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TECHNICAL REPORT

Wind energy generation systems –
Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application

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WIND ENERGY GENERATION SYSTEMS –

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FOREWORD

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IEC TR 61400-21-3, which is a Technical Report, has been prepared by IEC Technical Committee 88: Wind energy generation systems.

The text of this Technical Report is based on the following documents:

DTR	Report on voting
88/698/DTR	88/717/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

The purpose of this IEC Technical Report (TR) is to provide a methodology that will ensure understanding, consistency and accuracy in application, structure and validation of the harmonic model of grid connected wind turbines (WTs).

There is an understandable requirement from wind power industry shareholders, e.g. transmission system operators (TSOs) and distribution system operators (DSOs), wind power plant (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 standardized harmonic model 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. Among others, this could be the evaluation of the WT harmonic performance, system-level harmonic studies, electrical infrastructure design and proposal of harmonic mitigation measures.

Standardized WT harmonic models as a performance measure starts to be important in such multi stakeholder systems as large offshore WPPs where TSOs, WPP developers and operators as well as WT manufacturers need to have a common understanding about harmonic modelling of WTs and harmonic studies in WPPs.

WIND ENERGY GENERATION SYSTEMS –

Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application

1 Scope

This part of IEC 61400 provides guidance on principles which can be used as the basis for determining the application, structure and recommendations for the WT harmonic model. For the purpose of this Technical Report, a harmonic model means a model that represents harmonic emissions of different WT types interacting with the connected network.

This document is focused on providing technical guidance concerning the WT harmonic model. It describes the harmonic model in detail, covering such aspects as application, structure, as well as validation. By introducing a common understanding of the WT representation from a harmonic performance perspective, this document aims to bring the overall concept of the harmonic model closer to the industry (e.g. suppliers, developers, system operators, academia, etc.).

A standardized approach of WT harmonic model representation is presented in this document. The harmonic model will 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 structure of the harmonic model presented in this document will find an application in the following potential areas:

– evaluation of the WT harmonic performance during the design of electrical infrastructure and grid-connection studies;
– harmonic studies/analysis of modern power systems incorporating a number of WTs with line side converters;
– active or passive harmonic filter design to optimize electrical infrastructure (e.g. resonance characteristic shaping) as well as meet requirements in various grid codes;
– sizing of electrical components (e.g. harmonic losses, static reactive power compensation, noise emission, harmonic compatibility levels, etc.) within WPP electrical infrastructure;
– evaluation of external network background distortion impact on WT harmonic assessment;
– standardised communication interfaces in relation to WT harmonic data exchange between different stakeholders (e.g. system operators, generators, developers, etc.);
– universal interface for harmonic studies for engineering software developers;
– possible benchmark of WT introduced to the academia and the industry.

The advantage of having standardized WT harmonic performance assessment by means of the harmonic model is getting more and more crucial in case of large systems with different types of WTs connected to them, e.g. multi-cluster wind power plants incorporating different types of WTs connected to the same offshore or onshore substation.

The WT harmonic model can cover the integer harmonic range up to the 40th, 50th, or 100th. And can be expanded, depending on requirements and application, to higher harmonic range as well as can also cover interharmonic components.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-415:1999, *International Electrotechnical Vocabulary – Part 415: Wind turbine generator systems* (available at <http://www.electropedia.org/)

IEC TR 61000-3-6:2008, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

IEC 61400-21-1:2019, *Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Part 1 – Wind turbines*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-415 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
compatibility levels
reference levels of a particular disturbance in a particular environment defined for co-ordinating the emission and immunity of equipment which is part of, or supplied by, a supply system in order to ensure the EMC in the whole system (including system and connected equipment)

Note 1 to entry: Compatibility levels are generally based on the 95 % probability levels of entire systems, using statistical distributions which represent both time and space variations of disturbances.

Note 2 to entry: There is allowance for the fact that the system operator or owner cannot control all points of a system at all times. Therefore, evaluation with respect to compatibility levels should be made on a system-wide basis and no assessment method is provided for evaluation at a specific location.

3.1.2
factor K
indicator of the ability of a transformer to be loaded with non-sinusoidal currents

Note 1 to entry: The equivalent power rating is equal to the power based on the RMS value of the non-sinusoidal current multiplied by the factor K.

[SOURCE: EN 50464-3:2007, modified – additional elaboration, creation of a note to entry and deletion of the formula]

3.1.3
harmonic phase or angle
phase (angle) α_{h} of the spectral component y_{h}, that is, the phase between the harmonic current component or harmonic voltage component and the fundamental component voltage defined in Figure 1 and equation below

$$y_{\mathrm{h}} = c_{\mathrm{h}} \sin\left(h\omega_1 t + \alpha_{\mathrm{h}}\right)$$

where c_{h} is the spectral component magnitude

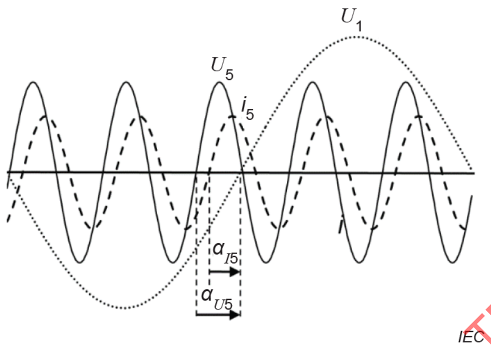


Figure 1 – Example of a phase angle between the harmonic current and the harmonic voltage component as well as the fundamental voltage

Note 1 to entry: The sign convention used for the voltages and currents is the generator convention as defined in IEC 61400-21-1:2019, Annex C.

Note 2 to entry: Please check IEC 61400-21-1:2019, Annex D for more details.

3.1.4
harmonic distortion
cyclic departure of a waveform from the sinusoidal shape

Note 1 to entry: This can be described by the addition of one or more harmonics to the fundamental.

3.1.5
harmonic model
model that represents harmonic emissions of a WT interacting with the connected network

Note 1 to entry: Different WT types may be modelled by changing the model parameters.

3.1.6
harmonic model terminals
reference point on the electric power system where here the harmonic model is connected

3.1.7
negative-sequence component of 3-phase voltages (or currents)
symmetrical vector system derived by application of the Fortescue's transformation matrix, and that rotates in the opposite direction to the power frequency voltage (or current)

[SOURCE: IEC TR 61000-3-13:2008, 3.26.4, modified – the formula has been deleted]

3.1.8
operational mode
<wind turbine> operation according to control setting, for example voltage control mode, frequency control mode, reactive power control mode, active power control mode, etc.

[SOURCE: IEC 61400-21-1:2019, 3.9]

3.1.9
percentile
the value of a variable below which a certain percent of observations fall

3.1.10
planning level
level of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions from the installations in a particular system, in order to co-ordinate those limits with all the limits adopted for equipment and installations intended to be connected to the power supply system

Note 1 to entry: Planning levels are considered internal quality objectives to be specified at a local level by those responsible for planning and operating the power supply system in the relevant area.

[SOURCE: IEC TR 61000-3-6:2008, 3.16]

3.1.11
point of connection
reference point on the electric power system where here the WPP is connected

[SOURCE: IEC 60050-617:2009, 617-04-01, modified – "user's electrical facility" has been replaced by WPP]

3.1.12
positive-sequence component of 3-phase voltages (or currents)
symmetrical vector system derived by application of the Fortescue's transformation matrix, and that rotates in the same direction as the power frequency voltage (or current)

[SOURCE: IEC TR 61000-3-13:2008, 3.26.3, modified – the formula has been deleted]

3.1.13
power bin
consecutive, non-overlapping intervals of WT active power measured at WT terminals

Note 1 to entry: The bins (intervals) shall be adjacent, and are usually equal size, e.g. 0, 10, 20, ... , 100 % of P_n. 0, 10, 20, ... , 100 % are the bin midpoints.

[SOURCE: IEC 61400-21-1:2019, 3.62, modified – "active" has been deleted from the term defined; in the note, "shall be adjacent" has been added and the text has been slightly modified]

3.1.14
prevailing angle
phase of the spectral component is described by

$$\alpha_{\mathrm{h,avg}} = \arctan\left(\frac{\sum_{i=1}^{n}\mathrm{Im}\left(\underline{C}_{\mathrm{h,i}}\right)}{\sum_{i=1}^{n}\mathrm{Re}\left(\underline{C}_{\mathrm{h,i}}\right)}\right), \quad \text{if } \sum_{i=1}^{n}\mathrm{Re}\left(\underline{C}_{h,i}\right) \geq 0$$

$$\alpha_{\mathrm{h,avg}} = \pi + \arctan\left(\frac{\sum_{i=1}^{n}\mathrm{Im}\left(\underline{C}_{\mathrm{h,i}}\right)}{\sum_{i=1}^{n}\mathrm{Re}\left(\underline{C}_{\mathrm{h,i}}\right)}\right), \quad \text{if } \sum_{i=1}^{n}\mathrm{Re}\left(\underline{C}_{h,i}\right) < 0$$

where

n is the number of DFT windows;

$\underline{C}_{h,i}$ is the complex value of the h-th harmonic from the estimated spectrum from each of i-th 10-cycle or 12-cycle window, and

C_h is the h-th harmonic magnitude.

Note 1 to entry: Definition of rectangular window as in IEC 61000-4-7:2002.

3.1.15
prevailing angle ratio
ratio describing the phase randomness of spectral component and expressed by

$$\text{PAR} = \frac{\left|\sum_{i=1}^{n} \underline{C}_{h,i}\right|}{\sum_{i=1}^{n} \left|\underline{C}_{h,i}\right|} = \frac{\left|\sum_{i=1}^{n} \left(a_{h,i} + jb_{h,i}\right)\right|}{\sum_{i=1}^{n} \left|a_{h,i} + jb_{h,i}\right|}$$

where

$\underline{C}_{h,i}$ is the complex spectral component from DFT;

$a_{h,i}$ and $b_{h,i}$ are the real and imaginary components of the complex spectral component of the i-th window, respectively.

3.1.16
short-circuit power
product of the current in the short-circuit I_k at a point of a system and a nominal voltage U_n, generally the operating voltage

$$S_k = \sqrt{3} I_k U_n$$

Note 1 to entry: Using physical units for line current (A) and nominal phase-to-phase voltage (V), the product should also include the factor $\sqrt{3}$.

[SOURCE: IEC 60050-601:1985, 601-01-14, modified – "conventional" has been replaced by "nominal"]

3.1.17
short-circuit ratio
ratio of the short-circuit power S_k at the point of connection to the nominal power S_n of the WPP or WT

$$SCR = \frac{S_k}{S_n}$$

[SOURCE: IEC 61400-27-1:2015, 3.1.18, modified – "active" has been deleted and the equation has been added]

3.1.18
system operator or responsible
entity responsible for making technical connection agreements with customers who are seeking connection of load or generation to a distribution or transmission system

[SOURCE: IEC TR 61000-3-6:2008, 3.23, modified – “owner” has been changed to responsible]

3.1.19
total harmonic distortion
ratio of the RMS value of the sum of all the harmonic components up to a specified order to the RMS value of the fundamental component

$$\mathrm{THD}=\sqrt{\sum_{h=2}^{H}\left(\frac{Q_\mathrm{h}}{Q_1}\right)^2}$$

where

Q represents either current or voltage;

Q_1 is the RMS value of the fundamental component;

h is the harmonic order;

Q_h is the RMS value of the harmonic component of order h;

H is generally 40, 50 or 100 depending on the application.

[SOURCE: IEC TR 61000-3-6:2008, 3.26.7, modified – H is defined differently]

3.1.20
wind power plant
power station comprising one or more WTs, auxiliary equipment and plant control

[SOURCE: IEC 61400-27-1:2015, 3.1.25]

3.1.21
wind turbine
rotating machinery in which the kinetic wind energy is transformed into another form of energy

[SOURCE: IEC 60050-415:1999, 415-01-01]

3.1.22
wind turbine terminals
point being a part of the WT and identified by the WT supplier at which the WT is connected to the power system

Note 1 to entry: Same definition as in IEC 61400-21 defining the measurement point of the tests.

3.2 Abbreviations

The following abbreviations are used in this document.

AUX	auxiliary equipment
CB	circuit breaker
DC	direct current
DCL	DC link
DFAG	doubly fed asynchronous generator[1]
DFT	discrete Fourier transform
GSC	generator (machine) side converter
HD	harmonic distortion
HIL	hardware in the loop
HMT	harmonic model terminals
HV	high voltage

1 Often referred to as a doubly-fed induction generator (DFIG), but it is not operated as an induction generator when the rotor current is controlled.

HVAC	high voltage alternating current
HVDC	high voltage direct current
LSC	line (grid) side converter
LV	low voltage
MV	medium voltage
PA	prevailing angle
PAR	prevailing angle ratio
POC	point of connection
PWM	pulse width modulation
RMS	root mean square
SCR	short circuit ratio
SIL	software in the loop
STATCOM	static synchronous compensator
TR	transformer
THD	total harmonic distortion
VSC	voltage source converter
WPP	wind power plant
WT	wind turbine
WTT	wind turbine terminals

4 General description

4.1 Overview

Harmonics are of special concern in power system studies. In the past, the power system comprised mainly passive components with a relatively linear operating range as well as synchronous generators.

Renewable energy sources, e.g. WTs, are becoming more prevalent in many power systems. Power electronic equipment in modern power systems is obviously a source of additional harmonic components not seen previously. On the other hand, the application of advanced and fast control in grid-connected voltage-source power converters (VSCs) introduces the possibility of controlling higher frequency components than the fundamental. Appropriately used power electronics can definitely improve power quality.

Therefore, due to the modern power converters complexity, there is a great necessity to perform a careful power quality evaluation including harmonic measurements, data processing, data analysis, and harmonic modelling of WTs.

Measurements are an important part in the WPP and WT evaluation process. In order to validate theoretical analysis and numerical simulations, measurements are required. Appropriate measurements as well as data processing techniques are crucial in the WT analysis and evaluation. Figure 2 is presenting how WPP main components relevant for the harmonic studies are contributing to potential challenges in harmonic performance. WT harmonic model is one of the most important parts required in overall system modelling and behaviour estimation.

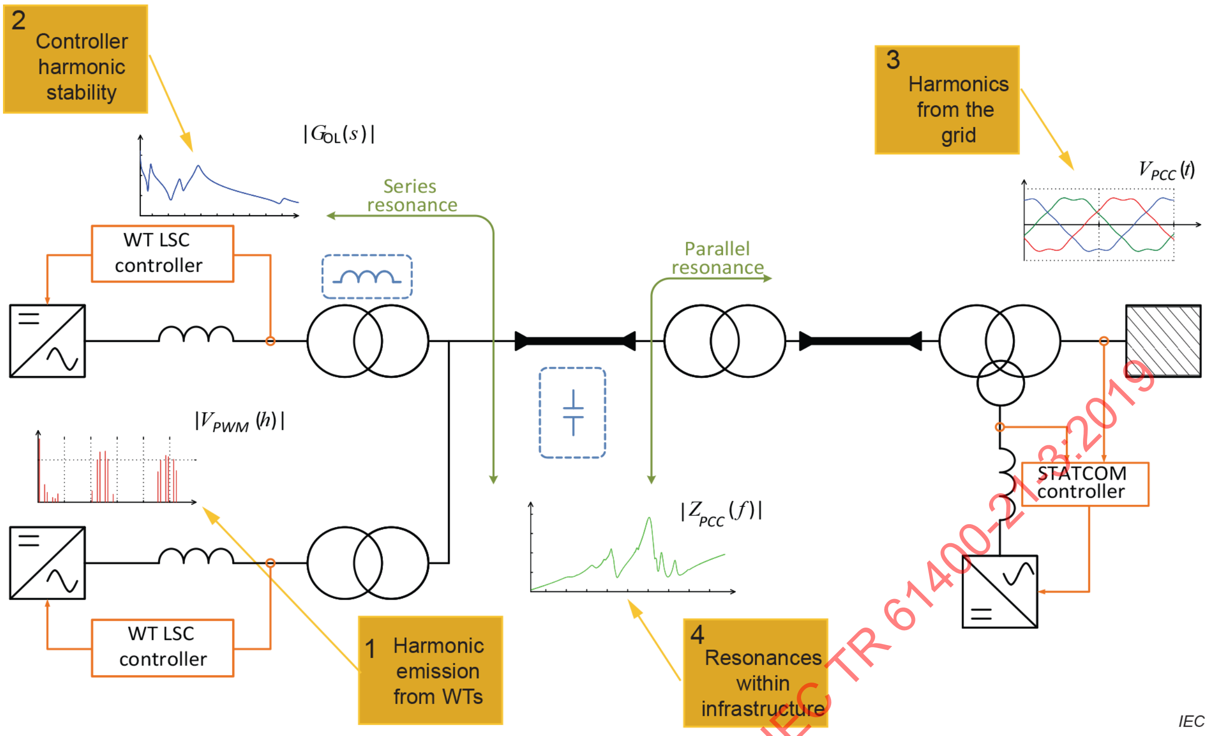


Figure 2 – Example of wind power plant typical components relevant for the harmonic studies and potential challenges in harmonic performance

4.2 Background

Nowadays, large offshore WPPs with complex structures including WT, array cable systems, and HVAC or HVDC offshore/onshore transmission systems are being introduced (see Figure 3 and Figure 4). This represents new challenges to the industry in relation to prediction and mitigation of harmonic emission and propagation [7][2]. 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 the 2nd edition of IEC 61400-21 [5] is based on a harmonic current evaluation dependent on local grid conditions. Moreover, the direct application of the harmonic current measurements to other grid scenarios has been reported by the industry to be potentially inaccurate, causing incorrect design and dimensioning of passive filters. This is mainly due to the fact that the existing standard provides only current spectrum of a WT and as a consequence can be considered as an ideal harmonic current source neglecting the internal impedance. This approach also neglects any grid impedance impact on the generated harmonic currents. More accurate evaluation methods are described in IEC 61400-21-1:2019, Annex D.

[2] Figures in square brackets refer to the Bibliography.

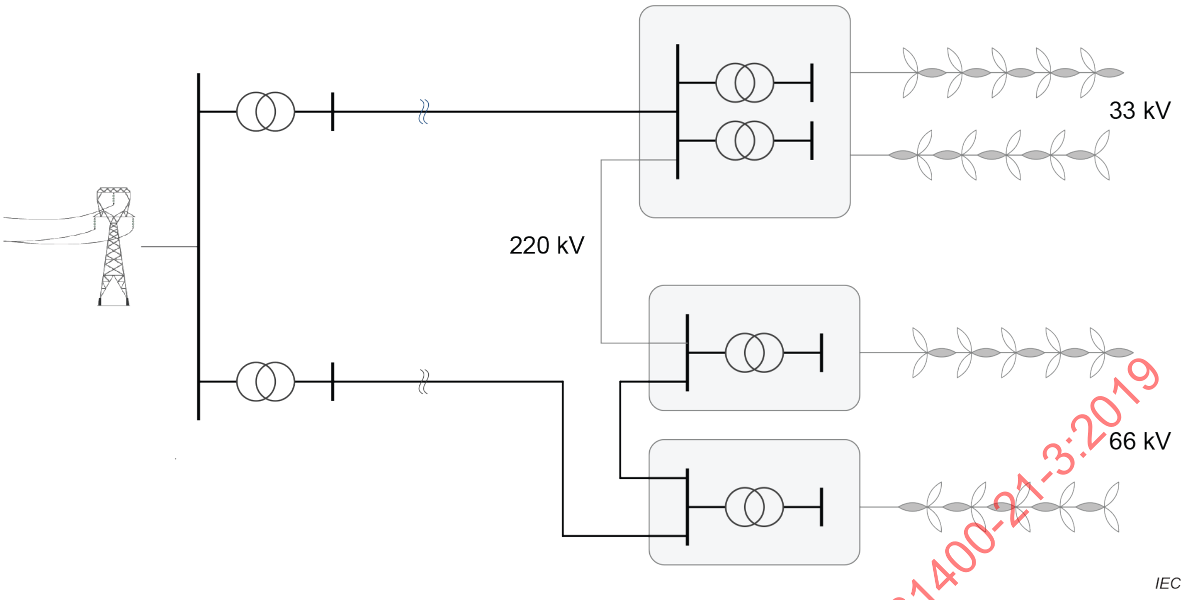


Figure 3 – Example of a WPP complex structure

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 a more accurate assessment procedure, IEC 61400-21-1:2019, Annex D recommends besides the harmonic currents also harmonic voltage measurement procedures, including phase information and aggregation techniques [8]. Additionally, a number of recommendations and guidance is provided to exclude the impact of the external network during the measurement process. Afterwards, such extensive measurement dataset can be used either for WT harmonic model validation or even development as shown for example in [9].

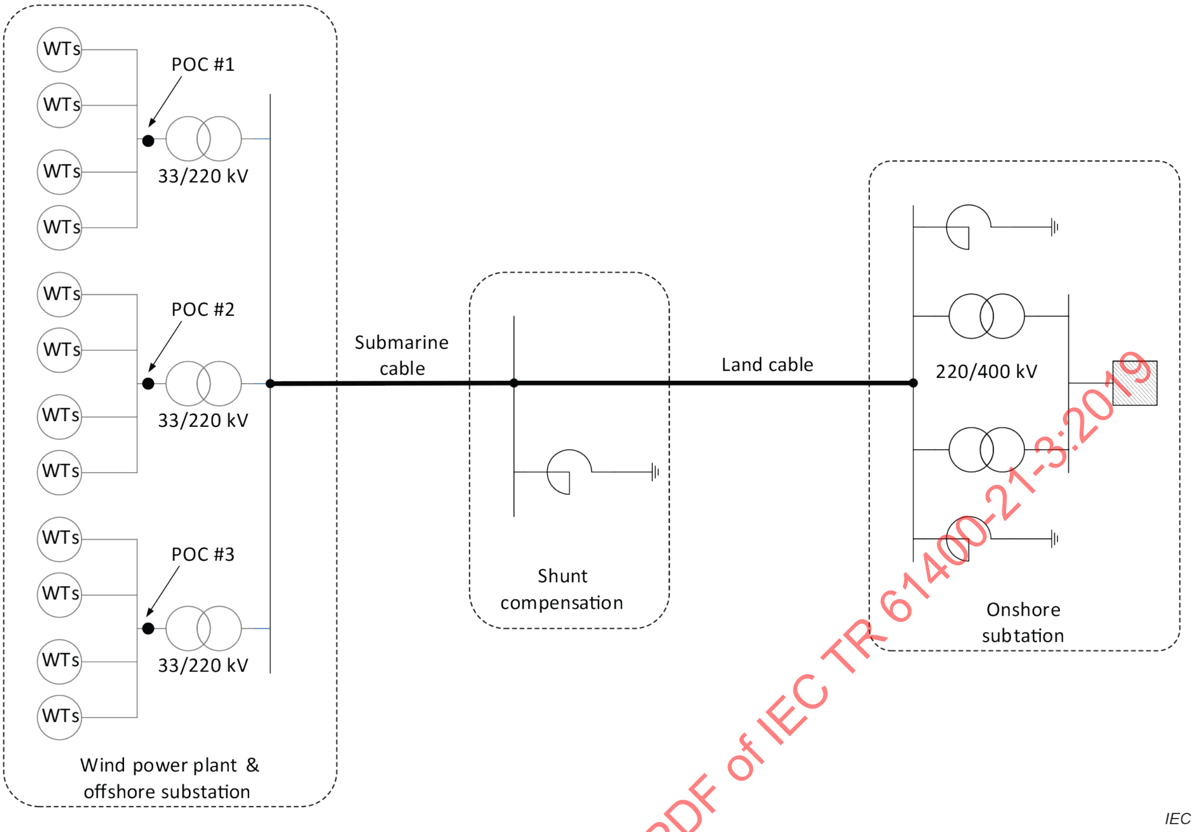


Figure 4 – Example of a WPP complex electrical infrastructure with many WTs

Furthermore, it also addresses the evaluation of uncertainties of the measurements and the data analysis. IEC 61400-21-1 provides guidelines on how to detect which harmonic currents are affected by the background harmonic distortion which is specified in Annex D.

In terms of harmonic evaluation, IEC 61400-21 [5] specifies a standard approach on how to take into account the impacts of the grid. The state-of-the-art approach is to report current based power quality characteristics like current harmonics in the test report. This is based on the assumption that the current emission is independent on the grid voltage, i.e. the emission can be described as a current source which is characteristic to the specific unit type. However, such an assumption is not valid for WTs and complex WPP systems (see for example Figure 3 and Figure 4) comprising many WTs and characterised by various resonance phenomena (see Figure 5).

Unfortunately, until now there has been no systematic approach of representing WTs from a harmonic performance perspective. This brings inconsistency in WT harmonic performance assessment, background distortion evaluation in grid-connected WTs, harmonic analysis of WPPs, etc.

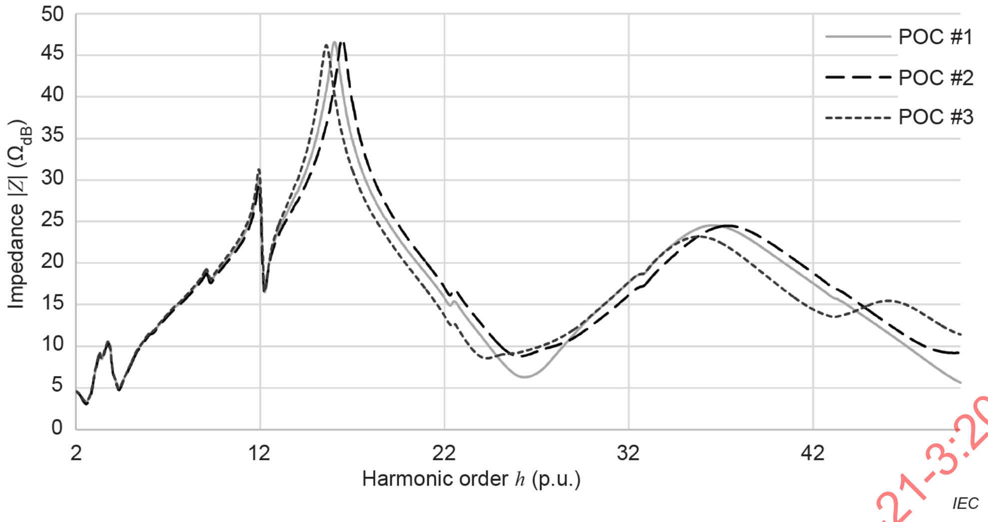


Figure 5 – Harmonic impedance estimated at the point of connection specified in Figure 4

Having a standardized WT harmonic model definition allows consistent and fluent communication between parties within the wind power industry. 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 61400-21-1;
- introduce a standardised way of performing harmonic analysis in WPPs;
- assess the influence of the external network on the harmonic distortion at POC;
- introduce common interfaces to various engineering tools for harmonic analysis;
- define a common basis for dialog with manufacturers, developers, system operators or owners;
- provide a benchmark for the academia and industry.

Desired properties of the WT harmonic model are as follows:

- allows estimating the influence of the grid where the WT under test is connected;
- correctly represents the WT reaction to background harmonic voltages in the connection grid;
- provides a universal measure of WT harmonic performance;
- can be applied in harmonic assessment studies comprising various grid conditions, e.g. contingency scenarios or outage conditions, whereas the harmonic current measurements from a single scenario cannot;
- represent all possible WT operational modes affecting harmonic performance;
- has a standard and commonly recognized engineering structure as well as can be widely used for harmonic analysis/studies on a system level.

5 Recommendations of minimal requirements

5.1 General

The WT harmonic model, in order to be broadly used by the industry, needs to have a standardised and universal structure. This would allow WT manufacturers, WPP developers, system operators or owners, universities and other potential stakeholders to have a common understanding and to more easily establish a dialog between each other. Therefore, the minimal requirements need to be defined. It would be:

– application,
– input parameters,
– harmonic model terminal,
– output variables,
– structure.

5.2 Application

The WT harmonic model in the basic form is expected to be applicable to broadly understood harmonic analysis of WPPs. This will include harmonic emission studies as well as harmonic propagation/resonance studies. Harmonic analysis of WPPs is focused on the following aspects:

– grid code requirements,
– harmonic filter design,
– WPP components sizing (e.g. planning levels, compatibility levels, factor K, etc.),
– overall electrical infrastructure optimisation.

Therefore, the WT harmonic model should reflect the WT electrical behaviour including harmonic emission and impedance characteristic.

Typically, the electrical infrastructure of large WPPs is developed and designed based on the design guidance available in applicable recommendations and standards [10]. Planning levels are applied to determine harmonic distortion limits, taking into consideration all distorting installations. These are levels of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions from the installations in a particular system, in order to co-ordinate those limits with all the limits adopted for equipment and installations intended to be connected to the power supply system. Planning levels are considered as internal quality objectives to be specified at a local level by those responsible for planning and operating the power supply system in the relevant area.

5.3 Input parameters

The input parameters characterising the WT harmonic behaviour need to be considered in the model development. Such parameters are dependent on the model application, i.e. simplified model for basic studies and detailed to evaluate more precisely WT harmonic behaviour. Depending on the application, it should be decided and defined by the model developer whether such parameters, as for example active and reactive power setpoints, generator RPM speed, converter modulation index, fundamental frequency phase, etc., can affect the model harmonic behaviour. Any limitations and uncertainties should be addressed and described.

In IEC 61400-21, the WT harmonic performance is evaluated depending on active power bins. Active power is one of the recommended input parameters to be taken during the harmonic model development. Of course, for the sake of simplicity, the worst case harmonic magnitude for each harmonic component from all active power bins can be taken. However, this leads to too conservative results. If the application of a harmonic model reflecting the worst-case magnitude allows, for example, fulfilling the requirements of the TSO or design a feasible harmonic filter, then the simplification can be justified. If this is not the case, a detailed analysis based on power bins is recommended for analysing in which situation the limits are violated or filter oversizing is obtained. The more extensive harmonic model representation is usually a good information for the WPP owner/developer or utility.

5.4 Harmonic model terminal

It is important that the WT harmonic model reflects the harmonic behaviour of the whole WT as one of the components in modern power systems (e.g. WPPs). Therefore, it is important to define which part of the WT the harmonic model reflects. Based on the model, it should be possible to estimate the level of harmonic distortion at the WT terminals (WTT), i.e. LV or HV side of the WT transformer (TR).

For models intended to represent a WT in power systems analysis, the harmonic model terminals (MHTs) should be defined as the WTT. Therefore, any relevant components which are part of the WT internal power circuit (e.g. filters or auxiliary circuits) should be considered in model development and included in the model. It is the model developer's responsibility to evaluate which component properties (e.g. frequency dependent inductor losses) need to be considered in order to achieve the desired level of accuracy.

5.5 Output variables

To perform typical harmonic analysis in frequency/harmonic domain and evaluate the WT harmonic performance, there is a need to express WT as harmonic source covering all relevant harmonic components (typically up to the 40^{th}, 50^{th} order), [10] and frequency-dependent impedance incorporating the WT active (e.g. converter controller, etc.) and passive (e.g. filter, reactor, etc.) components. The harmonic model is devoted to allow estimating the harmonic distortion level (i.e. harmonic magnitude and phase) as well as frequency-dependent impedance at HMT. The harmonic range needs to be adjusted accordingly to specific studies and grid code requirements.

Assessment of harmonic disturbance in offshore WPPs is becoming an increasingly important task as they are increasing in size. It has been customary in the past to base all compliance and design studies on positive sequence simulation models. However, the use of long high voltage cables (for example in WPPs) gives rise to the need for more sophisticated modelling. It is justified that on unsymmetrical cable systems, a decoupled sequence model (i.e. no coupling in the sequence impedance matrix or only simple positive sequence representation) can lead to underestimation of the harmonic distortion in the system [11].

However, for systems with strong unbalanced impedance profile (e.g. long underground HVAC cables with flat formation), it starts to be important to also address the sequence of the harmonic components as well as the 3-phase WT harmonic model representation. The structure of the model should be specified depending on the level of details in modelling as well as electrical infrastructure of the investigated system. In classical power systems, harmonic analysis, the sequence decomposition typically shows that the harmonics in general follow their natural sequences. However, in WTs with grid-tied converters, the harmonics, due to the WT system complexity, can be generated of any sequence. Furthermore, in the proximity of resonance points in asymmetrical systems, the harmonics will contain some portion of the two other sequence components [11].

5.6 Structure

It is of common practice to represent the WT harmonic model as a Norton/Thévenin equivalent circuit. Therefore, using the WT harmonic model by means of simulations in engineering tools 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; this model structure is able to represent both aspects of the WT behaviour.

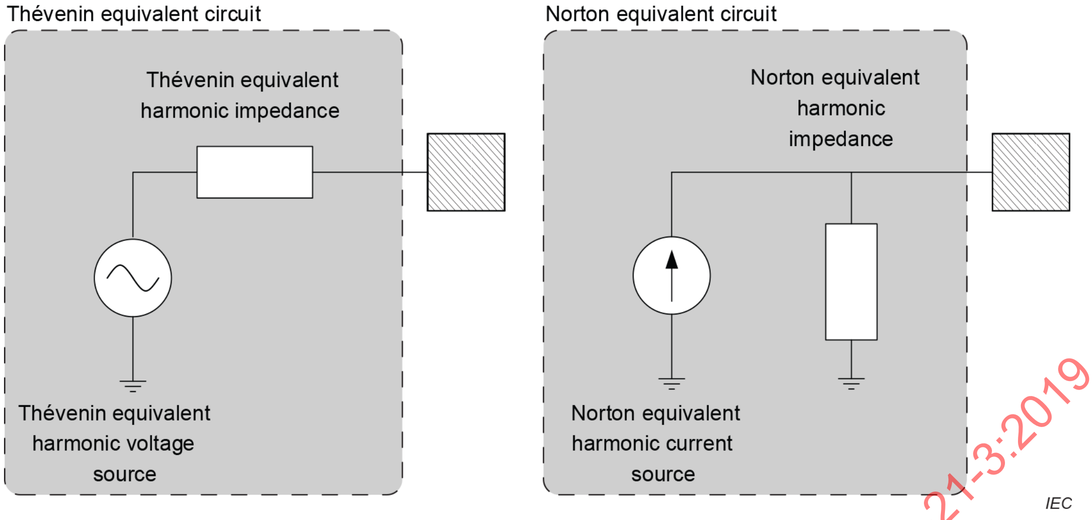


Figure 6 – Generic harmonic model structure represented as Norton/Thévenin equivalent circuit

A generic harmonic model structure represented as a Norton/Thévenin equivalent circuit is shown in Figure 6. The Norton/Thévenin equivalent circuit is represented by means of an equivalent ideal current/voltage source and an equivalent impedance for each harmonic/frequency order of interest. Thus, an appropriate harmonic model may be applied in harmonic/frequency domain studies. Further elaboration about the harmonic model structure (with some examples) is given in Clause 7.

6 Interfaces to other IEC documents

6.1 IEC 61400-21-1:2019, Annex D – Harmonic evaluation

The harmonic current emission of a WT can be influenced for example by:

- external grid harmonic background distortion,
- resonances in the grid frequency-dependent short-circuit impedances,
- short circuit power at the grid connection point.

The aim of Annex D is to evaluate the harmonic emission of a WT independently of the above influences as accurately as possible. Thus, it may be necessary to identify other influences on the harmonic emission of the WT and possibly exclude these influences.

The aforementioned influences are dependent on the WT type, on the grid configuration and situation at the site of the measured WT as well as on the actual grid background harmonic voltage distortion during the measurements. Thus, it is still not possible to give a specific procedure on how to identify the influences and how to exclude them.

The WT harmonic assessment can also be done based on the WT harmonic model evaluation. The model can be developed based on measurement data as well as sophisticated simulation tools. The model would describe the harmonic behaviour of the WT in theory, excluding the influence of a distorted grid to which the WT is connected.

The model can be used in order to evaluate the background harmonic distortion impact on the measurement process as specified in Annex D.

6.2 IEC 61400-21-1:2019, Annex E – Assessment of power quality of wind turbines and wind power plants

The total installed power per WPP is increasing. This creates new challenges in the harmonic analysis of such complex systems (see Figure 4), leading to the harmonic emission evaluation at the POC and as a consequence to the introduction of harmonic mitigation measures by means of active or passive filtering.

Therefore, there is a need to have an appropriately developed and validated harmonic model in order to estimate the influence of the WT on the harmonic level at the point of interest. This would cover possible harmonic summation and cancellation between WTs.

Nowadays, there is no standard approach of doing harmonic analysis in WPPs. Within the scope of IEC 61400-21-1:2019, Annex E, recommendations and guidance on performing harmonic emission assessment on a WPP level will be provided [6]. This will include the estimation of harmonic current flows within a WPP system as an extension of the already existing recommendation in IEC TR 61000-3-6. Such recommendation will also directly be reflected in the WT harmonic model structure and its application.

7 Harmonic model

7.1 General

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) or its dual Norton equivalent circuit comprising an ideal current source (Table 2) and an equivalent impedance (Table 3). 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. The harmonic model should reflect WT harmonic behaviour independently on grid disturbances.

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

The WT harmonic model is expected to reflect the WT harmonic behaviour. However, as any model, it is an estimation trying to reflect the reality. Therefore, any information reflecting the uncertainties of the model introduced in the development process such as components tolerances, non-linearities, aggregation or averaging, etc. should be addressed. The knowledge about uncertainties of the model is critical in case of model application in harmonic analysis/studies on a system level where multi-WT systems are considered.

Prevailing angle ratio (PAR) can be helpful in the assessment of uncertainties. If the PAR is close to unity, it means that there is no significant variation of the harmonic phase during the analysed interval. However, the harmonic phase behaviour between WTs can vary depending on the system topology changes, WTs power production level, etc., thus PAR cannot be used directly to define the harmonic angle displacement (harmonic cancellation) between WTs at POC. If the value is much lower than 1, it means that the harmonic phase variation can be caused either by uncertainties, significant changes in the analysed system or lack of analysed harmonic phase lock to the fundamental frequency. If the PAR is low and the harmonic magnitude is low, the estimated harmonic component can be significantly affected by uncertainties in measurements or data processing. Please note that the PAR is one of the supplementary indices and cannot give absolute guidance about the system uncertainties.

7.2 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 $Z^{\mathrm{Th}} = Z^{\mathrm{No}}$). 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.

7.3 Equivalent harmonic voltage/current sources

7.3.1 General

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

The magnitude aggregation considered in IEC 61400-21-1 is performed using the square root of the arithmetic mean of the squared input values (i.e. RMS), and grouping of the spectral components can be performed according to IEC 61000-4-7. The other statistical forms of magnitude can also be used to demonstrate the variation of the WT harmonic behaviour, such as 95$^{\mathrm{th}}$ percentile according to IEC TR 61000-3-6 or maximum values, which is regarded as the worst scenario case, generally speaking. It gives the opportunity for system operators or owners and other model users to select appropriate values for harmonic simulation studies according to different needs.

The phase can be determined as prevailing angle (PA) and the randomness of the PA can be estimated from the PAR. If the PAR is close to unity, it means that there is not significant variation of the harmonic phase during the analysed interval. If the value is much lower than 1, it means that the harmonic phase 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. Note that it is difficult to combine grouped amplitudes with phase angles of ungrouped values. Phase angle aggregation is not possible with grouped values. PA should be done without grouping and smoothing directly from DFT.

One should note that harmonic phase aggregation is not specified in any of the standards concerning the power quality. Therefore, another aggregation approach can sometimes be seen, e.g. taking into consideration magnitude as well as phase aggregation as complex values where harmonic magnitude and harmonic phase are aggregated together, complex unity vectors with harmonic phases directly from DFT where harmonic phase is aggregated separately or generating from the phase distribution (for example point with highest probability of occurrence). The PA method is preferred; however, other methods can also be applied. The phase aggregation method shall be described.

Table 1 – Example of a representation/template of the harmonic voltage source

Harmonic order	Frequency	Harmonic voltage	
[-]	Hz	Magnitude (RMS) V	Phase in degrees
2	100		
3	150		
4	200		
…	…		

Table 2 – Example of a representation/template of the harmonic current source

Harmonic order	Frequency	Harmonic current	
[-]	Hz	Magnitude (RMS) A	Phase in degrees
2	100		
3	150		
4	200		
…	…		

Exemplary harmonic model representations as lookup tables as presented in Table 1 and Table 2 are reflecting a specific WT operational mode. Therefore, it should be defined by the harmonic model developer or WT manufacturer which input parameters are relevant and can change the harmonic profile of the model. Moreover, possible interharmonic components can be addressed in the harmonic model if their existence and modelling is relevant to express the overall harmonic behaviour of the WT under consideration. The harmonic components specified in Table 1 and Table 2 can, instead of the phase representation, refer to both positive and/or negative sequence components which are defined as in Clause 3.

For simplified studies, a positive-sequence harmonic model representation would be sufficient. However, in order to investigate the system in detail, a more extended WT harmonic model is needed, given in a table representation for each specified operational mode for which harmonic characteristics of the WT are different. Furthermore, a general harmonic source table or a general current source table which includes different operating points does not include a column for phase. A general source table (together with the equivalent harmonic impedance table) is used for a simplified and conservative study. If the simple model gives too conservative results, further complexity in the modelling can be introduced to more precisely estimate the harmonic distortion level and consequently avoid system overdesigning.

7.3.2 Harmonic equivalent impedance

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

Due to the extensive utilisation of power electronics and feedback controllers in WPPs, the Thévenin impedance includes not only the passive components of WTs but also the line side converter (LSC) internal impedance defined by the operational mode. The most dominating part should be expected from the passive components; however, for lower frequencies (especially within the converter control bandwidth), 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 in capacitive behaviour at the controlled/tuned frequency. It should be noted that in LSCs, the positive and negative sequence impedance is not necessarily the same; however, it is the model developer's or WT manufacturer's responsibility to define whether the WT model should also distinguish the sequences. Typically, the characteristic harmonics are the most prominent in power systems, i.e. the positive sequence (e.g. 7^{th}, 13^{th}, etc.) and the negative sequence (e.g. 5^{th}, 11^{th}, etc.). As soon as the WT (or the controller of the LSC) behaves differently in the negative sequence (compared to the behaviour in the positive sequence of the same frequency), the model has to reflect positive and negative sequence, i.e. two models are needed.

Table 3 – Example of a representation/template of the harmonic equivalent impedance

Harmonic order	Frequency	Harmonic impedance	
[-]	Hz	Resistance, R Ω	Reactance, X Ω
2	100		
3	150		
4	200		
…	…		

It should be noted that the part of the harmonic equivalent impedance influenced by the WT control strategy can also vary depending on the operational mode. Typically, the WT LSC impedance is a small-signal representation of the system and thus it also should be defined by the manufacturer which operational modes it is covering.

7.4 Wind turbine types

7.4.1 General

In Subclause 7.4, one can read how the harmonic model described in a generic way can reflect the behaviour of different WT types. An exemplary application of the harmonic model is described based on the references provided. This part elaborates about the harmonics in WTs and how they could be potentially included in the modelling.

7.4.2 Type 1 and Type 2

A Type 1 WT uses asynchronous generators directly connected to the grid, i.e. without power converter. Most Type 1 WTs have a soft-starter, but this is only active during start-up. A Type 2 WT is similar to a Type 1 WT in many aspects, but the Type 2 turbine is equipped with a variable rotor resistance and therefore uses a variable rotor resistance asynchronous generator [6].

Historically [4], Type 1 and Type 2 WTs were not evaluated from a harmonic perspective and thus there was no need to provide/develop a harmonic model for them. According to [4], harmonic emissions have been reported from few installations of WTs with induction generators but without power electronic converters. Thus, one can measure harmonics directly from the generator. Furthermore, there is no known instance of customer annoyance or damage to equipment due to harmonic emissions from such WTs. Nowadays, Type 1 and Type 2 WTs are less and less commonly seen in modern power systems and not present in new WPP installations, thus this document will not elaborate further about this type of WTs.

7.4.3 Type 3

Type 3 WTs uses a doubly fed asynchronous generator (DFAG), where the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter. Figure 7 shows the main electrical and mechanical components of a Type 3 WT. The power converter consists of the generator side converter (GSC), the LSC and the DC link (DCL) with the DCL capacitor (C). Type 3 WTs can have sufficiently dimensioned GSC and chopper (CH) for undervoltage ride-through without bypassing or disconnecting the converter. Other Type 3 WTs include a crowbar device (CRB) which short-circuits the rotor during electromagnetic transients and converts the WT generator during this time into an induction machine [6].

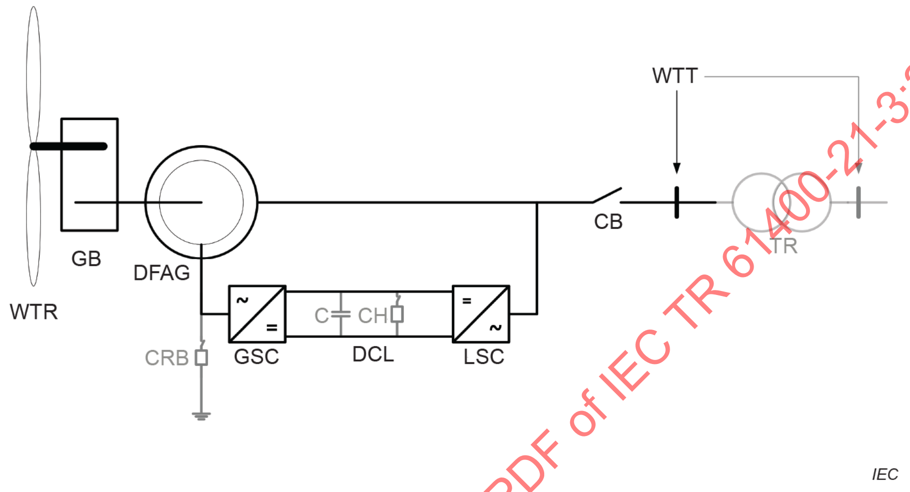


Figure 7 – Main electrical and mechanical components of Type 3 WTs [6]

The WT with a DFAG 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 power quality 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 power electronic grid interfaces in VSCs potentially causes the production of harmonics and interharmonics [12]. According to [13], harmonics are produced in DFAGs via the following predominant means:

– LSC: converter fast switching produces high-frequency harmonics and interharmonics caused by the modulation technique (also characteristic for Type 4).
– GSC: low- and high-order rotor harmonic components propagate to the grid.
– DFAG 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 DFAG 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 [14], whereby the frequency dependence of the equivalent shunt (or series) impedance can be modelled accurately. In addition, the high-frequency harmonic filters used in DFAGs 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 DFAG, taken from [13], is illustrated in Figure 8. The mechanism of harmonic generation by LSCs in Type 3 is similar as in Type 4.

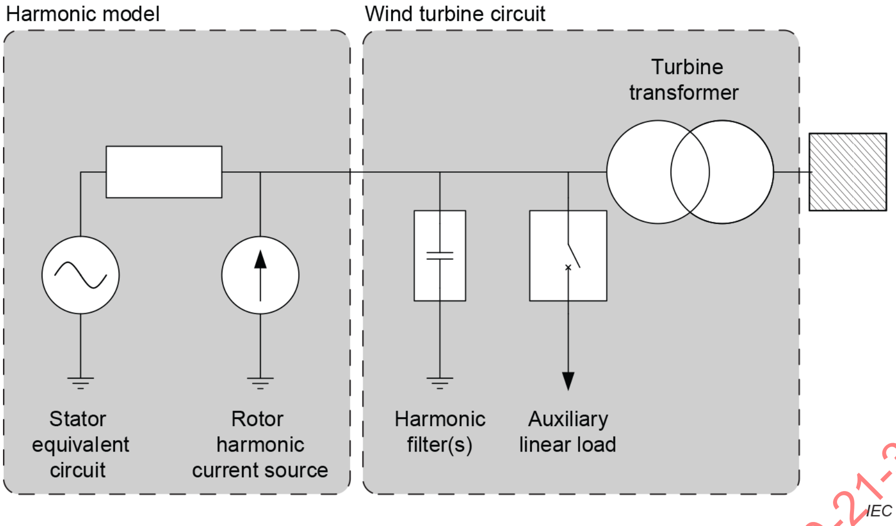


Figure 8 – Example of a structure of a DFAG harmonic model (from [13])

7.4.4 Type 4

Type 4 WTs are WTs connected to the grid through a full-scale power converter. Figure 9 shows the main electrical and mechanical components of Type 4 WTs. Type 4 WTs use either synchronous generators (SG) or asynchronous generators (AG). Some Type 4 WTs use direct drive synchronous generators, and therefore have no gearbox [6].

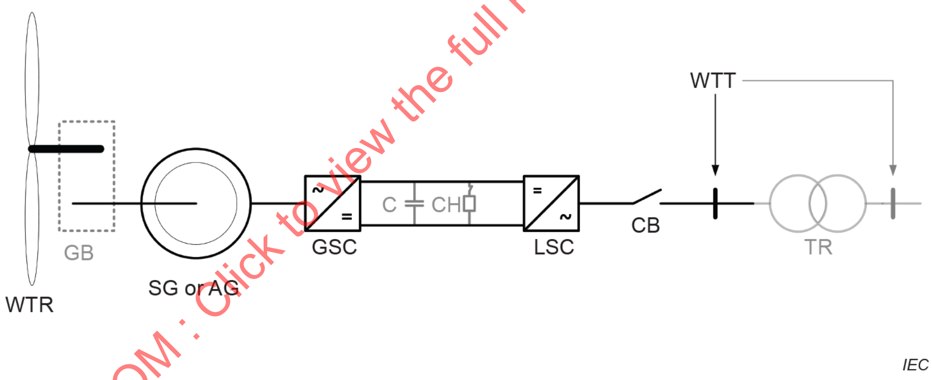


Figure 9 – Main electrical and mechanical components of Type 4 WTs [6]

According to [9], the following examples for distinct harmonic sources can occur in the Type 4 WT VSC:

- Pulse width modulation (PWM) 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.
- Converter control related harmonics 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).
- Non-characteristic power converter harmonics which are due to effects in the power electronic hardware such as different voltage drop characteristics in semiconductors, 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 the WT manufacturer competences and responsibility. The equivalent WT/converter impedance is dependent for example on the LSC control strategy and filter topology. This approach can represent the WT from a harmonic perspective independently of the grid to which it is connected [15].

In the following, an exemplary structure of a Thévenin equivalent converter harmonic model is shown based on reference [16]. 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 for example 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 WT 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 [9]:

– The harmonic emissions from the converter are 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 (also interharmonic if applicable) 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 caused 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 10.

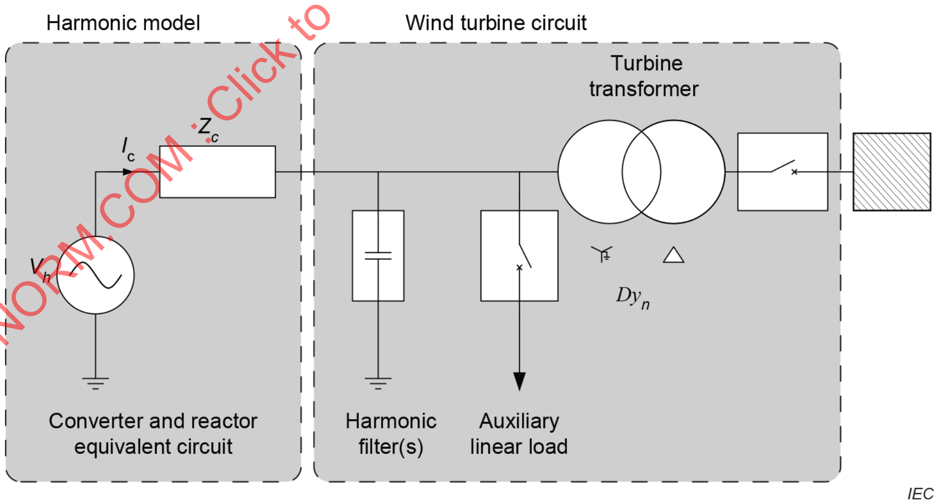
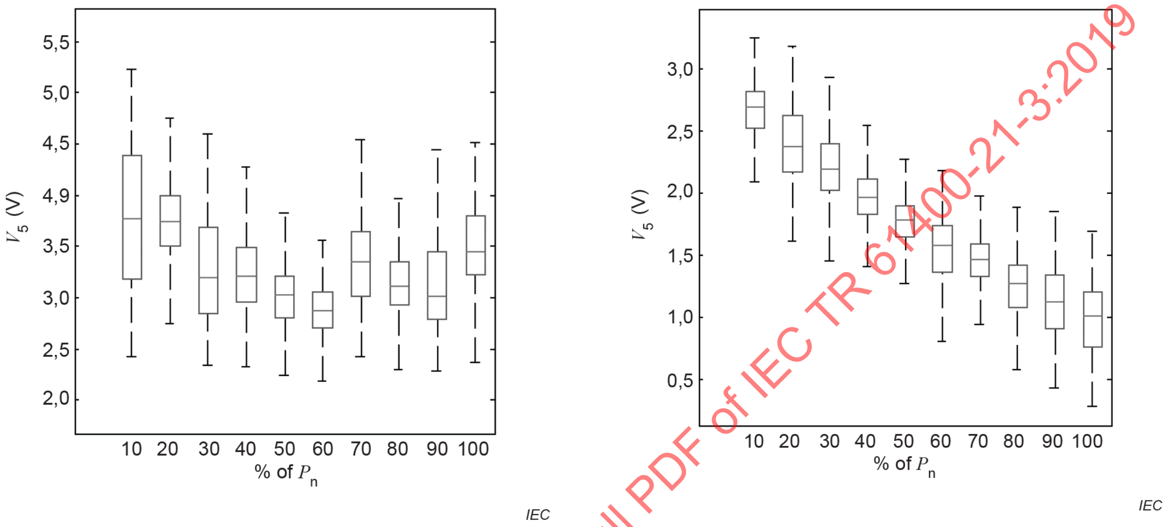


Figure 10 – Example of a converter harmonic model as Thévenin equivalent circuit together with an example of a WT power circuit (from [9])

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

Exemplary harmonic voltage measurements at the WT transformer LV terminals can be seen in Figure 11a. Such measurements are influenced by the grid to which the WT is connected as well as by the WT itself. In Figure 11b, it can be seen how the voltage at the same WT terminals is represented by the open-circuit Thévenin equivalent model excluding the influence of harmonic background distortions. In Figure 11, harmonics are presented as box plots 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[3] extend to the most extreme data points where outliers are not considered, and outliers are not plotted.



a) Harmonic voltage measured at the LV side of the WT transformer

b) Harmonic voltage of the Thévenin equivalent model

Figure 11 – Harmonic voltage comparison for respective power bins

8 Validation

8.1 General

The WT model needs to be validated either by harmonic measurements or by means of previously validated benchmark system simulations. The validation process should be unified for harmonic models from all WT types, independently of the technology included in the WT. At this moment, the validation procedure guideline is giving harmonic model developers some flexibility to carry out that process. However, the validation process should be well described and included as a part of harmonic model documentation.

8.2 Overview

Validation is a procedure that is used for checking that the model meets the requirements and that it 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 trustworthy. 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.

3 The default whisker length w used in the box plots is of 1,5 IQR (interquartile range). Points are drawn as outliers if they are larger than $Q_3 + w(Q_3 - Q_1)$ or smaller than $Q_1 - w(Q_3 - Q_1)$.