Wind Turbine Harmonic Model and Its Application

Overview, Status and Outline of the new IEC Technical Report

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***Abstract*—This paper presents the ongoing work within the IEC Technical Committee 88 Maintenance Team 21 standardization group focused on providing technical guidance concerning the wind turbine harmonic model. The task of the working group is to prepare a technical report which describes the harmonic model in detail covering such aspects as application, structure as well as validation. By introducing a common understanding of the wind turbine representation from a harmonic performance perspective, the technical report aims to bring the overall concept of the harmonic model closer to the industry (e.g. suppliers, developers, system operators, academia, etc.)**

Keywords-harmonic analysis; harmonic model; wind turbine; standards; technical report

I. INTRODUCTION

Nowadays large offshore wind power plants (WPPs) are complex structures including wind turbines (WTs), array cable systems, and HVAC or HVDC offshore/onshore transmission systems (see Figure 1). This represents new challenges to the industry in relation to prediction and mitigation of harmonic emission and propagation [1]. Due to increasing complexity of WPPs it is more and more important to appropriately address harmonic analysis of WTs as well as WPP on a system level by means of modelling during the design stage as well as harmonic evaluation during operation.

The measurement procedure and assessment of harmonics in IEC 61400-21:2008 has been reported by the industry to be inaccurate and potentially causing e.g. wrong or oversized passive filter design. This is due to the fact that the WT current spectrum as measured according to the standard can be considered as an array of ideal harmonic current sources neglecting the internal impedance of the WT. This approach also neglects any grid impedance impact on the generated harmonic currents. To enable a more accurate assessment procedure, the new revision of the standard recommends besides the harmonic currents also harmonic voltage measurement procedures including phase angle information and aggregation techniques [2]. Such an extensive measurement dataset can also be used for harmonic model development and validation.

A. Background

Harmonic current emissions from the WT are strongly dependent on the WT internal impedances as well as the external network frequency-dependent short circuit impedance. To enable more accurate assessment procedure, the new revision of IEC 61400-21 recommends besides the harmonic currents also harmonic voltage measurement procedures including phase angle information and aggregation techniques. Additionally a number of recommendations and guidance is provided to exclude the impact of the external network impact during the measurement process. Afterwards such extensive measurement dataset can be used either for WT harmonic model validation or even development as shown e.g. in [3].

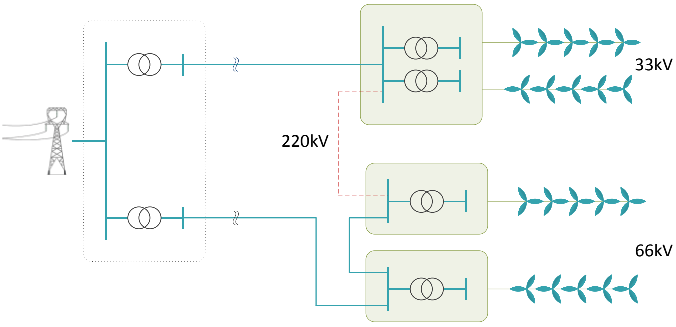

Figure 1 An example of WPP complex structure.

Furthermore the evaluation of measurement uncertainties and methods for data analysis are addressed. The new edition also provides guidelines for detecting which harmonics currents are affected by background harmonic distortion.

In terms of harmonic evaluation IEC 61400-21:2008 specifies a state-of-the-art approach for taking the impacts of the grid into account. This is to provide in the test report power quality characteristics based on current harmonics only. This is based on the assumption that the current emission is independent of the grid voltage, i.e. the emission can be described as originating from a current source which is characteristic to the specific unit type. However such an assumption is not valid for complex WPP systems (see Figure 2) comprising many WTs and characterized by various resonance phenomena (see Figure 3).

Unfortunately until now there has been no systematic approach to represent a WT from its harmonic performance perspective. This brings inconsistency in WT harmonic performance assessment, evaluation of background distortion in grid-connected WT and harmonic analysis of WPPs. Therefore a working group under the umbrella of the Maintenance Team (MT) 21 within Technical Committee

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The working group under the umbrella of the Maintenance Team (MT) 21 within Technical Committee (TC) 88 has been initiated to prepare a Technical Report (TR).

(TC) 88 has been initiated to prepare a Technical Report (TR) providing guidance to the wind power industry.

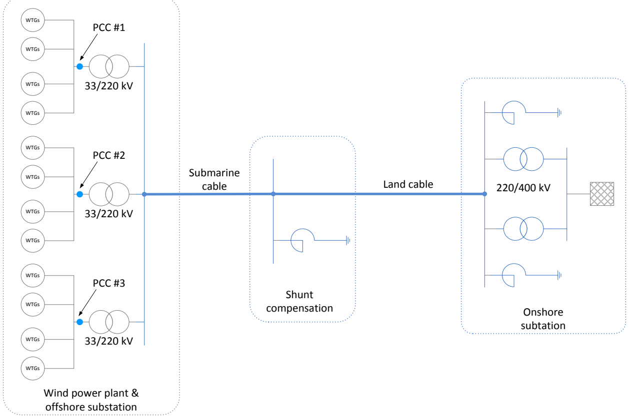


Figure 2 Single line diagram of an exemplary wind power plant where point of common coupling is defined at the LV side of the offshore transformer (e.g. Denmark).

II. WHY A HARMONIC MODEL IS NEEDED?

There is an understandable requirement from transmission system operators (TSOs), distribution network operators (DNOs), WPP developers, WT manufacturers, WT component suppliers, academic units, research institutions, certifying bodies and standardization groups (e.g. TC88 MT21), for having a standardized WT harmonic model. The WT harmonic model could be used as follows:

– Provide a more comprehensive characterization of WT harmonic performance.
– Supplement the harmonic measurements report from IEC 61400-21.
– Introduce a standardised way of performing harmonic analysis in WPPs.
– Assess the influence of the external network.
– Introduce common interfaces to various engineering tools for harmonic analysis.
– Define a common basis for dialog with manufacturers, developers, TSOs and DNOs.
– Provide a benchmark for the academia and industry.

A. *Properties of WT Harmonic Model*

Desired properties of the WT harmonic model are as follows:

– The WT harmonic model allows removing the influence of the connection grid from the measured WT characteristics.
– The WT harmonic model correctly represents the WT reaction to background harmonic voltages in the connection grid.
– The WT harmonic model can be applied in harmonic assessment studies comprising various grid conditions whereas the harmonic current measurements from a single scenario cannot.
– The harmonic model has a standard structure and can be widely used for harmonic analysis/studies on a system level.

B. *Application of Harmonic Models*

Standardized harmonic models would find a broad application in many areas of electrical engineering related to design, analysis and optimisation of electrical infrastructure of onshore as well as offshore WPPs. The following possible applications can be identified:

– Evaluation of WT harmonic performance.
– Harmonic studies/analysis of power systems including wind power plant electrical infrastructures to meet requirements specified in various grid codes and harmonic emission standards.
– Active or passive harmonic filter design to meet grid code requirements.
– Sizing of electrical components within the WPP electrical infrastructure, e.g. K-factor, etc.
– WPP electrical infrastructure optimisation and global parameters adjustment, e.g. components sizing according to Planning Levels or Compatibility Levels, resonance profile/characteristic optimisation, etc.
– Evaluation of external network background distortion impact on WT harmonic assessment.
– Standardised harmonic model provision to TSOs and DNOs.
– Universal interface for harmonic studies for engineering software developers.
– Possible benchmark introduced to the academia and the industry.

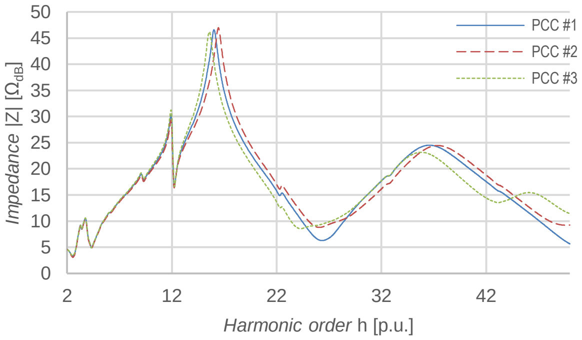


Figure 3 Harmonic impedance estimated at the point of common coupling.

The advantage of having a standardized WT harmonic model, consequently being a performance measure, is becoming ever larger in case of large systems with different types of WTs connected to them, e.g. multi-cluster WPP incorporating different WT types connected to the same offshore or onshore substation.

III. HARMONIC MODEL

Due to the different approaches in electrical design taken by WT manufacturers it is convenient to represent WT harmonics in a generic way by means of a Thévenin equivalent circuit comprising an ideal voltage source (Table 1) and an equivalent impedance (Table 2). Such an equivalent circuit is to be provided for each harmonic component of interest to be included in the model.

Therefore using the WT harmonic model, as either Norton or Thévenin equivalent circuits, in simulations with commonly used engineering tools one can estimate the harmonic contribution to the system to which it is connected. WTs as a part of a WPP system can be potentially considered as harmonic sources as well as harmonic mitigation units by means of active and passive filtering thus the structure of the harmonic model should reflect that behaviour, e.g. harmonic source and equivalent impedance adjusted accordingly to active filter software settings, equivalent impedance adjustment if the WT passive harmonic filter is incorporated in it.

Based on measurement data obtained and processed according to the new edition IEC 61400-21-1 one can potentially develop and/or validate a WT harmonic model. Appropriate model development can also require measurements of harmonic voltage and current distortion and harmonic phase angle information. Thus the standard procedure described in IEC 61400-21-1 should be extended accordingly, i.e. voltage and phase angle measurements as specified in Annex D. The model would describe the harmonic behaviour of a WT in theory excluding influence of a distorted grid to which the WT is connected [2].

A. Thévenin/Norton Equivalent Circuit

According to Thévenin's (or Norton's) theorem any linear electrical network with voltage and current sources and only impedances can be replaced at the terminals of interest by an equivalent voltage source V^{Th} in series connection (or an equivalent current source I^{No} in parallel connection) with an equivalent impedance Z^{th} (or Z^{No}, where $Z^{Th} = Z^{No}$). Thévenin's theorem is dual to Norton's theorem and is widely used for circuit analysis simplification and to study the circuit initial-condition and steady-state response.

1) Equivalent Harmonic Voltage/Current Sources

Independently whether the WT harmonic behaviour is investigated based on simulations or measurements the time-domain steady-state response should be represented in frequency/harmonic domain. As the magnitude and the phase angle of the spectral components may vary largely between discrete Fourier transform (DFT) windows, aggregation is often needed.

The magnitude aggregation considered in the new standard release is aggregated as arithmetic average and possible grouping of the spectral components can be performed according to IEC 61000-4-7. The other statistical forms of magnitude can be also used to demonstrate variation of WT harmonic behaviour, such as 95 percentile according to IEC 61000-3-6 or maximum values which is regarded as worst scenario case, generally speaking. It gives the opportunity for TSOs, DNOs and other model users to select appropriate values for harmonic simulation studies according to different needs.

The phase can be determined as prevailing phase angle and the randomness of the prevailing phase angle can be estimated from the prevailing angle ratio. If the prevailing angle ratio is close to unity it means that there is not significant variation of the harmonic angle during the analysed interval. If the value is much lower than 1 it means that the angle variation can be caused either by uncertainties, significant topology changes in the analysed system or lack of analysed harmonic phase lock to the fundamental frequency.

One should note that phase angle aggregation is not specified in any of the standards concerning the quality of power. Therefore another aggregation approach sometimes can be seen taking into consideration magnitude as well as phase aggregation as complex values where amplitude and angle are aggregated together or complex unity vectors with angles directly from DFT where phase angle is aggregated separately.

Table 1 Exemplary representation/template of the harmonic voltage source.

Harmonic Order	*Frequency*	*Harmonic Voltage*	
[-]	[Hz]	Amplitude [V]	Angle [°]
2	100		
3	150		
4	200		
…	…		

2) Equivalent Impedance

In order to accurately predict the response of the WT or WPP to background harmonic voltage distortion occurring as result of harmonic sources in the external network to which the WT or WPP is connected it is needed to define harmonic impedance of the WT. Depending on the WT technology the impedance comprise various passive components in the main power circuit (e.g. series reactor, shunt harmonic filter, generator windings, transformer, etc.) as well as equivalent impedance of the dynamic feedback control system.

Due to the extensive utilisation of power electronics and feedback controllers in WPPs the Thévenin impedance can potentially include not only the passive components of WTs but also the grid-side converter internal impedance defined by the control scheme and operating points. The most dominating part should be expected from the passive components, however, for lower frequencies (especially within the converter control bandwidth) also the influence of the converter frequency response can be seen, e.g. controllers in order to achieve nil steady-state error ideally have infinite impedance which results at capacitive behaviour at controlled/tuned frequency. It should be noted that in grid-tied converters the positive and negative sequence impedance is not necessarily the same, however, it is the model developer or WT manufacturer responsibility to define whether the WT model should also distinguish the sequences.

Table 2 Exemplary representation/template of the harmonic equivalent impedance.

Harmonic Order	*Frequency*	*Harmonic Impedance*	
[-]	[Hz]	Resistance [Ω]	Reactance [Ω]
2	100		
3	150		
4	200		
…	…		

B. Wind Turbine Types

1) Doubly-Fed Asynchronous/Induction Generator (Type 3)

The WT with a doubly-fed asynchronous/induction generator DF(A/I)G is a variable-speed system with converters connected to the rotor and grid side, respectively. The power converter within the WT is typically controlled so that the quality of power is high/satisfactory. To achieve that a harmonic filter is included within the WT internal electrical infrastructure to absorb most of the distortion energy (i.e. harmonics) created by the converter/generator system.

The presence of voltage source converters (VSCs) power electronic grid interfaces potentially causes the production of harmonics and interharmonics [4]. According to [5], harmonics are produced in DFIGs via the following predominant means:

- Grid-side converter: fast switching produces high-frequency harmonics and interharmonics caused by the modulation technique.

- Rotor-side converter: low- and high-order rotor harmonic components propagate to the grid.
- DFIG windings: high-frequency harmonics are present in the air gap flux as well as space harmonics directly related to the slip.

The VSC used in a DFIG may have a very low harmonic impedance and, due to its frequency dependence, cannot be accurately represented by a constant current source. A Norton (or Thévenin) equivalent is therefore recommended [6], [7], whereby the frequency dependence of the equivalent shunt (or series) impedance can be modelled accurately. In addition, the high-frequency harmonic filters used in DFIGs should be considered as they influence resonances which can be also included/aggregated, for the sake of simplicity, into one common Norton/Thévenin impedance. An example harmonic representation of a DFIG, taken from [5], is illustrated in Figure 4.

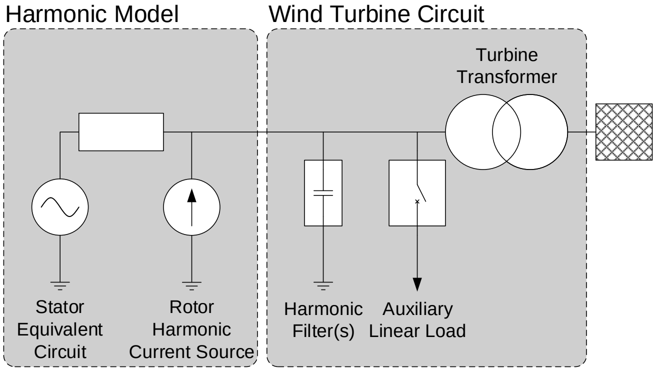


Figure 4 Exemplary structure of DFIG harmonic model (from [5]).

2) *Full Scale/Power Converter (Type 4)*

According to [3] the following examples for distinct harmonic voltage sources can occur in the Type 4 WT VSC:

- U_{PWM}: modulation related harmonics at sidebands of the integer multiples of the switching frequency, which can be calculated as a function of modulation depth and DC link voltage.
- U_C: a controlled voltage source, which can be determined from the current and voltage feedback and the open loop transfer functions of the current controller (i.e. inner loop) and voltage controller (i.e. outer loop).
- U_{Bridge}: a set of non-characteristic voltage sources which are due to effects in the power hardware such as, different voltage drop characteristics in the IGBTs and diodes, PWM command edge resolution, gate driver dynamics, and thermal effects, current sharing, etc.

Based on measurements which are field-dependent it is possible to represent Type 4 WT harmonic emissions by a Norton/Thévenin circuit comprising harmonic sources and equivalent impedances. However in order to obtain the harmonic source, knowledge of the WT impedance is needed which is within WT manufacturer competences and responsibility. The equivalent WT/converter impedance is dependent on e.g. the grid-side converter control strategy and filter topology. This approach can represent the WT from a harmonic perspective independently from the grid to which it is connected [8].

In the following an exemplary structure of a Thévenin equivalent converter harmonic model is shown based on reference [9]. In this example, passive filtering of harmonics is accomplished by a combination of converter reactor and a PWM shunt filter (as part of the WT circuit). There exist other arrangements such as e.g. a LCL filter included as part of the converter model. Also an equivalent Norton representation of the effect of converter controls and filter topology can be chosen. It is up to the WTG manufacturer to define the internal representation of the converter harmonic model. What is important is the correct response of the converter harmonic model to grid side impedances and (background) harmonic voltage sources.

Exemplary structure of the converter harmonic model based on [3]:

- The harmonic emissions from the converter is represented as a number of Thévenin equivalent circuits each representing the harmonic emissions and the interaction in terms of its controller to background harmonics at a particular harmonic frequency.
- The equivalent impedances (Z_c) in the model represent both the converter reactor and the converter control frequency response which represents converter interaction to background harmonic disturbances.
- The equivalent voltage sources (V_h) in the model represent the disturbances which are coursed by the PWM switching, the non-ideal properties of the converter hardware (e.g. network bridge, etc.) and control.

The Thévenin equivalent circuit is presented in Figure 5 [3].

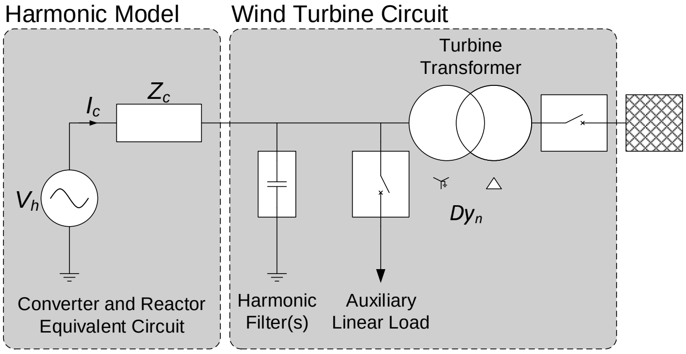
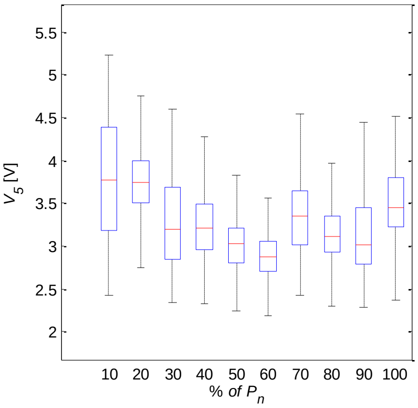


Figure 5 Exemplary converter harmonic model as Thévenin equivalent circuit together with exemplary WT power circuit (from [3]).

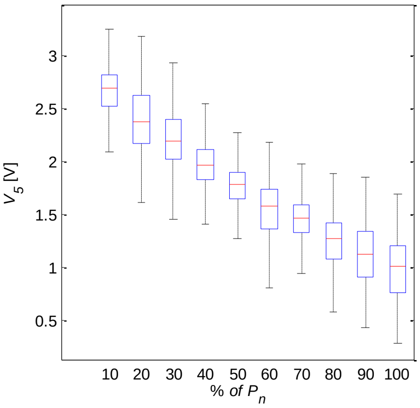
Harmonic current flow at the WT level can be significantly affected by the grid impedance and harmonic background distortion level. Harmonic modelling can allow to decouple harmonic contribution in the measurements from the grid and from the WT. Therefore developed model can constitute a good measure of WT harmonic performance.

An exemplary harmonic voltage measurements at the WT transformer LV terminals can be seen in Figure 6a. Such measurements are influenced by the grid to which the WT is connected as well by the WT itself. In Figure 6b it can be seen how the voltage at the same WT terminals is represented by the open-circuit Thévenin equivalent model. In Figure 6 harmonics are presented as box plot covering all possible active power production levels. On each box, the central mark is the median Q_2, the edges of the box are the 25th and 75th percentiles (lower quartile Q_1 and higher quartile Q_3

respectively), the whiskers[1] extend to the most extreme data points where outliers are not considered, and outliers are not plotted.



(a)



(b)

Figure 6 Harmonic voltage comparison for respective power bins: (a) harmonic voltage measured at the LV side of the WT transformer, (b) harmonic voltage of the Thévenin equivalent model.

C. *Minimum Requirements*

The WT harmonic model needs to have a standardised and universal structure in order to be broadly used by the industry. This would allow WT suppliers, WT manufacturers, WPP developers, system operators, software developers, academia, research institutions and other potential stakeholders to reach a common understanding and facilitate the dialog among each other. However for such a harmonic model to be really useful for harmonic impact studies a set of minimum requirements would need to be defined covering e.g.:

– Application,
– Input parameters and Output variables,
– Structure and Point of connection,
– Tolerances/uncertainties/accuracy and Limitations,
– Validation.

IV. VALIDATION AND ACCURACY

Validation is a procedure that is used for checking that the model meets the requirements and that can fulfil its intended purpose. Validation is a crucial part in harmonic model development and its further application. It also provides a measure to what extent the model is accurate and trustful. The possible discrepancy between the model and reality as measured during the validation process can constitute a basis for estimation of uncertainties and risk evaluation.

Every modern WT has built-in unique technical solutions in many cases protected by patents. Therefore it is up to the WT manufacturer how the harmonic model structure and model development is done. However results from the harmonic model validation process can provide a common understanding of WT harmonic performance to the industry and academia.

A. *Model accuracy*

The model accuracy can be estimated in the proposed scale covering three classes of accuracy. An overview about the harmonic model uncertainties can be used for risk evaluation and contingency estimation.

Class 1. Simulated/calculated based on WT design.

Harmonic model development based on simulations/calculations or software in the loop (SIL) studies incorporating actual design of a WT taking into account precise product specification, e.g. harmonic model developed based on WT design documentation and detailed models (e.g. EMTP-based, C-code from the control software, etc.).

Class 2. Verified by lab or field measurements.

Harmonic model development based on simulations/calculations, hardware in the loop (HIL) studies or measurements and model outputs are verified by independent measurements of the WT done by the model developer. The measurements can be done either at the test rig/bench or in the field, e.g. harmonic model verified by measurements on a prototype WT or at the test stand.

Class 3. Validated by third parties.

Harmonic model is verified and certified during independent measurement campaign by an accredited third party, e.g. certifying body according to internationally accepted procedures and standards.

Ideally the complete validation needs to be verified in 2 independent testing environments with distinct background harmonics and grid characteristics (e.g. SCR, etc.). This is to make sure that the model has correct responses to different background harmonics regardless the strengths of connected grid.

B. *Limitations*

The above simplified approach in representing WT from harmonic perspective also brings some limitations which should be understood and accepted:

– Many circuits are only linear over a certain range of values, thus the Thévenin equivalent is valid only within this linear range. Different input parameters or operating point can affect the WT harmonic performance therefore it should be decided and defined by the model developer or WT manufacturer whether such parameters as e.g. active and reactive power setpoint, generator RPM speed, converter modulation index, fundamental frequency phase angle,

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[1] The default whisker length *w* used in the box plots is of 1.5. Points are drawn as outliers if they are larger than $Q_3 + w(Q_3 - Q_1)$ or smaller than $Q_1 - w(Q_3 - Q_1)$.

short-circuit ratio, etc. affect the model harmonic behaviour in a significant way.

- The model component values are strongly linked to the converter control parameters and features especially within converter control bandwidth. Therefore the studies conducted in a specific version might need to be checked repeatedly when there comes new updates on converter software/features. It is up to model developer or WT manufacturer to judge and inform if such a re-check is needed in a coming converter software update.
- The Thévenin equivalent has an equivalent *I–V* characteristic only from the point of view of the load/grid. Thus the investigation of harmonic behaviour within the internal WT structure incorporated in the Thévenin equivalent impedance can be difficult or impossible. Thus it should be defined by the WT manufacturer which part of the system should be covered by the harmonic model and which should be excluded for further more detailed investigation.
- The power dissipation of the Thévenin equivalent is not necessarily identical to the power dissipation of the real system. However, the power dissipated by an external system between the two output terminals is the same regardless of how the internal circuit is implemented.
- Potentially it could be difficult to integrate the angle into the measurements when the party for carrying out the measurements does that with a standard PQ analyzer according to IEC 61000-4-30, in which the harmonic angle is usually not available. That is the case in e.g. Mexico and Brazil where it is required to measure with an equipment listed in an official document from Operador Nacional do Sistema Elétrico (ONS) which does not necessarily provide angle information.
- Small uncertainties in the WT harmonic model can be amplified to a significant level in WPPs characterized by resonance characteristics. In such a case, even small harmonic current injections can cause large local harmonic voltage distortion due to undamped parallel resonances. Thus careful application and engineering judgement in results interpretation is needed.
- The applicable frequency range of the model should be at least cover the first sidebands of switching frequency harmonics if the switching frequency of converter is not within the typical grid compliance frequency range.

V. ACKNOWLEDGMENT

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- Fritz Santjer, UL-International GmbH (DE)
- Sokratis Tentzerakis, UL-International GmbH (DE)

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