

INTERNATIONAL STANDARD



**Wind energy generation systems –
Part 27-2: Electrical simulation models – Model validation**

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**Wind energy generation systems –
Part 27-2: Electrical simulation models – Model validation**

INTERNATIONAL
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WIND ENERGY GENERATION SYSTEMS –**Part 27-2: Electrical simulation models –
Model validation**

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International Standard IEC 61400-27-2 has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this International Standard is based on the following documents:

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88/763/FDIS	88/772/RVD

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

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

A list of all parts in the IEC 61400, 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.

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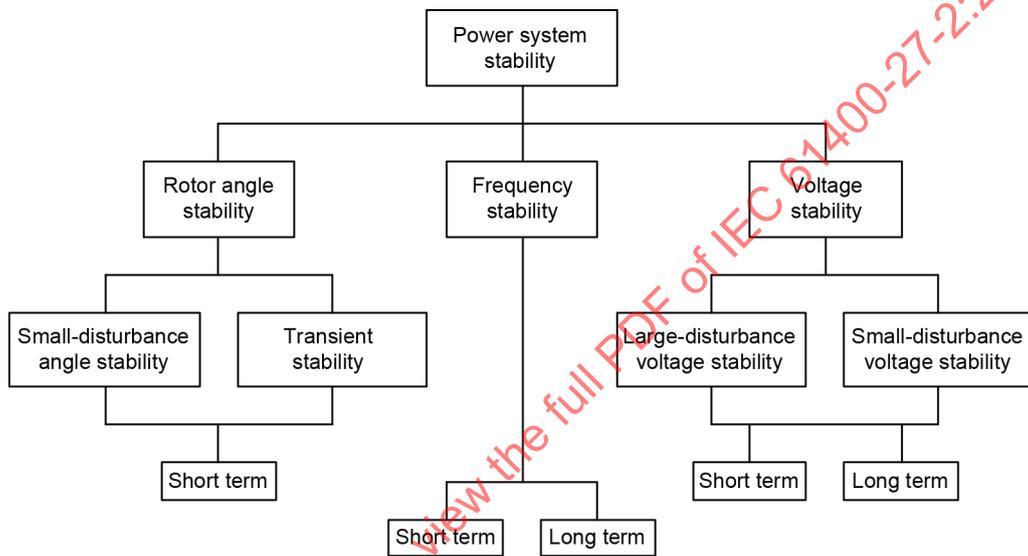
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INTRODUCTION

IEC 61400-27-2 specifies model validation procedures for electrical simulation models of wind turbines and wind power plants.

The increasing penetration of wind energy in power systems implies that Transmission System Operators (TSOs) and Distribution System Operators (DSOs) need to use dynamic models of wind power generation for power system stability studies.

The purpose of this International Standard is to specify validation procedures for dynamic models, which can be applied in power system stability studies. The IEEE/CIGRE Joint Task Force on Stability Terms and Definitions [1]¹ has classified power system stability in categories according to Figure 1.



IEC

Figure 1 – Classification of power system stability according to IEEE/CIGRE Joint Task Force on Stability Terms and Definitions [1]

Referring to these categories, the models to be validated have been developed to represent wind power generation in studies of large-disturbance short term stability phenomena, i.e. short term voltage stability, short term frequency stability and short term transient stability studies referring to the definitions of IEEE/CIGRE Joint Task Force on Stability Terms and Definitions in Figure 1. Thus, the models are applicable for dynamic simulations of power system events such as short-circuits (low voltage ride through), loss of generation or loads, and system separation of one synchronous area into more synchronous areas.

The validation procedure specified in this document assesses the accuracy of the fundamental frequency response of wind power plant models and wind turbine models. This includes validation of the generic positive sequence models specified in IEC 61400-27-1 and validation of positive sequence as well as negative sequence response of more detailed models developed by the wind turbine manufacturers.

¹ Figures in square brackets refer to the Bibliography.

The validation procedure has the following limitations:

- The validation procedure does not specify any requirements to model accuracy. It only specifies measures to quantify the accuracy of the model^{2,3}.
- The validation procedure does not specify test and measurement procedures, as it is intended to be based on tests specified in IEC 61400-21-1 and IEC 61400-21-24.
- The validation procedure is not intended to justify compliance to any grid code requirement, power quality requirements or national legislation.
- The validation procedure does not include validation of steady state capabilities e.g. of reactive power, but focuses on validation of the dynamic performance of the models.
- The validation procedure does not cover long term stability analysis.
- The validation procedure does not cover sub-synchronous interaction phenomena.
- The validation procedure does not cover investigation of the fluctuations originating from wind speed variability in time and space.
- The validation procedure does not cover phenomena such as harmonics, flicker or any other EMC emissions included in the IEC 61000 series.
- The validation procedure does not cover eigenvalue calculations for small signal stability analysis.
- This validation procedure does not address the specifics of short-circuit calculations.
- The validation procedure is limited by the functional specifications in Clause 5.

The following stakeholders are potential users of the validation procedures specified in this document:

- TSOs and DSOs need procedures to validate the accuracy of the models which they use in power system stability studies;
- wind plant owners are typically responsible to provide validation of their wind power plant models to TSO and/or DSO prior to plant commissioning;
- wind turbine manufacturers will typically provide validation of the wind turbine models to the owner.
- developers of modern software for power system simulation tools may use the standard to implement validation procedures as part of the software library;
- certification bodies in case of independent model validation;
- education and research communities, who can also benefit from standard model validation procedures.

² Specification of requirements to model accuracy is the responsibility of TSOs e.g. in grid codes. The scope of IEC 61400-27-2 is to provide a standard for how to measure accuracy and this way remove indefiniteness.

³ Clause 7 specifies a large number of measures for model accuracy. The importance of the individual measure depends on the type of grid and type of stability study. Annex D describes limits to the possible accuracy of the models.

⁴ Under consideration.

WIND ENERGY GENERATION SYSTEMS –

Part 27-2: Electrical simulation models – Model validation

1 Scope

This part of IEC 61400 specifies procedures for validation of electrical simulation models for wind turbines and wind power plants, intended to be used in power system and grid stability analyses. The validation procedures are based on the tests specified in IEC 61400-21 (all parts). The validation procedures are applicable to the generic models specified in IEC 61400-27-1 and to other fundamental frequency wind power plant models and wind turbine models.

The validation procedures for wind turbine models focus on fault ride through capability and control performance. The fault ride through capability includes response to balanced and unbalanced voltage dips as well as voltage swells. The control performance includes active power control, frequency control, synthetic inertia control and reactive power control. The validation procedures for wind turbine models refer to the tests specified in IEC 61400-21-1. The validation procedures for wind turbine models refer to the wind turbine terminals.

The validation procedures for wind power plant models is not specified in detail because IEC 61400-21-2 which has the scope to specify tests of wind power plants is at an early stage. The validation procedures for wind power plant models refer to the point of connection of the wind power plant.

The validation procedures specified in IEC 61400-27-2 are based on comparisons between measurements and simulations, but they are independent of the choice of software simulation tool.

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 (IEV) – Part 415: Wind turbine generator systems* (available at www.electropedia.org)

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

IEC 61400-27-1, *Wind energy generation systems – Part 27-1: Electrical simulation models – Generic models*

3 Terms, definitions, abbreviations and subscripts

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

application range

specification of the boundaries for the situations where the electrical simulation model is applicable

3.1.2

available active power

predicted optimal active power of wind turbine or wind power plant, either based on power curves and measured wind speeds or as an output from wind turbine controller or wind power plant controller, where more parameters are taken into the calculation

3.1.3

base unit

unit of parameter values, which is the per-unit base value if the parameter is given in per-unit or the physical unit if the value is given in a physical unit

3.1.4

generic model

model that can be adapted to simulate different wind turbines or wind power plants by changing the model parameters

3.1.5

integration time step

simulation time interval between two consecutive numerical solutions of the model's differential equations

3.1.6

negative (sequence) component (of a three-phase system)

one of the three symmetrical sequence components which exists only in an unsymmetrical three-phase system of sinusoidal quantities and which is defined by the following complex mathematical expression:

$$\underline{X}_2 = \frac{1}{3}(\underline{X}_{L1} + a^2 \underline{X}_{L2} + a \underline{X}_{L3})$$

where a is the 120 degree operator, and \underline{X}_{L1} , \underline{X}_{L2} and \underline{X}_{L3} are the complex expressions of the phase quantities concerned, and where \underline{X} denotes the system current or voltage phasors

[SOURCE: IEC 60050-448:1995, 448-11-28]

3.1.7

nominal active power

nominal value of active power, which is stated by the manufacturer and is used as a per-unit base for all powers (active, reactive, apparent)

[SOURCE: IEC 61400-21-1:2019, 3.15, modified – Removed “wind turbine” from definition]

3.1.8

nominal voltage

nominal value of line-to-line voltage, which is stated by the manufacturer and is used as a per-unit base

3.1.9

overshoot

difference between the maximum value of the response and the steady-state final value

Note 1 to entry: Overshoot is defined by the response to a step change of a controller reference variable, see Figure 5.

[SOURCE: IEC 61400-21-1:2019, 3.47, modified – The note to entry has been changed]

3.1.10

phasor

complex RMS value

representation of a sinusoidal integral quantity by a complex quantity whose argument is equal to the initial phase and whose modulus is equal to the RMS value

Note 1 to entry: For a quantity $a(t) = \hat{A} \cos(\omega t + \vartheta_0)$ the phasor is $\underline{A} = A \exp(j\vartheta_0)$ where $A = \frac{\hat{A}}{\sqrt{2}}$ is the RMS value and ϑ_0 is the initial phase. A phasor can also be represented graphically.

Note 2 to entry: Electric current phasor \underline{I} and voltage phasor \underline{U} are often used.

Note 3 to entry: The similar representation with the modulus equal to the amplitude is sometimes also called "phasor".

[SOURCE: IEC 60050-103:2017 103-07-14]

3.1.11

point of connection

reference point on the electric power system where the user's electrical facility is connected

[SOURCE: IEC 60050-617:2009, 617-04-01]

3.1.12

positive (sequence) component (of a three-phase system)

one of the three symmetrical sequence components which exists in symmetrical and unsymmetrical three-phase system of sinusoidal quantities and which is defined by the following complex mathematical expression:

$$\underline{X}_1 = \frac{1}{3} (\underline{X}_{L1} + \underline{a} \underline{X}_{L2} + \underline{a}^2 \underline{X}_{L3})$$

where \underline{a} is the 120 degree operator, and \underline{X}_{L1} , \underline{X}_{L2} and \underline{X}_{L3} are the complex expressions of the phase quantities concerned, and where \underline{X} denotes the system current or voltage phasors

[SOURCE: IEC 60050-448:1995, 448-11-27]

3.1.13

power system stability

capability of a power system to regain a steady state, characterized by the synchronous operation of the generators after a disturbance due, for example, to variation of power or impedance

Note 1 to entry: IEEE/CIGRE Joint Task Force on Stability Terms and Definitions: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

[SOURCE: IEC 60050-603:1986, 603-03-01, modified – addition of Note 1 to entry]

3.1.14 quasi steady state of a system

short-term steady state, for instance during a voltage dip or voltage swell which is long enough to include a period where the system state variables can be considered sensibly constant

3.1.15 reaction time

elapsed time from test command issued until the change in amplitude reaches 10 % of the measured output variable of the step height

Note 1 to entry: Reaction time is defined by the response to a step change of a controller reference variable, see Figure 5.

[SOURCE: IEC 61400-21-1:2019, 3.48, modified – The note to entry has been changed]

3.1.16 reference variable

input variable to a comparing element in a controlling system, which sets the desired value of the controlled variable and is deducted from the command variable

[SOURCE: IEC 60050-351:2013, 351-48-02, modified – The note to entry and the figure have been deleted]

3.1.17 response time

elapsed time from the start of a step change or start of event until the observed value first time enters the predefined tolerance band of the target value

Note 1 to entry: Response time is defined by the response to a step change of a controller reference variable, see Figure 5.

[SOURCE: IEC 61400-21-1:2019, 3.44, modified – The note to entry has been changed]

3.1.18 rise time

time from when the observed value reaches 10 % of the step change until the observed value reaches 90 % of the step change

Note 1 to entry: Rise time is defined by the response to a step change of a controller reference variable, see Figure 5.

[SOURCE: IEC 61400-21-1:2019, 3.46, modified – The note to entry has been changed]

3.1.19 settling time

elapsed time from the start of a step change event until the observed value continuously stays within the predefined tolerance band of the target value

Note 1 to entry: Settling time is defined by the response to a step change of a controller reference variable, see Figure 5.

[SOURCE: IEC 61400-21-1:2019, 3.45, modified – The note to entry has been changed]

3.1.20

short-circuit power

the product of the current in the short circuit at a point of a system and a conventional voltage, generally the operating voltage

Note 1 to entry: Transient and subtransient currents are not considered.

[SOURCE: IEC 60050-601:1985, 601-01-14, modified – The note 1 to entry has been added]

3.1.21

system state variables

variable quantities associated with the electrical state of a system

Examples: Voltages, currents, powers, electric charges, magnetic fluxes.

[SOURCE: IEC 60050-603:1986, 603-02-02]

3.1.22

target value

final value of the reference variable after a step change.

Note 1 to entry: Reaction time is illustrated in Figure 5.

3.1.23

Thevenin equivalent

equivalent representation of a circuit by a Thevenin voltage in series with a Thevenin impedance

3.1.24

transient time period

time periods with measured electromagnetic transients which are not included in fundamental frequency models

3.1.25

voltage dip

limited duration non-periodic sudden decrease of the power supply network's voltage magnitude and associated change of its phase

Note 1 to entry: In some articles, publications, etc. the expression "voltage sags" is used for the same event.

[SOURCE: IEC 61400-21-1:2019, 3.26]

3.1.26

voltage swell

limited duration non-periodic sudden increase of the power supply network's voltage magnitude above its nominal value and associated change of the phase of the voltage

[SOURCE: IEC 61400-21-1:2019, 3.27]

3.1.27

wind power plant

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

3.1.28

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]

3.1.29

wind turbine terminals

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

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

3.2 Abbreviations and subscripts

3.2.1 Abbreviations

The following abbreviations are used in this document:

CIGRE	the International Council on Large Electric Systems
IEEE	the Institute of Electrical and Electronics Engineers, Inc.
WP	wind power plant
WT	wind turbine
WTT	WT terminals

3.2.2 Subscripts

base	per-unit base value
E	error between simulation and measurement
MAE	mean absolute error between simulation and measurement
max	maximum
ME	mean error between simulation and measurement
mea	measured
MXE	maximum error between simulation and measurement
n	nominal
u	voltage
WTref	WT reference value
sim	simulated variable
WT	variable at WTT

4 Symbols and units

4.1 General

In this document, voltage and current values are positive sequence fundamentals, unless otherwise stated.

The following symbols are used in this document. Small letters are used for per-unit values whereas capital letters are used for values in physical units. For values with physical units, the units are given in brackets. For per-unit values, the per-unit bases are given in brackets. Active and reactive current as well as active and reactive power use generator sign convention.

4.2 Symbols (units)

f_{cut}	cutoff frequency of critically damped filter according to the description in Annex E (Hz)
I_{base}	phase current per-unit base $I_{\text{base}} = \frac{S_{\text{base}}}{\sqrt{3}U_{\text{base}}} \text{ (A)}$
i_{p120}	positive sequence or negative sequence active current sequence processed from i_{raw} according to IEC 61400-21-1 (generation sign convention) (I_{base})
i_{pds}	down sampled active current time series processed according to 6.4.2 (I_{base})
i_{pfun}	active current time series simulated according to 6.4.2 (I_{base})
i_{pmea}	measured active current time series processed according to 6.4.2 (I_{base})
i_{psim}	simulated active current time series processed according to 6.4.2 (I_{base})
i_{q120}	positive sequence or negative sequence reactive current sequence processed from i_{raw} according to IEC 61400-21-1 (capacitive sign convention) (I_{base})
i_{qds}	down sampled reactive current time series processed according to 6.4.2 (I_{base})
i_{qfun}	reactive current time series simulated according to 6.4.2 (I_{base})
i_{qmea}	measured reactive current time series processed according to 6.4.2 (I_{base})
i_{qsim}	simulated reactive current time series processed according to 6.4.2 (I_{base})
i_{raw}	raw current measured according to IEC 61400-21-1 or IEC 61400-21-2 (I_{base})
p_{120}	positive sequence or negative sequence active power sequence processed from u_{raw} and i_{raw} according to IEC 61400-21-1 (generation sign convention) (S_{base})
p_{ds}	down sampled active power time series processed according to 6.4.2 (S_{base})
p_{fun}	active power time series simulated according to 6.4.2 (S_{base})
p_{mea}	measured active power time series processed according to 6.4.2 (S_{base})
p_{sim}	simulated active power time series processed according to 6.4.2 (S_{base})
P_{WTn}	nominal active power of WT (W)
P_{WPn}	nominal active power of WP (W)
q_{120}	positive sequence or negative sequence reactive power sequence processed from u_{raw} and i_{raw} according to IEC 61400-21-1 (generation sign convention) (S_{base})

q_{ds}	down sampled reactive power time series processed according to 6.4.2 (S_{base})
q_{fun}	reactive power time series simulated according to 6.4.2 (S_{base})
q_{mea}	measured reactive power time series processed according to 6.4.2 (S_{base})
q_{sim}	simulated reactive power time series processed according to 6.4.2 (S_{base})
S_{base}	power per-unit base $S_{base} = \begin{cases} P_{WTn} & \text{referring to WT} \\ P_{WPn} & \text{referring to WP} \end{cases}$ (VA)
t_{begin}	begin time for data analysis of FRT test case
t_{fault}	fault initiation time for data analysis of FRT test case
$t_{faultQS}$	time with quasi steady state after fault initiation for data analysis of FRT test case
t_{clear}	fault clearance time for data analysis of FRT test case
$t_{clearQS}$	time with quasi steady state after fault clearance for data analysis of FRT test case
t_{end}	end time for data analysis of FRT test case
T_{com}	common sample time used to compare measured and simulated values (s)
T_{mea}	sample rate of raw measured data (s)
T_s	integration time step (s)
U_{base}	phase-to-phase voltage per-unit base $U_{base} = \begin{cases} U_{WTn} & \text{referring to WT} \\ U_{WPn} & \text{referring to WP} \end{cases}$ (V)
u_{120}	positive sequence or negative sequence voltage sequence processed from u_{raw} according to IEC 61400-21-1 (U_{base})
u_{ds}	down sampled voltage time series processed according to 6.4.2 (U_{base})
u_{fun}	voltage time series simulated according to 6.4.2 (U_{base})
u_{mea}	measured positive or negative sequence voltage time series processed according to 6.4.2 (U_{base})
u_{raw}	raw voltage measured according to IEC 61400-21-1 or IEC 61400-21-2 (U_{base})
u_{sim}	simulated positive or negative sequence WTT voltage time series processed according to 6.4.2 (U_{base})
U_{WPn}	nominal phase-to-phase voltage at POC (V)
U_{WTn}	nominal phase-to-phase voltage at WTT (V)
W_{fault}	time window defining the fault period from t_{fault} to t_{clear} (s)

W_{faultQS}	quasi steady state part of W_{fault} from t_{faultQS} to t_{clear} (s)
W_{post}	time window defining the post-fault period from t_{clear} to t_{end} (s)
W_{postQS}	quasi steady state part of W_{post} from t_{clearQS} to t_{end} (s)
W_{pre}	time window defining the pre-fault period from t_{begin} to t_{fault} (s)
$x_E(n)$	simulation error time series provided by signal processing
x_{MAE}	mean absolute error in time window
x_{ME}	mean error in time window
$x_{\text{mea}}(n)$	measured time series provided by signal processing
x_{MXE}	maximum error in time window
$x_{\text{sim}}(n)$	simulated time series provided by signal processing

5 Functional specifications and requirements to validation procedures

5.1 General

Clause 5 provides the functional specifications and requirements to the validation procedure for wind turbine models specified in Clause 7 and validation procedure for WP models specified in Clause 8. The general specifications applying to both WT model validation and WP model validation are provided in 5.2, whereas the specific WT model validation requirements is specified in 5.3, and the specific WP model validation requirements is specified in 5.4.

5.2 General specifications

The procedures for validation of WT models and WP models have been developed with the following specifications in mind:

- The validation procedures specified in this document shall be applicable to the generic models specified in IEC 61400-27-1 and to other fundamental frequency wind power plant models and wind turbine models. Annex G describes a generic software interface for user defined models which may be applied to fundamental frequency or EMT models, but the validation procedures specified in this document are only intended for fundamental frequency models.
- The validation procedure specified in this document compares the fundamental frequency positive and negative sequence response of wind power plant models and wind turbine models against measurements.
- The possible model accuracy according to the validation procedure specified in Clause 5 is limited because of simulation and measurement uncertainties, which are further described in Annex D. For the models specified in IEC 61400-27-1, although the model parameters are chosen to represent manufacturer's specific behaviour, the possible accuracy is further limited because the models are generic and thus cannot represent as many details as manufacturer's specific models.
- The results of the validation procedure shall be appropriate for quantifying the simulation model accuracy with the purpose of being applied in various grid stability evaluations and planning studies.

- The validation procedure does not include specification of test procedures. Specification of test procedures for wind turbines is in the scope of IEC 61400-21-1 and specification of test procedures for wind power plants is in the scope of IEC 61400-21-2. Tests performed and documented according to the requirements in IEC 61400-21-1 and IEC 61400-21-2 are therefore used for specification of model validation.
- Existing test results (obtained prior to the release date of this document) covering the same operational range as the ones specified in the IEC 61400-21-1 and IEC 61400-21-2 should be accepted for the validation provided that these results are performed and documented according to the requirements for such results in IEC 61400-21-1 and IEC 61400-21-2.
- To comply with the validation procedure, simulated positive sequence values shall be validated against the measured positive sequence values. For models including negative sequence components, the simulated negative sequence components shall be validated against the measured negative sequence components in addition to the validation of the positive sequence components.
- The results of the validation procedure shall be:
 - time series of measured and simulated fundamental frequency quantities;
 - time series of errors between simulated and measured fundamental frequency currents and voltages;
 - mean error, mean absolute error and maximum error in pre-fault, during-fault and post-fault windows of voltage dips and voltage swells;
 - measured and simulated reaction time, rise time, settling time and overshoot of reference point changes.
- Sampling and signal processing for comparison of measurement and simulation time series data should be performed with a common sampling time of $\frac{1}{2}$ cycle, i.e. 10 ms for 50 Hz frequency. Visualisation of measured and simulated data shall be in accordance with IEC 61400-21-1 or IEC 61400-21-2, as fundamental positive and negative phase sequence systems are required.
- In order to calculate the deviation between simulated and measured values, a mutual time base shall be established for the two data sets. A joint time base should be obtained via time synchronization, decimation or interpolation between sampled values.
- Any observed high-frequency phenomena that is of electromagnetic origin and lasts for e.g. less than 1 cycle shall be neglected. For example, harmonic distortion and related peak transformer inrush phenomena that are outside the interest in stability studies.
- If a measured value does not have a corresponding simulated value, an interpolated value shall be used, in order to create a data set of errors.
- The measured, processed and simulated values shall be presented, in per-unit values, using base values for power, voltage and current according to definitions in 4.2.
- The simulations used for the model validation should include additional representation of the grid and relevant test equipment. Alternatively, model validation may be done using playback of the measured voltage.

5.3 Wind turbine model validation

The procedure for validation of WT models meets the following specifications in addition to the general specifications in 5.1:

- The WT models shall be validated against measurements acquired according to IEC 61400-21-1. In case of model-to-model validation, the same methodology shall be applied⁵. Annex C describes a reference grid, which can be used for model-to-model validation.
- The validation procedure shall include the dynamic response to fault ride through and control of the WT.
- The model and test shall refer to the same WT terminals to ensure that measurements and simulations refer to the same point. According to IEC 61400-21-1, the WT terminals are defined by the manufacturer and thus can be either:
 - 1) the low voltage side of the WT transformer, or
 - 2) the high voltage side of the WT transformer.

5.4 Wind power plant model validation

The procedure for validation of WP models meets the following specifications in addition to the general specifications in 5.1:

- The WP models shall be validated against measurements acquired according to IEC 61400-21-2. In case of model-to-model validation, the same methodology shall be applied⁶.
- The validation procedure shall include the dynamic response to active power control and reactive power control of the WP.
- The model and test shall refer to the same WP connection point to ensure that measurements and simulations refer to the same point.

6 General methodologies for model validation

6.1 General

Clause 6 provides specifications of general model validation approaches which are used in Clause 7 and Clause 8.

6.2 Test results

The test results used for the model validation shall be documented in a test report. The applied control modes shall be specified for each test.

The measured time series shall be available as positive sequence values of active and reactive current components and voltage calculated according to IEC 61400-21-1. The measured active and reactive power shall be calculated using the measured voltage and measured active and reactive current.

⁵ There are cases where a new variant of a wind turbine within a wind turbine product platform defined in IEC 61400-21-1 does not require new tests according to IEC 61400-21-1. In such cases, validation of the model for the new variant may be done as model-to-model validation using a detailed manufacturer model.

⁶ An aggregated WP model may be validated against a detailed WP model using nonaggregated validated models for WTs and other components such as STATCOM or other device supplementing WTs in WP.

If the model is applied to unbalanced faults then measured negative sequence values are also required for the validation. If the required positive sequence or negative sequence time series are not available then the instantaneous 3 phase voltages and currents measured according to IEC 61400-21-1 or IEC 61400-21-2 shall be used to calculate the missing data according to IEC 61400-21-1.

6.3 Simulations

The validation shall be performed using one of the following two simulation approaches:

- The full-system approach. In this approach, the WT model or WP model to be validated will be simulated as part of a full system also including a model of the grid and a model of equipment which is applied during the test. With this method, all the measured quantities (typically voltage, active and reactive current as well as active and reactive power) can be validated comparing simulations to measurements.
- The play-back approach. In this approach, the WT model or WP model to be validated will be simulated using one of the measured signals (typically the voltage) as input to the simulation. With this method, only the measured quantities which are not played back (typically active and reactive current as well as active and reactive power) can be validated comparing simulations to measurements.

Full-system simulation validation approach is required to verify the model stability with all control loops closed under all practical operating conditions. The drawback of using full-system simulations is that it includes models of grid and test equipment, which introduces additional uncertainties not originating from the WP or WT model under validation.

Play-back validation approach removes the uncertainties due to grid and test equipment models and is therefore recommended for assessing the WP or WT model accuracy. One drawback of the voltage play-back approach is that it opens the voltage control loop, and therefore the play-back approach shall not be used to validate that the reactive power control is stable. Thus, the play-back approach shall be used with care when validating the model voltage control. Another drawback is that an instantaneous voltage step measured according to IEC 61400-21-1 will typically ramp over one line period. Therefore, the play-back approach shall be used with care when validating response to voltage dips and voltage swells, especially for type 3B where the crowbar will not activate if the played-back voltage ramps down over several integration time steps.

Power can also be played back to include the wind power variability in long term simulations for instance to validate power factor control as in [11].

6.4 Signal processing

6.4.1 General

To ensure that the validation is reflecting the actual properties of the model considering the specifications given in IEC 61400-27-1 on the bandwidth of such models, a signal processing procedure is defined. Annex F describes a performance-based model validation methodology which can be applied which as a supplement to the signal processing procedure.

All the variables in the signal processing structure are per-unit values, taking the base value specified in brackets for the corresponding variable in the symbol list of 4.2.

6.4.2 Time series processing

The time series processing procedure is illustrated in Figure 2 for the play-back simulation approach and in Figure 3 for the full-system simulation approach.

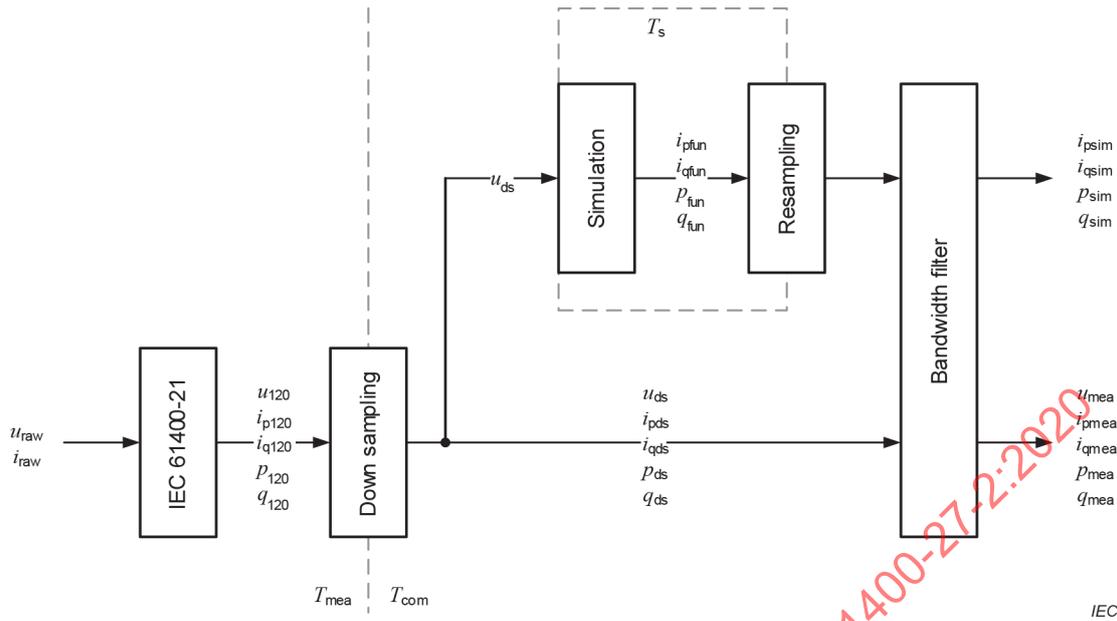


Figure 2 – Signal processing structure with play-back simulation approach applied

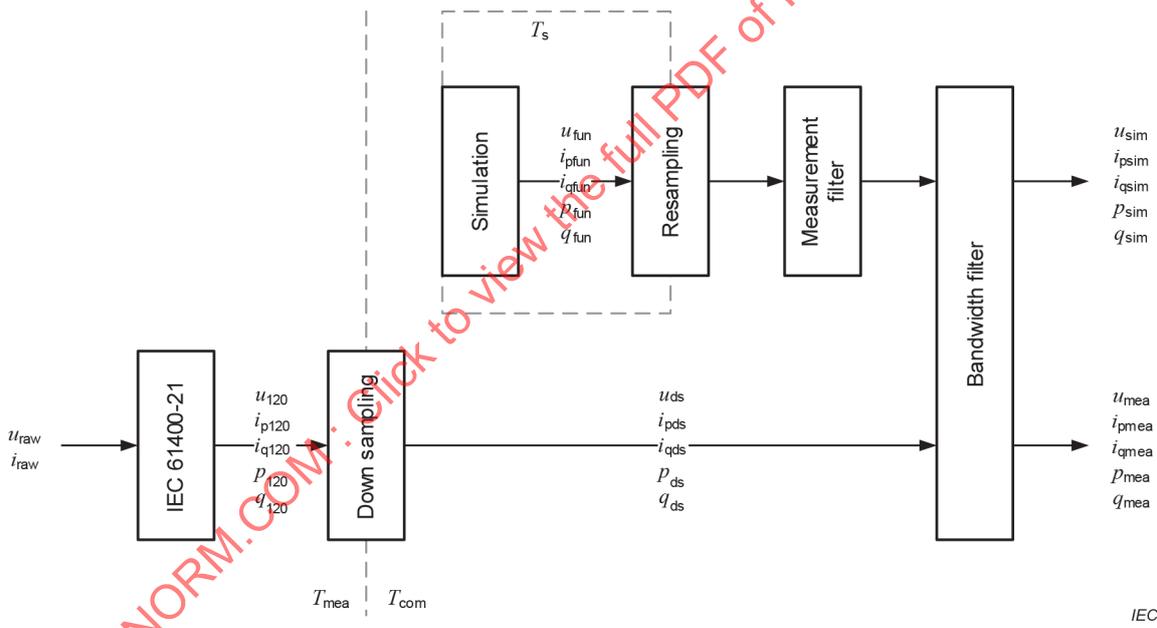


Figure 3 – Signal processing structure with full-system simulation approach applied

In the figures, T_{mea} is the sample rate of the raw measured data (current and voltage waveforms), T_{com} is the common sample time used to compare measured and simulated values and T_s is the integration time step of the simulation model under evaluation. For fixed integration time step models, T_{com} is equal to T_s . For solvers using variable integration time steps, the simulation model output needs to be re-sampled to T_{com} for the final validation.

The down sampling from T_{mea} to T_{com} can be done as an integrated part of the positive and – if demanded – negative sequence calculation in the block IEC 61400-21-17.

⁷ Using the fundamental frequency methods described in IEC 61400-21-1 for the measurement calculation, the bandwidth of T_{mea} is assumed to be low enough to avoid any considerable aliasing due to the down sampling.

The "Bandwidth Filter" incorporated in the signal processing structure shall be implemented as a second order critically damped filter according to the description in Annex E using a cut off frequency, f_{cut} of 15 Hz corresponding to the bandwidth of the models specified in IEC 61400-27-1⁸.

The "Measurement filter" incorporated in the full-system simulation signal processing structure shall be implemented as a moving average with one line period average time. This filter on the simulations matches the filtering of the measurements due to the fundamental frequency calculations according to IEC 61400-21-1⁹.

6.4.3 Windows error statistics

For each variable x to be validated (u , i_p , i_q , p and q), the time series of the error $x_E(n)$ is derived from the processed measured time series $x_{\text{mea}}(n)$ and simulated time series $x_{\text{sim}}(n)$ according to

$$x_E(n) = x_{\text{sim}}(n) - x_{\text{mea}}(n) \quad (1)$$

From these time series of errors, three different characteristic quantities shall be extracted from each time window defined, for each of the variables considered in the validation:

The maximum error (MXE) is mainly focused on giving a measure of the transient performance of the model, but can also indicate large errors in "steady state" performance. The maximum error incorporates a maximum absolute tolerance band for the model within the required bandwidth of the model.

The mean error (ME) is concerned with the steady state performance of the model, both in the time before and after the fault as well as the steady state period within the fault. The mean error incorporates a tolerance band on the energy deviation between measured and simulated results.

The mean absolute error (MAE) is concerned with the steady state performance of the model, both in the time before and after the fault as well as the steady state period within the fault. The mean error incorporates an absolute tolerance band on the mean deviation between measured and simulated results.

The maximum error x_{MXE} in a time window with N time steps is calculated as the maximum value of the absolute errors over the entire window according to

$$x_{\text{MXE}} = \max(|x_E(1)|, |x_E(2)|, \dots, |x_E(N)|) \quad (2)$$

The mean error x_{ME} in a time window is calculated as the mean value of the error over the entire window according

⁸ The 15 Hz bandwidth is justified in IEC 61400-27-1 as follows: It is generally accepted that the minimum time constant which can be included in a dynamic model is two times the integration time step. Thus, requiring $\frac{1}{4}$ cycle integration time steps, the models should work with integration time steps 0,005 s in the worst (50 Hz) case. The minimum time constant then becomes 0,01 s. For a first order lag with time constant 0,01 s, the 3 dB bandwidth is 10 rad/s = 15,9 Hz, which is rounded down to 15 Hz.

⁹ The "measurement filter" is not included in the play-back signal processing structure because the input voltage disturbance is the measured voltage, which is already filtered according to IEC 61400-21-1.

$$x_{ME} = \frac{\sum_{n=1}^N x_E(n)}{N} \tag{3}$$

The mean absolute error x_{MAE} in a time window is calculated as the mean value of the absolute error over the entire window according to

$$x_{MAE} = \frac{\sum_{n=1}^N |x_E(n)|}{N} \tag{4}$$

6.4.4 FRT windows specification

In order to validate the model performance for a given FRT test case, the measurement data shall be divided into three adjacent windows. Figure 4 shows the windows for a voltage dip [12]. The same three windows shall be applied for a voltage swell.

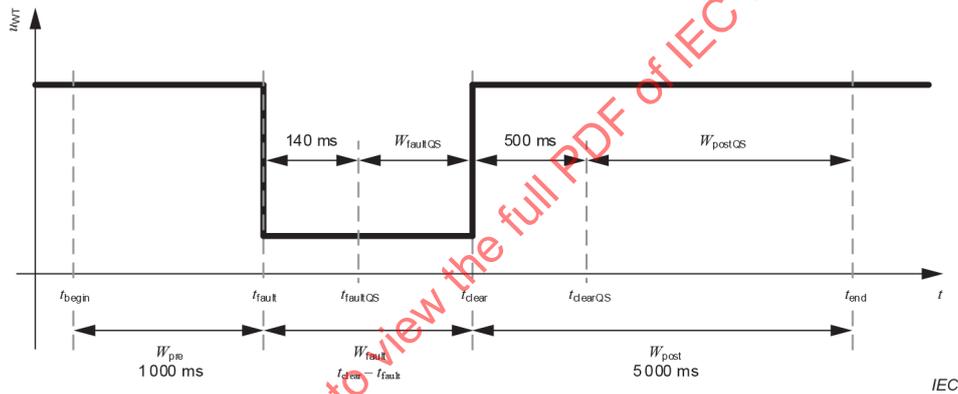


Figure 4 – Voltage dip windows [12]

The three windows are defined as:

- W_{pre} is the pre-fault window covering the time period from t_{begin} to t_{fault} .
- W_{fault} is the fault window covering the time period from t_{fault} to t_{clear} .
- W_{post} is the post-fault window covering the time period from t_{clear} to t_{end} .

where generally $t_{begin} = t_{fault} - 1\ 000\ ms$ and $t_{end} = t_{clear} + 5\ 000\ ms$.

NOTE In case of the switching of a serial impedance prior to the fault, t_{begin} starts after the transients corresponding to the switching event have decayed.

t_{fault} and t_{clear} are followed by transient time periods with measured electromagnetic transients which are not included in fundamental frequency models. Instead of quantifying the maximum transient errors in W_{fault} and W_{post} , x_{MXA} is used to quantify the maximum absolute errors in the following quasi steady state sub-windows:

- $W_{faultQS}$ is the quasi steady state part of the fault window covering the time period from $t_{faultQS}$ to t_{clear} , where $t_{faultQS} = t_{fault} + 140\ ms$ ¹⁰.

¹⁰ The exclusion of the first 140 ms of W_{fault} from $W_{faultQS}$ is mainly due to the limitation of the model to replicate the DC-component of the generator flux.

- W_{postQS} is the quasi steady state part of the post-fault window covering the time period from t_{clearQS} to t_{end} , where $t_{\text{clearQS}} = t_{\text{clear}} + 500 \text{ ms}$ ¹¹.

The calculated error values and calculation windows are summarised in Table 1.

Table 1 – Windows applied for error calculations

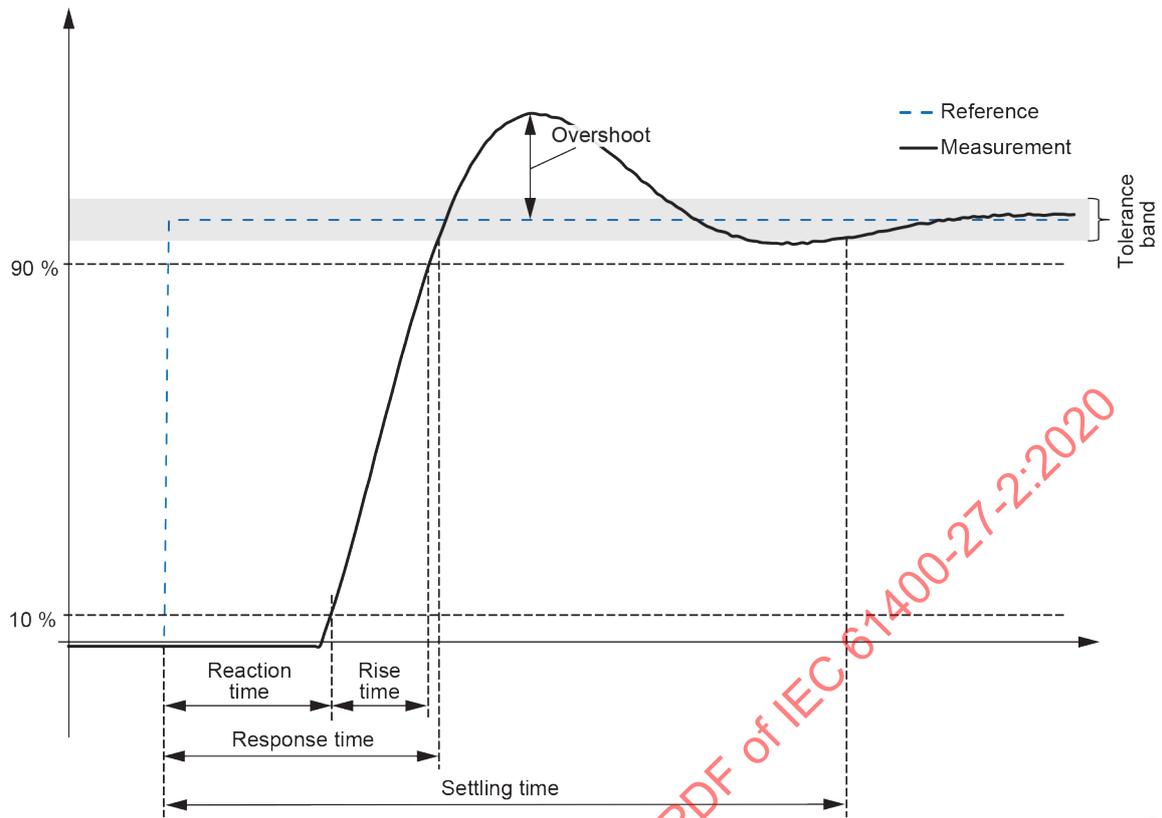
Period	x_{MXE}	x_{ME}	x_{MAE}
Pre-fault	W_{pre}	W_{pre}	W_{pre}
Fault	W_{faultQS} ^a	W_{fault}	W_{faultQS}
Post-fault	W_{postQS}	W_{post}	W_{post}
^a If W_{fault} is less than 280 ms and consequently W_{faultQS} is less than 140 ms for a specific case, then x_{MAXE} shall not be calculated in the fault period for that case.			

6.4.5 Step response characteristics

IEC 61400-21-1 and IEC 61400-21-2 specify a number of step responses to test the dynamics of the control performance. The specifications include a description of how the individual step tests are implemented.

According to IEC 61400-21-1, step responses shall be quantified by the characteristics illustrated in Figure 5.

¹¹ The exclusion of the first 500 ms of W_{post} from W_{postQS} is due to the limitation of the model. The accuracy of the reactive power is affected by transformer inrush, which could in some cases be longer than 500 ms. The accuracy of the active power recovery is affected by non-linear aerodynamic effects.



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Figure 5 – Step response characteristics

The step response characteristics are defined as follows:

- Reaction time defined as the elapsed time from the issue of a step change command until the observed value reaches 10 % of the step change.
- Rise time defined as the elapsed time from the observed value reached 10 % of the step change until the observed value reaches 90 % of the step change.
- Response time defined as the elapsed time from the issue of a step change command until the observed value first time enters the predefined tolerance band of the target value.
- Settling time defined as the elapsed time from the issue of a step change command until the observed value continuously stays within the predefined tolerance band of the target value.
- Overshoot defined as the difference between the maximum value of the response and the final reference value.

It shall be noted that an inexpedient choice of tolerance band can lead to a significant mismatch between simulated and measured settling times although the simulated response matches the measured response quite well. Such a case is illustrated in Figure 6 where the measurement stays within the tolerance band after one swing while the simulation stays in tolerance band after half a swing. In such cases, the tolerance band should be adjusted so that the simulation stays within the tolerance band after the same number of swings as the measurements if possible. In the case below, this will be possible by a small decrease of the tolerance band.

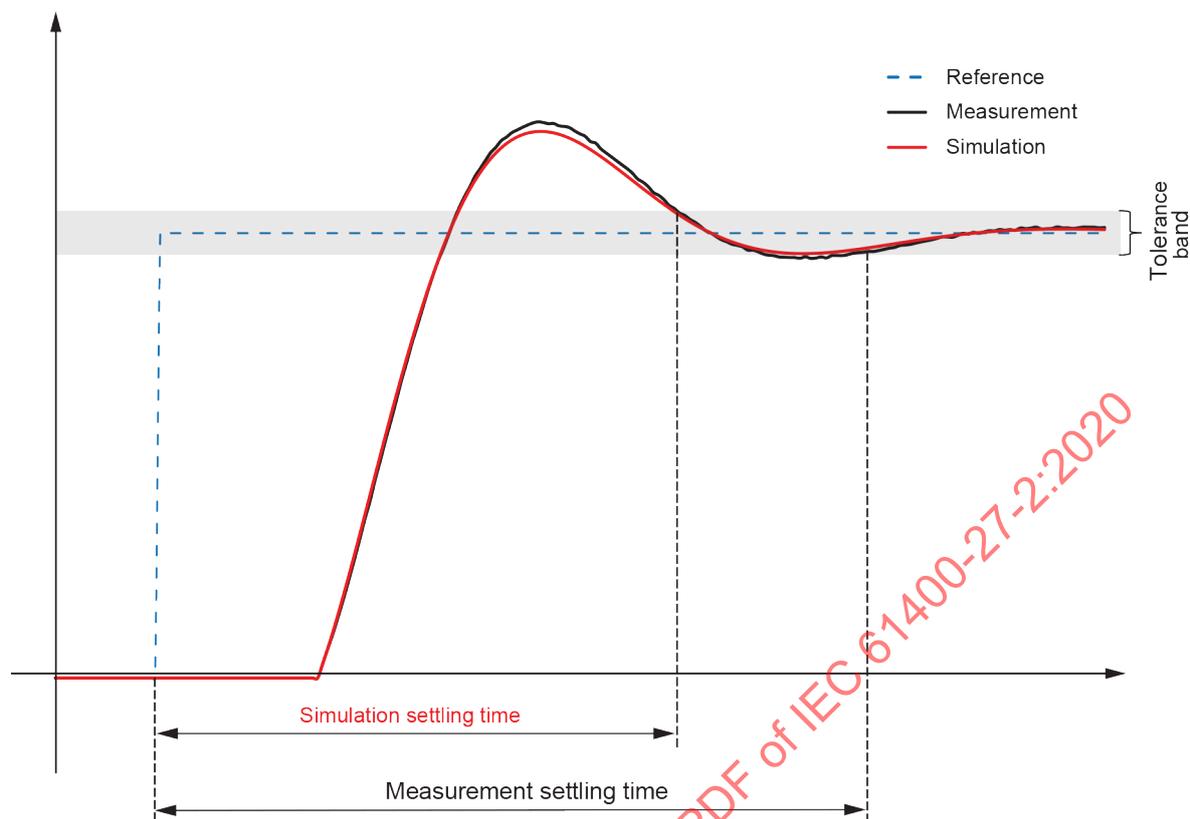


Figure 6 – Measured and simulated settling time with inexpedient choice of tolerance band

7 Validation of wind turbine models

7.1 General

The objective of Clause 7 is to provide formal specifications of the procedure for validation of a WT simulation model against WT test results. The validation procedure is based on tests of WT control performance and dynamic performance specified in IEC 61400-21-1, but other test results should also be accepted provided that the required measurement results are available.

Based on the tests specified in IEC 61400-21-1, Clause 7 specifies validation procedures for the following WT functionalities:

- fault ride through capability,
- active power control,
- frequency control,
- synthetic inertia control,
- reactive power control or equivalent control method.

Annex A gives suggestions for the reporting of results of wind turbine model validation.

7.2 Fault ride through capability

7.2.1 General

Fault ride through capability of the WT refers to the response of the WT to voltage dips and voltage swells according to IEC 61400-21-1. Symmetrical as well as asymmetrical faults are considered.

7.2.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT fault ride through capability. Each test case is characterised by the number of faulted phases¹² as well as magnitude and duration of the fault. Although several measurements can be available for a test case, it is sufficient to use one measurement to validate the model against the test case.

Each test case shall provide the following output to the validation:

- number of faulted phases,
- magnitude of the fault,
- duration of the fault,
- applied WT control modes and reference values,
- time series of measured fundamental frequency positive sequence component of
 - voltage,
 - active current,
 - reactive current.

For validation of models, which include negative sequence, each asymmetrical test case shall provide the following additional output to the validation:

- time series of measured fundamental frequency negative sequence component of
 - voltage,
 - active current,
 - reactive current.

If full-system simulation approach is applied, then each test case shall provide the following additional information about the test:

- data for short circuit test equipment:
 - a single line diagram of the test equipment,
 - fundamental frequency values for electrical components in the test equipment,
 - time t_{fault} when the fault is initiated¹³,
 - time t_{clear} when the fault clearance is initiated¹⁴,
- data for the grid:
 - complex Thevenin impedance as a minimum,
 - in some cases, grid dynamic models are appropriate to replicate control influences during the fault within the grid.

¹² IEC 61400-21-1 specifies how to test symmetrical 3-phase fault cases as well as asymmetrical 2-phase fault cases. Positive sequence models like the generic models specified in IEC 61400-27-1 are widely used in power system stability studies. Positive sequence models can have the limitation of not giving the negative sequence response to asymmetrical faults.

¹³ The intention is to identify the first time when the short-circuit occurs in one of the phases. If t_{fault} is not logged, then it should be identified by inspection of u_{WTraw} .

¹⁴ The intention is to identify the first time when the short-circuit is cleared in one of the phases. If t_{clear} is not logged, then it should be identified by inspection of u_{WTraw} .

7.2.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. A full-system simulation shall include model for the test equipment as well as the grid. A play-back simulation shall play-back the measured voltage¹⁵.
- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution¹⁶.

7.2.4 Validation results

The following validation results shall be provided:

- plots showing time series of the following positive sequence components:
 - measured and simulated voltage,
 - measured and simulated active current,
 - measured and simulated reactive current,
 - absolute errors of active and reactive currents.
- a table showing MXE, ME and MAE of positive sequence active power, reactive power, active current and reactive current in the pre-fault, fault and postfault windows according to the specifications in Table 1.

In the case of validation of models including negative sequence, the validation of unbalanced fault cases shall include the equivalent values as for the positive sequence.

7.3 Active power control

7.3.1 General

Active power control of the WT refers to the dynamic response of the WT to step changes in active power references as specified in IEC 61400-21-1.

The validation of the active power control of the WT model can only be performed for WTs which support active power control providing access to an active power reference value.

7.3.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT active power control including test of the dynamic response to a step change in the active power reference.

Each test case shall provide the following output to the validation:

- applied WT control modes and reference values including power ramp rate,
- time series of

¹⁵ Fundamental frequency voltages measured according to IEC 61400-21-1 are smoothed over 1 cycle which can affect the performance of some simulation models. In such cases, full-system simulations should be applied.

¹⁶ The generic models in IEC 61400-27-1 are required to work with integration time steps up to $\frac{1}{4}$ cycle.

- available active power,
- measured active power¹⁷,
- power reference (set point) value.

7.3.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage, active power reference and available active power can be played back.
- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

7.3.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following variables:
 - active power reference,
 - available active power,
 - measured active power,
 - simulated active power,
- a table showing the reaction time, rise time, settling time and overshoot of the simulated and measured active power.

7.4 Frequency control

7.4.1 General

Frequency control of the WT refers to the response of the WT to grid overfrequency as specified in IEC 61400-21-1.

The validation of the frequency control of the WT model shall only be performed for WTs which support frequency control and provide access to a frequency reference value.

7.4.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT frequency control, either by changing the measured grid frequency or by changing the reference value of the grid frequency.

Each test case shall provide the following output to the validation:

- applied WT control modes and reference values including frequency control settings and power ramp rate,
- time series of
 - grid frequency measurement input to WT controller,

¹⁷ Tests according to IEC 61400-21-1 shall be reported as 200 ms average data.

- reference (set point) value of grid frequency,
- available active power,
- measured active power.

7.4.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured frequency, reference value of grid frequency and available active power can be played back.
- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of frequency, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

7.4.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following variables:
 - grid frequency measurement input to WT controller,
 - reference value of the grid frequency,
- a plot showing time series of the following variables:
 - available active power,
 - measured active power,
 - simulated active power.

7.5 Synthetic inertia control

7.5.1 General

Synthetic inertia control of the WT refers to the WT ability to support the grid by providing additional active power in the case of under frequency as specified in IEC 61400-21-1.

The validation of the synthetic inertia control of the WT model shall only be performed for WTs which support synthetic inertia control.

7.5.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT active power control including test of the dynamic response to a step change in the active power reference.

Each test case shall provide the following output to the validation:

- applied WT control modes and reference values including inertia setting parameters,
- time series of measured fundamental frequency positive sequence component of
 - grid frequency measurement input to WT controller,
 - reference (set point) value of the grid frequency,
 - available active power,
 - measured active power.

7.5.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage, reference value of grid frequency change and available active power can be played back.
- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

7.5.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following positive sequence components:
 - grid frequency measurement input to WT controller,
 - reference (set point) value of the grid frequency,
- a plot showing time series of the following positive sequence components:
 - available active power,
 - measured active power,
 - simulated active power.

7.6 Reactive power reference control

7.6.1 General

Reactive power reference control of the WT refers to the dynamic response of the WT to step changes in reactive power reference value according to IEC 61400-21-1.

The validation of the reactive power reference control of the WT model shall only be performed for WTs which support reactive power reference control providing access the reactive power reference value.

7.6.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT reactive power control including test of the dynamic response to a step change in the reactive power reference.

Each test case shall provide the following output to the validation:

- applied WT control modes and reference values,
- time series of
 - reactive power reference values,
 - measured reactive power,
 - measured active power.

7.6.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage and measured active power can be played back.
- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

7.6.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following variables:
 - reactive power reference value,
 - measured reactive power,
 - simulated reactive power,
- a plot showing time series of the following variables:
 - measured active power,
 - simulated active power,
- a table showing the reaction time, rise time, settling time and overshoot of the simulated and measured reactive power.

7.7 Reactive power – voltage reference control

7.7.1 General

Voltage reference control of the WT refers to the dynamic response of the WT to step changes in voltage reference values (set points) depending on the WT control system as specified by the manufacturer according to IEC 61400-21-1.

The validation of the voltage reference control of the WT model shall only be performed for WTs which support voltage reference control providing access to the voltage reference value.

7.7.2 Test requirements

IEC 61400-21-1 specifies the requirements to test of WT reactive power control including test of the dynamic response to a step change in the reactive power reference.

Each test case shall provide the following output to the validation:

- applied WT control modes and reference values,
- time series of
 - measured active power and measured reactive power.

7.7.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage and measured active power can be played back.

- The WT simulation model shall use the same control modes and reference values as the WT during the test.
- The WT simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

7.7.4 Validation results

The following validation results shall be provided:

- plot showing time series of the following variables:
 - measured and simulated reactive power¹⁸.

7.8 Grid protection

7.8.1 General

Grid protection of the WT refers to the response of the WT to over voltage, under voltage, over frequency and under frequency as specified in IEC 61400-21-1.

7.8.2 Test requirements

At least one test of over voltage protection, under voltage protection, over frequency protection and under frequency protection shall be used in the validation. The following inputs are required from IEC 61400-21-1 for protection function:

- measured trip level,
- measured disconnection time.

7.8.3 Simulation requirements

IEC 61400-21-1 separates the test procedure into a first part, which detects the protection levels and a second part which measures the corresponding disconnection times. The validation procedure in IEC 61400-27-1 requires simulations corresponding to the measurement of disconnection times. Those simulations are used to validate protection levels as well as disconnection times.

The following procedure shall be applied to validate the protection test:

- Over voltage protection test:

The relay time and level in the model shall be verified by the following two steps:

- 1) With the simulations started at nominal voltage and frequency, apply a voltage step to 1 % above the set trip level and let the simulation continue until the model trips. Record the time from the step in the voltage and until the model trips. ¹⁹
- 2) With the simulation started at nominal voltage and frequency, apply voltage step to 1 % below the set trip level and let the simulation continue until the relay time setting plus an offset²⁰. The model protection system should not trip.

¹⁸ Measured and simulated reactive currents can be plotted instead of reactive powers.

¹⁹ Significant over-voltage can result in non-fundamental voltage components that affect the real protections, but are not modelled in the fundamental frequency positive sequence simulations.

²⁰ The offset shall be smaller than the difference of the tested relay time setting and the next relay time setting.

– Under voltage protection test:

The relay time and level in the model shall be verified by the following two steps:

- 3) With the simulations started at nominal voltage and frequency, apply a voltage step to 1 % below the set trip level and let the simulation continue until the model trips. Record the time from the step in the voltage and until the model trips.
- 4) With the simulation started at nominal voltage and frequency, apply voltage step to 1 % above the set trip level and let the simulation continue until the relay time setting plus an offset²⁰. The model protection system should not trip.

– Over frequency protection test:

The relay time and level in the model shall be verified by the following two steps:

- 5) With the simulations started at nominal voltage and frequency, apply a frequency change to 0,1 Hz above the set trip level and let the simulation continue until the model trips. Record the time from the frequency change and until the model trips.
- 6) With the simulation started at nominal voltage and frequency, apply frequency change 0,1 Hz below the set trip level and let the simulation continue until the relay time setting plus an offset²⁰. The model protection system should not trip.

– Under frequency protection test:

The relay time and level in the model shall be verified by the following two steps:

- 7) With the simulations started at nominal voltage and frequency, apply a frequency change to 0,1 Hz below the set trip level and let the simulation continue until the model trips. Record the time from the frequency change and until the model trips.
- 8) With the simulation started at nominal voltage and frequency, apply frequency change 0,1 Hz above the set trip level and let the simulation continue until the relay time setting plus an offset²⁰. The model protection system should not trip.

7.8.4 Validation results

The following validation results shall be provided:

- a table showing the setpoint, measured and simulated values for protection levels and disconnection times for each test.

8 Validation of wind power plant models

8.1 General

The objective of Clause 8 is to provide formal specifications of the procedure for validation of a WP simulation model against WP test results. The validation procedure is based on tests of WP control performance and dynamic performance specified in IEC 61400-21-2, but other test results should also be accepted provided that the required measurement results are available.

Based on the tests specified in IEC 61400-21-2, Clause 8 specifies validation procedures for the following WP functionalities:

- active power control,
- reactive power control or equivalent control method.

Annex B gives suggestions for the reporting of results of wind plant model validation.

8.2 Active power control

8.2.1 General

Active power control of the WP refers to the dynamic response of the WP to step changes in active power references as specified in IEC 61400-21-2.

The validation of the active power control of the WP model can only be performed for WPs which support active power control providing access to an active power reference value.

8.2.2 Test requirements

IEC 61400-21-2 specifies the requirements to test of WP active power control including test of the dynamic response to a step change in the active power reference.

Each test case shall provide the following output to the validation:

- applied WP control modes and reference values including power ramp rate,
- time series of
 - available active power, measured active power²¹ and power reference (set point) value.

8.2.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage, active power reference and available active power can be played back.
- The WP simulation model shall use the same control modes and reference values as the WT during the test.
- The WP simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

8.2.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following variables:
 - active power reference, available active power, measured active power and simulated active power,
- a table showing the reaction time, rise time, settling time and overshoot of the simulated and measured active power.

8.3 Reactive power reference control

8.3.1 General

Reactive power control of the WP refers to the dynamic response of the WP to step changes in reactive power, voltage or $\cos \phi$ reference values (set points) depending on the WP control system as specified by the manufacturer according to IEC 61400-21-2.

The validation of the reactive power control of the WP model shall only be performed for WPs which support reactive power control providing access to one of the above mentioned reference values.

²¹ Tests according to IEC 61400-21-1 shall be reported as 200 ms average data.

8.3.2 Test requirements

IEC 61400-21-2 specifies the requirements to test of WP reactive power control including test of the dynamic response to a step change in the reactive power reference.

Each test case shall provide the following output to the validation:

- applied WP control modes and reference values,
- time series of
 - reactive power reference values,
 - measured active power and measured reactive power.

8.3.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage and measured active power can be played back.
- The WP simulation model shall use the same control modes and reference values as the WT during the test.
- The WP simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

8.3.4 Validation results

The following validation results shall be provided:

- a plot showing time series of the following variables:
 - reactive power reference value,
 - measured reactive power,
 - simulated reactive power,
- a plot showing time series of the following variables:
 - measured active power,
 - simulated active power.

For dynamic response test cases of reactive power control according to IEC 61400-21-2, the following additional results shall be provided:

- a table showing the reaction time, rise time, settling time and overshoot of the simulated and measured reactive power.

8.4 Reactive power – voltage reference control

8.4.1 General

Voltage reference control of the WP refers to the dynamic response of the WP to step changes in voltage reference values (set points) depending on the WP control system as specified by the manufacturer according to IEC 61400-21-2.

The validation of the voltage reference control of the WP model shall only be performed for WPs which support voltage reference control providing access to the voltage reference value.

8.4.2 Test requirements

IEC 61400-21-2 specifies the requirements to test of WP reactive power control including test of the dynamic response to a step change in the reactive power reference.

Each test case shall provide the following output to the validation:

- applied WP control modes and reference values,
- time series of
 - measured active power and measured reactive power.

8.4.3 Simulation requirements

The following requirements apply to the simulations of the test case:

- Full-system simulation approach as well as play-back simulation approach should be accepted. Measured voltage and measured active power can be played back.
- The WP simulation model shall use the same control modes and reference values as the WP during the test.
- The WP simulation model shall be initialised in accordance with the measured initial values of voltage, active power and reactive power. If the model includes other independent variables such as wind speed or pitch angle, then those variables shall be initialised accordingly.
- The simulated time series shall be provided with minimum $\frac{1}{4}$ cycle time step resolution.

8.4.4 Validation results

The following validation results shall be provided:

- plot showing time series of the following variables:
 - measured and simulated reactive power²².

²² Measured and simulated reactive currents can be plotted instead of reactive powers.

Annex A (informative)

Validation documentation for wind turbine model

A.1 General

Annex A gives suggestions for the reporting of results of WT model validation according to Clause 7.

In addition to the test report, measured values and simulated values should be provided as files with time series values in a standardized file format – e.g. COMTRADE or UFF format.

A.2 Simulation model and validation setup information

For the simulation model and validation setup, the information given in Table A.1 should be presented:

Table A.1 – Required information about simulation model and validation setup

Request	Description
Type of model	Reference to name of models in IEC 61400-or other models
Parameter set used	To be attached to the report
Description of validation setup	State if play-back or full-system simulation method is used

Table A.2 specifies additional information which is required if full-system method is applied.

Table A.2 – Additional information required if full-system method is applied

Request	Description
Information about the test equipment	Type of equipment (e.g. voltage divider or full scale converter, fault recorder) Key data for equipment, e.g. series and shunt impedances in voltage divider equipment
Information about the grid where WT and test equipment are connected to.	Thevenin equivalent for the grid

With the information above, it should be possible to reproduce the validation results.

A.3 Template for validation results

A.3.1 General

There should be reported a set of figures and tables for each case as defined in Clause 7. The reporter should fill in the empty fields in the tables and insert the graphics at the figure captions.

A.3.2 Fault ride through capability

For each fault ride through validation case, the following graphs should be provided (see Figure A.1 to Figure A.4):



Figure A.1 – Time series of measured and simulated positive sequence voltage



Figure A.2 – Time series of measured and simulated positive sequence active current



Figure A.3 – Time series of measured and simulated positive sequence reactive current



Figure A.4 – Time series of calculated absolute error of positive sequence active and reactive current

The X axis should include the complete measured and simulation sequence from 1 s prior to the applied voltage dip or voltage swell and at least 5 s after the applied voltage dip or voltage swell sequence.

The Y axis should be linear and should include the complete measured and simulated per-unit values.

The positive sequence validation results should be summarized in Table A.3 using per-unit values:

Table A.3 – Positive sequence validation summary for each voltage dip and voltage swell validation case

Case description	Window	Active power			Reactive power			Active current			Reactive current		
		MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE
Case dependent information such as pre-fault voltage, estimated grid impedance and test equipment settings such as short circuit impedance if used	prefault												
	fault												
	postfault												

For each asymmetrical fault ride through validation case, the following graphs should be provided (see Figure A.5 to Figure A.8) :



Figure A.5 – Time series of measured and simulated negative sequence voltage



Figure A.6 – Time series of measured and simulated negative sequence active current



Figure A.7 – Time series of measured and simulated negative sequence reactive current



Figure A.8 – Time series of calculated absolute error of negative sequence active and reactive current

The X axis should be the same as the X axis in Figure A.1 to Figure A.4.

The Y axis should be linear and should include the complete measured and simulated per-unit values.

The negative sequence validation results should be summarized in Table A.4 using per-unit values:

Table A.4 – Negative sequence validation summary for each voltage dip and voltage swell validation case

Case description	Window	Active power			Reactive power			Active current			Reactive current		
		MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE
Case dependent information such as pre-fault voltage, estimated grid impedance and test equipment settings such as short circuit impedance if used	prefault												
	fault												
	postfault												

A.3.3 Active power control

For validation of an active power control case, the following graph should be provided (see Figure A.9):



Figure A.9 – Time series of active power reference, available active power, measured active power and simulated active power

The validation results should be summarized in Table A.5.

Table A.5 – Validation summary for active power control

Case description	Rise time		Reaction time		Settling time	
	Measured	Simulated	Measured	Simulated	Measured	Simulated

A.3.4 Frequency control

For validation of a frequency control case, the following graphs should be provided (see Figure A.10 and Figure A.11):



Figure A.10 – Time series of frequency reference value and measured input to WT controller



Figure A.11 – Time series of available active power, measured active power and simulated active power

A.3.5 Synthetic inertia control

For validation of a synthetic inertia control case, the following graphs should be provided (see Figure A.12 and Figure A.13):



Figure A.12 – Time series of frequency reference value and measured input to WT controller



Figure A.13 – Time series of available active power, measured active power and simulated active power

A.3.6 Reactive power reference control

For validation of a reactive power reference control, the following graph should be provided (see Figure A.14 and Figure A.15):



Figure A.14 – Time series of reactive power reference, measured reactive power and simulated reactive power



Figure A.15 – Time series of measured active power and simulated active power

The validation results should be summarized in Table A.6.

Table A.6 – Validation summary for reactive power control

Case description	Rise time		Reaction time		Settling time	
	Measured	Simulated	Measured	Simulated	Measured	Simulated

A.3.7 Reactive power – voltage reference control

For validation of a reactive power voltage reference control, the following graph should be provided (see Figure A.16):



Figure A.16 – Time series of measured and simulated reactive power

A.3.8 Grid protection

For each grid protection validation test case, the applied setpoint, measured and simulated per-unit values shall be summarized in Table A.7:

Table A.7 – Validation summary for grid protection

Case description	Protection level			Protection disconnection time		
	setpoint	measured	simulated ^a	setpoint	measured	simulated
Over voltage						
Under voltage						
Over frequency						
Under frequency						
^a The protection level is not detected but only validated by the simulations. The protection level setpoint used in the simulations should be stated in this column.						

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Annex B
(informative)

Validation documentation for wind power plant model

B.1 General

Annex B gives suggestions for the reporting of results of WP model validation according to Clause 8.

In addition to the test report, measured values and simulated values should be provided as files with time series values in a standardized file format – e.g. COMTRADE or UFF format.

B.2 Simulation model and validation setup information

For the simulation model and validation setup, the information given in Table B.1 should be presented:

Table B.1 – Required information about simulation model and validation setup

Request	Description
Type of model	Reference to name of models in IEC 61400-27-1 or other models
Parameter set used	To be attached to the report
Description of validation setup	State if play-back or full-system simulation method used

Table B.2 specifies additional information which is required if full-system method is applied.

Table B.2 – Additional information required if full-system method is applied

Request	Description
Information about the grid where WP is connected to (or the reference grid applied in model-to-model validation)	Thevenin equivalent for the grid

With the information above, it should be possible to reproduce the validation results.

B.3 Template for validation results

B.3.1 General

Depending on the validation case, the corresponding template for validation of the WT model given in Clause A.3 should be applied.

B.3.2 Active power control

For validation of an active power control case, the following graph should be provided (see Figure B.1):



Figure B.1 – Time series of active power reference, available active power, measured active power and simulated active power

The validation results should be summarized in Table B.3.

Table B.3 – Validation summary for active power control

Case description	Rise time		Reaction time		Settling time	
	Measured	Simulated	Measured	Simulated	Measured	Simulated

B.3.3 Reactive power reference control

For validation of a reactive power reference control, the following graph should be provided (see Figure B.2 and Figure B.3):



Figure B.2 – Time series of reactive power reference, measured reactive power and simulated reactive power



Figure B.3 – Time series of measured active power and simulated active power

The validation results should be summarized in Table B.4.

Table B.4 – Validation summary for reactive power control

Case description	Rise time		Reaction time		Settling time	
	Measured	Simulated	Measured	Simulated	Measured	Simulated

B.3.4 Reactive power – voltage reference control

For validation of a reactive power voltage reference control, the following graph should be provided (see Figure B.4):



Figure B.4 – Time series of measured and simulated reactive power

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Annex C (informative)

Reference grid for model-to-model validation

Annex C describes a reference grid, which can be used for model-to-model validation. The idea is to use this reference grid to validate a generic WT model or WP model specified in IEC 61400-27-1 against a validated detailed WT manufacturer model. Validation against a manufacturer model is particularly relevant for validation of WP model response to voltage dips because there are no generally feasible full scale tests for such cases.

The reference grid layout is a slightly modified version of the Western Electricity Coordinating Council (WECC) test system [13]. The layout of the reference grid is shown in Figure C.1. It represents an aggregated WP model connected to an aggregated grid model.

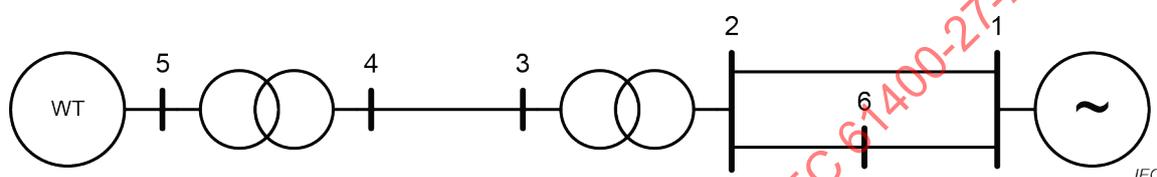


Figure C.1 – Layout of reference grid

Two sets of data are given for the WECC test system: one for a strong grid and one for a weak grid. Table C.1 gives the data for the individual lines in per-units. This data is known to be within the application range of the generic models specified in IEC 61400-27-1. Other test systems should also be accepted provided that the test system is within the application range of the models under validation.

Table C.1 – Line data for the WECC test system in per-unit

Line	Strong grid			Weak grid		
	R	X_L	B_C	R	X_L	B_C
L ₃₄	0,015	0,025	0,01	0,015	0,025	0,01
L ₂₁	0,01	0,1	0,02	0,03	0,3	0,05
L ₂₆	0,005	0,05	0,01	0,015	0,15	0,025
L ₆₁	0,005	0,05	0,01	0,015	0,15	0,025

The WECC test system transformer data is the same for the strong grid and the weak grid. This data is given in Table C.2.

Table C.2 – Transformer data for the WECC test system

Transformer	R	X_L	B_M
T ₅₄	0	0,05	0
T ₃₂	0	0,1	0

Annex D (informative)

Model validation uncertainty

D.1 General

The objective of this annex is to describe limits to possible model accuracy of the generic models specified in IEC 61400-27-1 and other fundamental frequency models of wind turbines and wind power plants. As stated in the introduction of this document, the validation procedure does not specify any requirements to model accuracy. The possible accuracy is partially illustrated in examples from literature about validation of the models [11], [12], [14]. Since the assessment of the model accuracy is based on comparisons between simulations and measurements, this annex includes a description of inevitable simulation errors as well as measurement errors.

D.2 Simulation uncertainties

The accuracy of the generic simulation models defined in this document is limited, due to the simplifications that have been applied with the aim of obtaining models compatible with power system transient stability simulations and in order to make the model suitable for representing a wide range of different WT technologies and configurations. To this respect, it is expected that the accuracy obtained by these models can vary when representing different WT technologies, configurations and specific controls. Therefore, differences in the accuracy of two different WTs represented by the same generic model type can cause that the generic model is more similar or easier to adapt to one of the WTs' real topology and does not necessarily mean that the model with less accuracy has not been tuned properly. Some specific reasons for deviations between simulation and measurement are

- The DC-Component of the stator flux of grid coupled generators (Type 1, Type 2 and Type 3 WTs) will lead to uncertainties of the active and reactive power output following severe voltage changes.
- Drive train oscillations following severe voltage drops can lead to negative torque and a backlash in the gearbox [15]. This will modify the (equivalent) drive train eigenfrequency during the fault which means that the eigenfrequency during the fault is different from the one following the fault clearance.
- If the measurements are made on the high voltage side of the transformer, then the transformer model should be included in the WT model. In this case, electromagnetic phenomena (such as non-linearity) can be introduced into the measurement signals that are a consequence of the electromagnetic behaviour of the transformer. These phenomena are not of interest for stability analysis (see model specifications in 6.2). Thus, these phenomena cannot be emulated by the models developed here and thus the assessment of the model should account for the added uncertainty due to the WT transformer.

D.3 Measurement uncertainties

In the process of model validation, there is always a requirement to measure data, whether from actual field tests at a power plant or factory tests of the equipment. This measured data is then used to compare with simulations using the model to be validated. It is important to understand the limitations and errors that are introduced by measurement. These can be broadly categorized as follows: