessment can be also done based on wind turbine harmonic model evaluation. The model can be developed based on measurements done according to the standard or using sophisticated simulation tools. The model would describe the harmonic behaviour of a wind turbine in theory excluding influence of a distorted grid to which the wind turbine is connected. Properties of such a wind turbine harmonic model include:

- The wind turbine harmonic model describes the wind turbine harmonic behavior without influence of the external network.
- The wind turbine harmonic model correctly represents the wind turbine reaction to background harmonic voltages in the connection grid.
- The wind turbine harmonic model can be applied in conventional harmonic assessment.

At this stage the wind turbine manufacturer decides how the harmonic development is done and how the model validation process should be performed. Therefore there is a need to provide generic description of the harmonic model taking into consideration uncertainties evaluation as well as guidelines regarding the application and validation process. The model can be used in order to evaluate the background distortion impact on the measurement process.

C. *Connection agreements*

A connection agreement for an industrial installation, wind power plant, solar panel, etc. often contains requirements on harmonic emission. Those requirements should not be too severe, for it would put unreasonable costs on the network user, but not too light either for that would lead to unacceptable harmonic levels for other network users. Several network users have indicated that they need guidance in this, beyond documents like IEC 61000-3-6 and IEEE 519.

Setting reasonable voltage and current distortion limits for the grid and translating these in reasonable emission limits for installation, is an important research task as well.

IV. MEASUREMENT ISSUES

A. *Conventional instrument transformers*

Measurement of harmonic voltages and currents requires in most cases (except voltage in LV networks) the use of appropriate transducers. The transfer function of classical voltage transformers shows distinctive resonances with ratio errors of 200% and more. The resonance frequency decreases considerably with increasing rated primary voltage (Fig. 8).

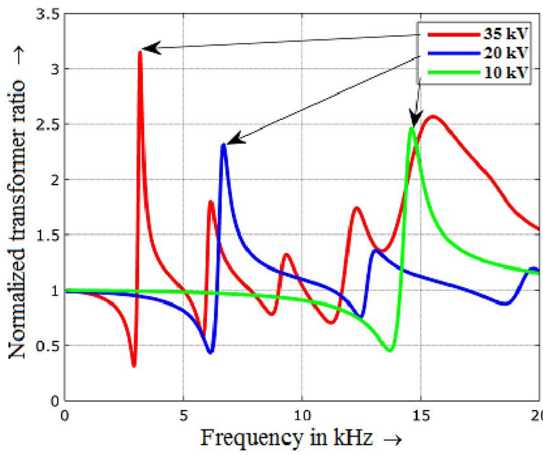

Fig. 8. ***Ratio error Spectrum of PV inverter for different voltage distortions compared with IEC 61000-3-2 class A limits***

The resonance parameters do not depend on the design of the voltage transformer only, but are also significantly influenced by operational parameters like burden or temperature. Therefore a full calibration based on a frequency response provided by the manufacturer is not recommended. As more robust approach the specification of a bandwidth is proposed, in which the instrument transformer doesn't exceed a specified accuracy. More research is needed, especially in the accurate measurement of the frequency response with transportable measurement systems [10].

B. *Rogowski coils*

Harmonic currents are usually measured either by current transformers or Rogowski coils. While current transformers do not have distinctive resonance points, their accuracy can be considerably affected by even very small inductive parts in the burden. Rogowski coils provide wider frequency ranges, but their accuracy can be considerably influenced by environmental conditions, like distance of phase conductor to the lock, distance of other phase conductors or the signal dynamic (Fig. 9).

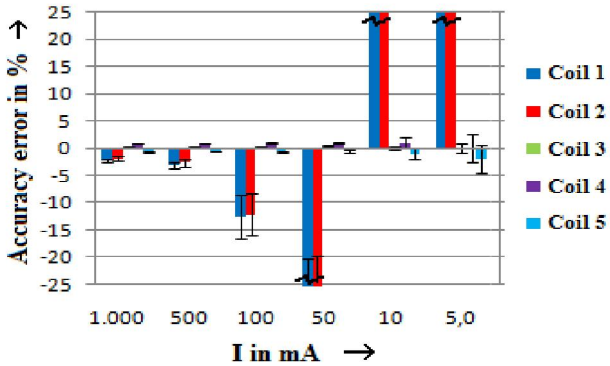

Fig. 9. ***Accuracy depending on signal dynamic for different Rogowski coil/measurement device combinations (x mA 50th harmonic are added to 10A fundamental current)***

C. *Measurement methods for supraharmonics*

As mentioned in Section II the frequency range 2-150 kHz becomes more and more important. A consistent measurement (e.g. to compare different measurements or to check compliance with future compatibility levels or emission limits) is essential and requires a single measurement method. Multiple approaches are currently available (e.g. IEC 61000-4-7 and IEC 61000-4-30 Ed.3 draft), which can result in considerable different results for the same signal.

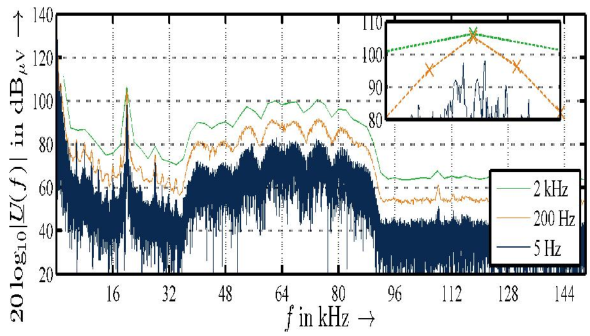

Fig. 10. ***Measurement results with different bandwidth***

Major parameters with influence on the measurement results are: way of signal filtering, length and number of gaps in the measurement, bandwidth and aggregation method. Fig. 10 exemplarily shows the impact of bandwidth (200 Hz vs. 2 kHz) on the measurement of the 1-MW-solar installation (cf. also to Part I, Section V.). Especially the broader emission show differences of up to 10dB. Therefore more research towards the development of a standardized measurement method is required. It should be sufficient accurate and without requiring intensive processing performance.

At higher frequencies, the high noise level of Rogowski coils compared with current probes can make a significant difference. This is shown in Fig. 11 for two different coils. Essential information may be lost due to the high noise level.

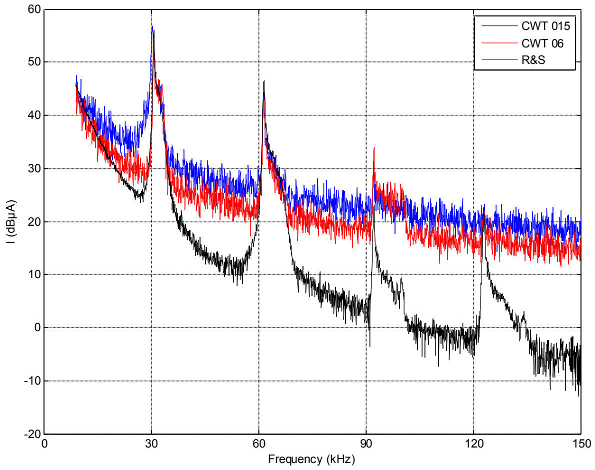

Fig. 11. ***Measurement with two Rogowski coils and R&S EZ-17 current probe, performed with measuring receiver***

V. Automatic Data Analysis

Data on harmonic voltages and currents in the grid is currently monitored by hundreds to thousands of instruments [13]. There are trends towards this number growing to millions of instruments in the not too far future [15][16]. Without strong automatic analysis methods, the enormous amount of information and knowledge than can be obtained from this data will disappear. Some of the challenges (read: research opportunities) are:

- ✓ How to ensure performance of data transfer and management? Device-independent distributed processing and storage approaches should be developed. Interoperability between devices, communication and storage infrastructure and analysis software is essential
- ✓ How to improve efficiency and detail of analysis? This includes extracting information on origin of disturbances, automatic identification of behavior changes, trends, etc and easy-to-understand and highly-scalable assessment indices [14][15].

An important early application of the data analysis is towards addressing the following two questions:

- ✓ What is the current harmonic emission in public grids? This holds for voltages and currents and especially in low-voltage grids.
- ✓ How will new equipment influence these levels?

VI. Conclusion

This paper and its companion paper have indicated a number of issues that should be addressed by researchers on power-system harmonics. The list of research challenges presented in these two papers is most likely not complete, but the authors hope that it will give some guidance to the future research on power-system harmonics and start a further discussion on the research directions needed.

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