Future Work on Harmonics – Some Expert Opinions Part I – Wind and Solar Power

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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. The results of this discussion are summarized in this paper and some of the issues are discussed in more detail in this paper and in its companion paper. This paper discusses emission from wind and solar power as well as advantages and disadvantages of active and passive filters.**

***Index Terms*—electric power systems, power quality, harmonics, wind power, solar power, supraharmonics, 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 was to address the following questions:

a. What research is on-going at universities at the moment and how does this fit in the challenges for existing and future grids? What are the open research questions where it concerns harmonics?

b. What are the harmonic-related issues in the electric power system at the moment?

c. Which new harmonic-related issues are expected in the future due to the changes in the grid or due to equipment connected to the grid?

d. How can universities help with this through research and education?

In this paper and in its companion paper we will summarize the results of the constructive discussion, where it concerns the second and third question. An overview of the issues that were identified is given in Section II; some of the issues are discussed in more detail in Section III through V and in the companion paper.

II. Harmonic-related issues

The following main issues were identified by the participants during the workshop:

- ✓ Harmonics due to connection of wind and solar power to the grid (Section III, Section V, and Part II)
- ✓ Resonances at lower frequencies due to the replacement of overhead lines by AC cables at transmission level.
- ✓ Voltage and current distortion in the frequency range 2 to 150 kHz, referred to here as "supraharmonics" by some and as "high-frequency harmonics" by others. Also terminology based on origin of the distortion is being proposed (Part II, Section II).
- ✓ The need for new and improved standardization. Specific examples discussed were the emission standard for small equipment (IEC 61000-3-2) and the standard for measuring of emission from wind turbines (IEC 61400-21). (Part II, Section III)
- ✓ The urgent need for methods to automatically analyze large amounts of power quality data, including mapping of existing levels of harmonic voltage and current distortion. (Part II, Section V)

Next to these major issues, a number of other issues were identified:

- How to measure higher frequencies at higher voltage, e.g. above 2 kHz for voltage levels above 20 kV. The conventional voltage and current transformers do not give an accurate value in these cases. Attempts of calibration have been made, but the resonance frequency, the main reason for the inaccuracy, has shown to be temperature dependent. Alternative, but equally cost-effective, measurement methods should be developed. (Part II, Section IV).

- Assessment of uncertainties in harmonic measurements at all frequencies (random errors, systematic errors, etc.) and data processing (e.g. avoiding spectral leakage of especially interharmonics), harmonics evaluation (e.g. modeling) and harmonic mitigation (e.g. filtering) which can constitute a basis for reliable risk management (Part I, Section IV and Part II, Section IV).

- A reduction in efficiency of end-user equipment was reported in cases with high voltage distortion. This phenomenon should be urgently studied further. If it is shown that this reduction in efficiency is significant, it could form the basis for new voltage-distortion limits.

- The use of active filters instead of passive filters. Active filters have many advantages compared to passive filters. They can improve overall control system design robustness (e.g. through active damping). They may however also introduce emission at higher frequencies and introduce a risk of "harmonic instability". The latter might occur when active filters are connected to resonant networks (e.g. for harmonic compensation) or when multiple active filters are connected close to each other. Example of this, observed typically during island ("microgrid") operation but also during grid-connected operation, are shown in [1][7][8][9][10][11][12]. It is important that this risk is studied and that measures are introduced to guarantee a sufficiently low probability that such instability occurs. (Section IV)

- The modeling of harmonic propagation and damping remains a difficult subject. This may not be a serious research challenge by itself; detailed models exist but are often not applicable due to lack of data. Estimating harmonic voltage and current levels remains a serious challenge when there is limited amount of network or component data available. Some serious guidance, from the research world, is needed to help network operators in doing practical but accurate calculations.

- The impact of harmonics, interharmonics and supraharmonics on protection and metering.

- Power quality issues in relation to microgrids (during island operation).

- Differences in power-quality disturbance levels between countries. Are there are significant differences and how can they be explained?

Some of these issues will be discussed in somewhat more detail in this and its companion paper.

III. WIND POWER

A. *Overview of the issues*

Modern wind turbines are equipped with power electronic converters and therewith a source of harmonic currents. By using active control of the grid-side converter, a close to sinusoidal current is obtained, as is confirmed by measurements [4][5][6]. However, even harmonics and interharmonics are found in the current emitted by wind turbines, at higher levels than is typical for other equipment. A unified generic model explaining the emission spectrum from wind turbines is still missing. Especially the high levels of even and interharmonics cannot be explained. Related to this is the need to find an explanation for the sometimes complex relations between harmonic emission and active-power production.

When wind turbines are gathered in wind power plants (WPPs), the collection grid plays an important role in the emission from the WPP as a whole. The transfer from individual turbines to the public grid is well understood by the experts, but not well described in the technical literature yet. Also is data not always available, especially not during the planning stage. Methods should be developed for making planning decisions despite uncertainty in data.

An uninvestigated subject is the aggregation between individual turbines especially taking the control aspects and its possible interactions. There is a lack of measurements as well as a need for more modeling efforts here.

The need to distinguish between primary and secondary emission (Part II, Section II.A) is also important for wind turbines and especially for WPP.

B. *Harmonic mitigation in wind power plants*

There are various techniques for dealing with the harmonic problem in large WPPs depending upon the nature and source of the problem.

WPPs, especially large offshore plants are characterized by complex structures including wide application of power electronic devices in wind turbines, FACTS devices and/or HVDC transmission. Furthermore, such complex structures include significant amount of passive components such as filters, cable arrays, transformers, transmission cables, and shunt compensation equipment. Consequently, there are many potential sources of harmonic problems (e.g. harmonic emission, resonances, harmonic stability, etc.), and simultaneously many ways of dealing with them [17].

Both passive and active filtering solutions could be used for harmonic mitigation. Passive filtering as the state-of-the-art technology requires extensive knowledge of the system during the WPP design. In many cases information about the system is uncertain and over-sizing of passive filters may take place to cover uncertainties and risks. The most severe uncertainties are listed below:

– lack of models provided by the WPP component manufacturers,
– component tolerances included in the WPP model,
– wind turbine harmonic emission model uncertainties,

- phase angle between harmonics from different wind turbines and any aggregation effects,
- different wind turbines operating points (e.g. power production due to the wake effect, voltage control, etc.),
- external network modelling – lack of information regarding harmonic background and frequency-dependent short-circuit impedance,
- possible changes in the wind turbine converter or STATCOM controller,
- linear modelling of WPP components (e.g. transformers, converters, cables, etc.),
- linear harmonic load flow calculation method excluding possible frequency coupling.

Due to the fact that more and more power electronic equipment (e.g. wind turbines with grid connected converters, STATCOMs, HVDC links, etc.) is being utilised in WPP, active filtering becomes an attractive solution (see Section IV).

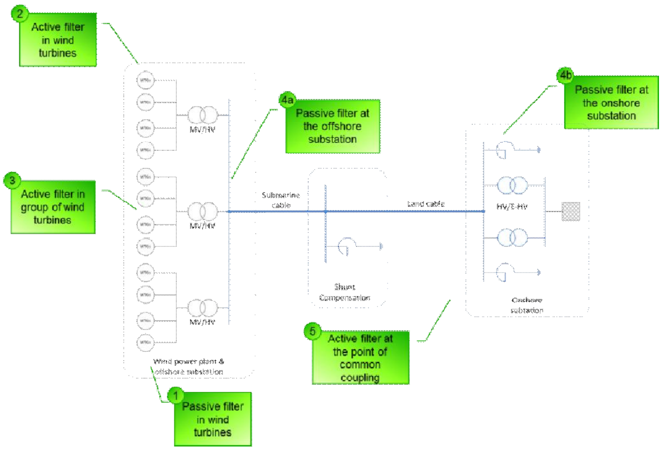

Fig. 1. Harmonic mitigation methods in wind power plants.

Considering the different attributes, probably hybrid solutions involving both the passive and the active filters at various locations, as shown in Fig. 1, would be the most beneficial for effective harmonic mitigation scheme. In order to optimise the WPP design from harmonic emission and stability perspective some more studies and research is required [19]. The hybrid solutions would comprise of:

(1) Passive filtering at the wind turbine level:
- trap or LCL filters designed for mitigation of harmonics caused by modulation techniques,
- low-pass filters for high frequency content,
- detuned C-type filters with limited bandwidth for harmonics within lower frequency range, etc.

(2) Active filtering at the wind turbine level:
- selective harmonic compensation reducing harmonic current from grid-side converters or space harmonics from generators in DFIG machines,
- high-pass active filtering in the control chain to reduce wide range of harmonic components,
- harmonic/noise rejection capability improvement to damp or shift possible resonances in the network,
- active notch filters, active damping, virtual resistors, etc.

(3) Filtering in a group of wind turbines:
- carrier signals de-synchronization, interleaving grid-connected converters,
- phase shifted transformer groups, etc.

(4) Passive filtering at the WPP level – (4a) offshore and (4b) onshore:
- selective trap filters,
- high-pass filters, detuned C-type high-pass filters,
- double-tuned filters, etc.

(5) Active filtering at the WPP level:
- shunt connected FACTS devices such as STATCOM systems,
- HVDC link, etc.

IV. Active and Passive Filters

In many cases, passive filters have been applied to reduce the harmonic current distortion in a WPP. However, such filters are tuned to limit a few harmonics and there is a risk of introducing new resonances. Active filters (Fig. 2), on the contrary, are designed to mitigate harmonics in a broader range and to improve both power factor and the THD of the network [13][14] as shown in Fig. 3 and Table I.

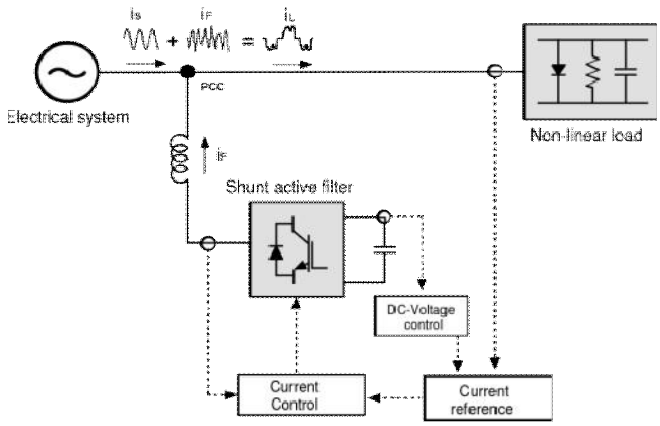

Fig. 2. Overview of the control system of an active harmonic filter

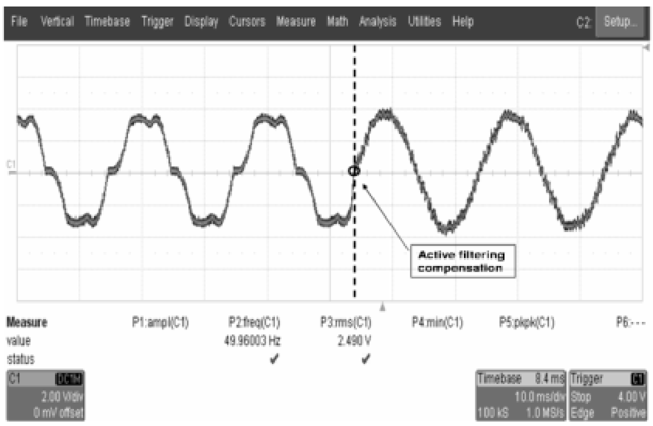

Fig. 3. Grid current before and after the compensation

TABLE I. TOTAL HARMONIC DISTORTION (THD) BEFORE AND AFTER THE COMPENSATION

THD (initial)	THD (final)
15.12%	3.2%

One of the remaining challenges is the interaction between different converters where multiple resonances appear. In [15] the combination of passive and active filters (hybrid filters) has shown to be effective for avoiding harmonic resonance. The work presented in [16] proposes the application of alternative control strategies in distributed generators for harmonic compensation under varying microgrid frequency conditions.

The most important advantages of active filtering are the following:

- Already existing technologies such as STATCOM systems can be utilised for the active filtering,
- Flexible active tuning might be permissible even during the operation,
- Almost unlimited control potential (e.g. selective harmonic compensation, wide band high-pass active filtering, etc.),
- Network impedance changes during many years of WPP operation could be addressed,
- Control method can be tuned for each of WPP independently taking into consideration Grid Code issues as well as WPP structure,
- Reduces risk due to uncertainties related with lack of information from manufacturers (e.g. models) and TSOs (e.g. harmonic background, models, etc.).

Active filtering can be implemented at the converter control level in a wind turbine (see Fig. 4), thereby avoiding or reducing the need for installing expensive passive filters. Moreover, active filter controllers could be tuned and retuned, sometimes adaptively, to overcome the uncertainties faced during the WPP design phase [18].

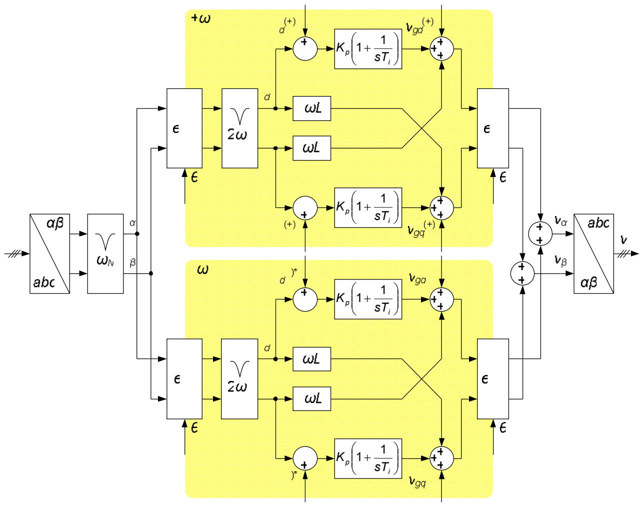

Fig. 4. Typical state-of-the-art wind turbine current control in double synchronous reference frame with notch filters in the main control chain.

Active filters do however introduce distortion at higher frequencies, related to the switching frequency in the converter. Typically distortion occurs around the switching frequency and around multiples of the switching frequency. Active filters will be one of the sources of distortion at higher frequencies (see Part II, Section II).

V. SOLAR POWER

Photovoltaic installations require inverters to feed power into the grid. In general these inverters use self-commutating technologies that operate at switching frequencies above a few kHz. While switching frequencies for larger inverters (100 kW) are well below 10 kHz, small inverters for roof-top installations use usually switching frequencies above 15 kHz. Studies performed this far indicate that these so-called "supraharmonics" (Part II, Section II) do not propagate far and mainly impact electronic equipment with shunt capacitors in the close neighborhood of the installation [2][3]. Fig. 5 illustrates the emission of a PV installation consisting of small as well as large inverters [20].

Fig. 5. Voltage spectrum measured at a 1-MW solar campus including narrow-band power-line communication.

In case of sinusoidal supply voltage, the harmonic emission of these inverters is negligible. Due to their internal control algorithms they can produce considerable harmonics in case of distorted supply voltage, even for voltage-distortion levels that are usually found in the grid. More details can be found in Part II, Section III.

The PV inverters itself usually have also shunt capacitors in their grid-side filter circuits. Especially in case of a large penetration with those inverters the sum of these capacitors can result in unwanted resonance conditions, as is for example illustrated for a practical case in [9]. Fig. 6 shows a measurement of the total 5th harmonic current of a LV grid with a penetration with PV inverters as high as 80% of the transformer rated power. The increased levels during the day-light hours are clearly visible.

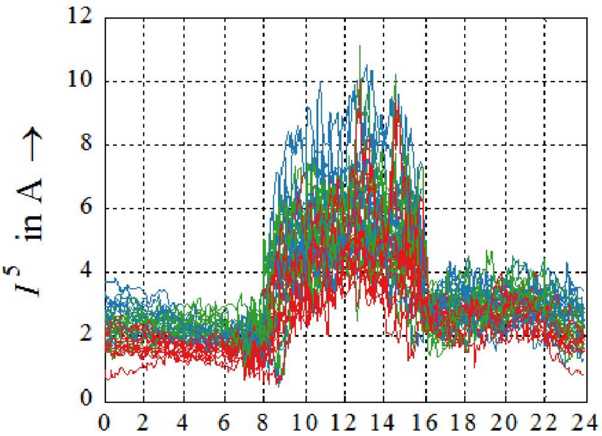

Fig. 6. Total 5th harmonic current as a function of time of day, measured at the busbar of a public LV grid with installed PV power of 332 kW

VI. CONCLUSION

This paper has indicated a number of issues that should be addressed by researchers on power system harmonics. Some of the issues related to the integration of wind and solar power are discussed in more detail. Further issues will be discussed in the companion paper.

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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