IEC 61400-27-1

Edition 2.0 2020-07

INTERNATIONAL STANDARD

Wind energy generation systems –
Part 27-1: Electrical simulation models – Generic models

IEC 61400-27-1:2020-07(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

IEC 61400-27-1

Edition 2.0 2020-07

INTERNATIONAL STANDARD

Wind energy generation systems –
Part 27-1: Electrical simulation models – Generic models

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.180

ISBN 978-2-8322-8505-3

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 27-1: Electrical simulation models – Generic models

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 61400-27-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

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

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

FDIS	Report on voting
88/762/FDIS	88/771/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.

This second edition cancels and replaces the first edition, published in 2015. This edition constitutes a technical revision and a restructure of the content into two parts. The new structure joins the models in part 27-1 and the validation procedures in part 27-2.

This edition includes the following significant technical changes with respect to the previous edition:

a) "Wind turbines" changed to "Generic models" because wind power plant models are also included, and the model validation is moved to IEC 61400-27-2;
b) specification of models for wind power plants including plant control, communication system model and aggregation procedure for power collection system in addition to the wind turbine models in the previous edition;
c) moving validation prodedures for wind turbine models from this edition to part 27-2;
d) a more detailed modular structure separating wind turbine control into pitch control and generator system control and extracting grid measurement modules from the control modules. Figures are revised accordingly;
e) inclusion of model for STATCOM;
f) inclusion of electrical components modules.

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.

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

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

INTRODUCTION

IEC 61400-27-1 specifies standard dynamic electrical simulation models for wind turbines and wind power plants. The specified wind turbine models can either be used in wind power plant models or to represent wind turbines without wind power plant relationships. Apart from the wind turbine models, the wind power plant model may include models for auxiliary equipment such as STATCOMs which are often used in 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 models developed by the wind turbine manufacturers reproduce the behaviour of their machines with a high level of detail. Such level of detail is not suitable for stability studies of large power systems with a huge number of wind power plants, firstly because the high level of detail increases the complexity and thus computer time dramatically, and secondly because the use of detailed manufacturer specific models requires a substantial amount of input data to represent the individual wind turbine types.

The purpose of this International Standard is to specify generic dynamic models, which can be applied in power system stability studies. The IEEE/CIGRE Joint Task Force on Stability Terms and Definitions [11][1] has classified power system stability in categories according to Figure 1.

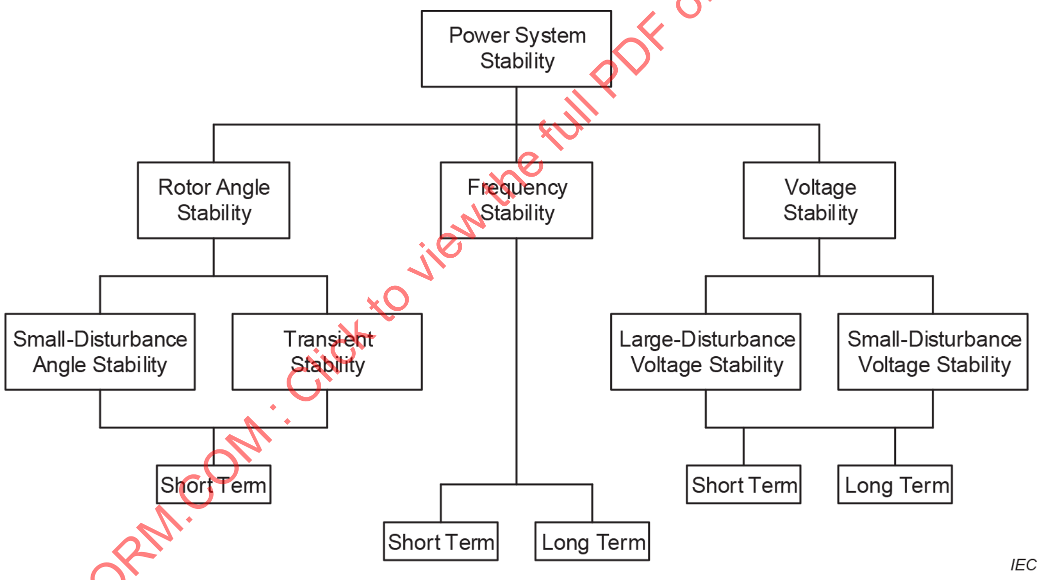


Figure 1 – Classification of power system stability according to IEEE/CIGRE Joint Task Force on Stability Terms and Definitions [11]

Referring to these categories, the models are 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 [12], and system separation of a synchronous system into more synchronous areas.

[1] The numbers in square brackets refer to the Bibliography.

The models shall be complete enough to represent the dynamic behavior of the wind power plant at the point of connection and of the wind turbine at the wind turbine terminals, but shall also be suitable for large-scale grid studies. Therefore, simplified models are specified to perform the typical response of known technologies.

The wind power plant models specified in this document are for fundamental frequency positive sequence response[2].

The models have the following limitations:

– The models are not intended for long term stability analysis.
– The models are not intended for investigation of sub-synchronous interaction phenomena.
– The models are not intended for investigation of the fluctuations originating from wind speed variability in time and space. This implies that the models do not include phenomena such as turbulence, tower shadow, wind shear and wakes.
– The models do not cover phenomena such as harmonics, flicker or any other EMC emissions included in the IEC 61000 series.
– The wind generation systems are highly non-linear and simplifications have been made in the development of the models. Thus, linearisation for eigenvalue analysis is not trivial nor necessarily appropriate based on these simplified models.
– This document does not address the specifics of short-circuit calculations.
– The models are not applicable to studies where wind turbines are islanded without synchronous generation.
– The models are not intended for studies of situations with short-circuit ratios less than 3. The short circuit limitation depends on wind turbine types, control modes and other settings. The WT manufacturer can specify a lower limit for the applicable short-circuit ratio provided that this application is validated according to part 27-2.
– The models are limited by the functional specifications in Clause 5.

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

– TSOs and DSOs are end users of the models, performing power system stability studies as part of the planning as well as the operation of the power systems.
– Wind plant owners are typically responsible to provide the wind power plant models to TSO and/or DSO prior to plant commissioning.
– Wind turbine manufacturers will typically provide the wind turbine models to the owner.
– Developers of modern software for power system simulation tools will use the standard to implement standard wind power models as part of the software library.
– Certification bodies in case of independent wind turbine model validation.
– Consultants who use models on behalf of TSOs, DSOs and/or wind plant developers.
– Education and research communities, who can also benefit from the generic models, as the manufacturer specific models are typically confidential.

[2] This document is dealing with balanced as well as unbalanced faults, but for unbalanced faults, only the positive sequence components are specified.

WIND ENERGY GENERATION SYSTEMS –

Part 27-1: Electrical simulation models – Generic models

1 Scope

This part of IEC 61400 defines standard electrical simulation models for wind turbines and wind power plants. The specified models are time domain positive sequence simulation models, intended to be used in power system and grid stability analyses. The models are applicable for dynamic simulations of short term stability in power systems.

This document defines the generic terms and parameters for the electrical simulation models.

This document specifies electrical simulation models for the generic wind power plant topologies / configurations currently on the market. The wind power plant models include wind turbines, wind power plant control and auxiliary equipment. The wind power plant models are described in a modular way which can be applied for future wind power plant concepts and with different wind turbine concepts.

This document specifies electrical simulation models for the generic wind turbine topologies/concepts/configurations currently on the market. The purpose of the models is to specify the electrical characteristics of a wind turbine at the wind turbine terminals. The wind turbine models are described in a modular way which can be applied for future wind turbine concepts. The specified wind turbine models can either be used in wind power plant models or to represent wind turbines without wind power plant relationships.

The electrical simulation models specified in IEC 61400-27-1 are independent of any 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 61970-301, *Energy management system application program interface (EMS-API) – Part 301: Common information model (CIM) base*

IEC 61970-302, *Energy management system application program interface (EMS-API) – Part 302: Common information model (CIM) dynamics*

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
auxiliary equipment
STATCOM or other device supplementing wind turbines in wind power plant

3.1.2
available power
maximum possible power taking into account wind speed, power rating, rotor speed limits and pitch angle constraints

Note 1 to entry: The aerodynamic power cannot be greater than available power.

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
fault ride through
ability of a wind turbine or wind power plant to stay connected during voltage dips (under voltage ride through) and voltage swells (over voltage ride through)

3.1.5
generator sign convention
specification of signs for active and reactive components of current and power e.g. from a wind turbine or a reactive power compensation component

Note 1 to entry: The active current and power are positive if power is generated and negative if power is consumed. Likewise, the reactive current and reactive power are positive if reactive power is generated as in the case of a capacitor and negative if reactive power is consumed as in the case of a reactance.

3.1.6
generic model
model that can be adapted to simulate different wind turbines or wind power plants by changing the model parameters

3.1.7
grid variable
voltage, current or frequency

3.1.8
hook
input to or output from a module which is not used in the generic models specified in this standard but may be used to expand generic models beyond the IEC 61400-27-1 scope e.g. to match manufacturer specific models or to match specific national grid connection requirements

3.1.9
integration time step
simulation time interval between two consecutive numerical solutions of the model's differential equations

3.1.10
module
part of a model which has a modular structure

3.1.11
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:

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

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, 448-11-28]

3.1.12
nominal active power
nominal value of active power which is stated by the manufacturer and is used as per-unit base for all powers (active, reactive, apparent)

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

3.1.13
nominal frequency
nominal value of wind turbine frequency stated by the manufacturer

3.1.14
nominal voltage
nominal value of wind turbine phase-to-phase voltage stated by the manufacturer

3.1.15
over voltage ride through
ability of a wind turbine or wind power plant to stay connected during voltage swells

3.1.16
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]

3.1.17
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]

3.1.18
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:

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

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]

3.1.19
power device
wind turbine or auxiliary equipment

3.1.20
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]

3.1.21
short-circuit power
product of the current in the short-circuit at a point of a system and a nominal voltage, generally the operating voltage

Note 1 to entry: Using physical units for line current (A) and nominal 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"]

3.1.22
short-circuit ratio
ratio of the short-circuit power at the point of connection to the nominal active power of the wind power plant or wind turbine

3.1.23
steady state of a system
operating conditions of a network in which the system state variables are considered to be sensibly constant

[SOURCE: IEC 60050-603:1986, 603-02-06]

3.1.24
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]

3.1.25
under voltage ride through
ability of a wind turbine or wind power plant to stay connected during voltage dips

3.1.26
voltage dip
sudden voltage reduction at a point in an electric power system, followed by voltage recovery after a short time interval, from a few periods of the sinusoidal wave of the voltage to a few seconds

[SOURCE: IEC 60050-614:2016, 614-01-08]

3.1.27
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]

3.1.28
wind power plant
power station comprising one or more wind turbines, auxiliary equipment and plant control

3.1.29
wind turbine
rotating machinery in which the kinetic wind energy is transformed into another form of energy

[SOURCE: IEC 60050-415:1999,1987, 415-01-01]

3.1.30
wind turbine terminals
point that is part of the wind turbine and identified by the wind turbine manufacturer as a point at which the wind turbine may be connected to the power collection system

[SOURCE: IEC 61400-21-1:2019, 3.25]

3.1.31
zero (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:

$$\underline{X}_0 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3}\right)$$

where $\underline{X}_{L1}$, $\underline{X}_{L2}$ 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, 448-11-29]

3.2 Abbreviations and subscripts

3.2.1 Abbreviations

The following abbreviations are used in this document:

ACL aggregated collector line

AG	asynchronous generator
AUX	auxiliary equipment
AUXT	AUX terminals
C	DC link capacitor
CB	circuit breaker
CH	chopper
CIGRE	the International Council on Large Electric Systems
CRB	crowbar
DCL	DC link
DFAG	doubly fed asynchronous generator[3]
FRT	fault ride through
GB	gearbox
IEEE	the Institute of Electrical and Electronics Engineers, Inc.
MSC	mechanically switched capacitor bank, which is not switched dynamically during voltage dips
NERC	the North American Electric Reliability Corporation
NLTC	no-load tap changer
OLTC	on-load tap changer
OVRT	over voltage ride through
PD	power device
POC	point of connection of WP
p.u.	per-unit
ROCOF	rate of change of frequency
SCADA	supervisory control and data acquisition
SG	synchronous generator
STATCOM	static synchronous compensator based on a power electronics voltage-source converter
SVC	static var compensator
TR	transformer
TRWP	WP transformer
TRWT	WT transformer
TSC	thyristor switched capacitor bank, which is switched dynamically during voltage dips

3 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.

UVRT	under voltage ride through
VRRAG	asynchronous generator with variable rotor resistance
WP	wind power plant
WT	wind turbine
WTR	WT rotor
WTT	WT terminals

3.2.2 Subscripts

0SS	steady state at zero time for initialisation
ACL	aggregated collector line
ag	air gap
AUX	auxiliary equipment
base	per-unit base value
cmd	current command to generator system
Com	communicated variable (output from communication module)
d	delayed
drt	drive train
DTD	active drive train damping
err	controller input error
gen	generator
gs	generator system
init	initial value
filt	filtered variable
FRT	fault ride through
hook	hook
max	maximum
min	minimum
n	nominal
OLTC	on-load tap changer
ord	active or reactive power order from WT controller
p	active component
PD	power device
q	reactive component
ref	controller reference value

sys power system

TC torque controller

u voltage

WTref WT reference value

UVRT under voltage ride through

WT variable at WTT

WTC grid measurement for the WT controller

WTP grid measurement for the WP grid protection

WTR WT rotor

4 Symbols and units

4.1 General

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

The symbols used globally in this document are listed in 4.2. Additional symbols used in module block diagram figures in Clause 7 and Annex B represent module parameters which are described in tables adjacent to the figures in the associated module clause. Those symbols are only used locally in the associated module and therefore not duplicated in the symbol list 4.2.

Small letters are used for per-unit variables whereas capital letters are used for variables in physical units. For variables with physical units, the units are given in brackets. For per-unit variables, the per-unit bases are given in the brackets. Currents as well as active and reactive power uses generator sign convention.

4.2 Symbols (units)

φ_{init} initial phase angle (deg)

Θ pitch angle (deg)

τ_{init} initial torque (T_{base})

T_{base} torque p.u. base value $\mathrm{T}_{\text{base}} = \dfrac{P_{\text{WTn}}}{\Omega_{\text{base}}}$ (Nm)

ω_{gen} generator rotational speed (Ω_{base})

ω_{ref} reference rotational speed (Ω_{base})

ω_{WTR} WTR rotational speed (Ω_{base})

Ω_{base} rotational speed p.u. base $\Omega_{\text{base}} = \begin{cases} \Omega_{\text{n}}\ (\text{rad/s}) & \text{referring to gen} \\ \dfrac{\Omega_{\text{n}}}{n_{\text{gear}}}\ (\text{rad/s}) & \text{referring to WTR} \end{cases}$

Ω_{n} nominal generator rotational speed (rad/s)

f_{AUXPfilt} filtered grid frequency measurement for AUX grid protection (f_{n})

f_{n} nominal grid frequency (50 Hz or 60 Hz)

F_{FRT} fault ride through flag (0,1,2)

F_{OCB} open-circuit-breaker flag (0,1)

f_{WTCfilt} filtered grid frequency measurement for WT control (f_{n})

f_{WTPfilt} filtered grid frequency measurement for WT grid protection (f_{n})

f_{sys} global power system grid frequency applied for frequency measurements because angles are calculated in the corresponding stationary reference frame (f_{n})

f_{WPfilt} filtered WP frequency measurement (f_{n})

$f_{\text{WPfiltCom}}$ filtered WP frequency measurement communicated to WP (f_{n})

F_{WPFRT} WP fault ride through flag

f_{WT} WTT grid frequency (f_{n})

$\underline{i}_{\text{AUX}}$ AUXT current phasor in power system coordinates (I_{base})

I_{base} phase current p.u. base $I_{\text{base}} = \frac{S_{\text{base}}}{\sqrt{3}U_{\text{base}}}$ (A)

$\underline{i}_{\text{conv}}$ converter current phasor in power system coordinates (I_{base})

$\underline{i}_{\text{gs}}$ generator current phasor in power system coordinates (I_{base})

$\underline{i}_{\text{WP}}$ WP current phasor in power system coordinates (I_{base})

$\underline{i}_{\text{WT}}$ WTT current phasor in power system coordinates (I_{base})

i_{pcmd} active current command to generator system (I_{base})

i_{pmax} maximum active current (I_{base})

i_{qcmd} reactive current command to generator system (I_{base})

i_{qmax} maximum reactive current (I_{base})

i_{qmin} minimum reactive current (I_{base})

J moment of inertia

n_{gear} mechanical gear ratio between WTR and generator

p_{ag} generator (air gap) power (S_{base})

p_{aero} aerodynamic power (S_{base})

p_{AUXref} AUX active power reference (S_{base})

p_{PDref} PD active power reference (S_{base})

p_{PDrefCom}	PD active power reference communicated to PD (S_{base})
p_{init}	initial power (S_{base})
p_{ord}	power order from WT controller (S_{base})
P_{WTn}	nominal active power of WT (W)
P_{WPn}	nominal active power of WP (W)
p_{WPfilt}	filtered WP active power measurement (S_{base})
$p_{\mathrm{WPfiltCom}}$	filtered WP active power measurement communicated to WP (S_{base})
p_{WPref}	WP active power reference (S_{base})
p_{WPrefCom}	WP active power reference communicated to WP (S_{base})
p_{WTCfilt}	filtered active power measurement for WT control (S_{base})
p_{WTref}	WTT active power reference (S_{base})
q_{AUXCfilt}	filtered reactive power measurement for AUX control (S_{base})
q_{max}	maximum reactive power (S_{base})
q_{min}	minimum reactive power (S_{base})
q_{WPfilt}	filtered WP reactive power measurement (S_{base})
$q_{\mathrm{WPfiltCom}}$	filtered WP reactive power measurement communicated to WP (S_{base})
q_{WTCfilt}	filtered reactive power measurement for WT control (S_{base})
q_{WTmax}	maximum WTT reactive power (S_{base})
q_{WTmin}	minimum WTT reactive power (S_{base})
r_{rot}	VRRAG rotor resistance (Z_{base})
S_{AUXn}	AUX nominal apparent power (S_{base})
S_{base}	power p.u. base $S_{\mathrm{base}} = \begin{cases} P_{\mathrm{WTn}}\ \text{(W)} & \text{referring to WT} \\ S_{\mathrm{AUXn}}\ \text{(VA)} & \text{referring to AUX} \\ P_{\mathrm{WPn}}\ \text{(W)} & \text{referring to WP} \end{cases}$
T_{s}	integration time step (s)
$\underline{u}_{\mathrm{AUX}}$	AUXT voltage phasor in power system coordinates (U_{AUXn})
u_{AUXCfilt}	filtered voltage measurement for AUX control (U_{base})
U_{AUXn}	nominal phase-to-phase voltage at AUXT (V)
u_{AUXPfilt}	filtered voltage measurement for AUX protection (U_{base})

U_{base}	phase-to-phase voltage p.u. base $U_{\text{base}} = \begin{cases} U_{\text{WTn}}\ (\text{V}) & \text{referring to WT} \\ U_{\text{AUXn}}\ (\text{V}) & \text{referring to AUX} \\ U_{\text{WPn}}\ (\text{V}) & \text{referring to WP} \end{cases}$
$\underline{u}_{\text{conv}}$	converter voltage phasor in power system coordinates (U_{base})
$\underline{u}_{\text{gs}}$	WT generator voltage phasor in power system coordinates (U_{base})
$\underline{u}_{\text{WP}}$	WP voltage phasor in power system coordinates (U_{base})
u_{WPfilt}	filtered WP voltage measurement (U_{base})
$u_{\text{WPfiltCom}}$	filtered WP voltage measurement communicated to WP (U_{base})
U_{WPn}	nominal phase-to-phase voltage at POC of WP (V)
$\underline{u}_{\text{WT}}$	WTT voltage phasor in power system coordinates (U_{base})
u_{WTC}	unfiltered voltage measurement for WT control (U_{base})
u_{WTCfilt}	filtered voltage measurement for WT control (U_{base})
U_{WTn}	nominal phase-to-phase voltage at WTT (V)
u_{WTPfilt}	filtered voltage measurement for WT grid protection (U_{base})
x_{AUXref}	AUX reactive power reference or delta voltage reference, depending on AUX control mode (x_{base})
x_{base}	reactive power or voltage p.u. base $x_{\text{base}} = \begin{cases} S_{\text{base}} & \text{in reactive power control mode (VA)} \\ U_{\text{base}} & \text{in delta voltage control mode (V)} \end{cases}$
x_{PDref}	PD reactive power reference or delta voltage reference, depending on PD control mode (x_{base})
x_{WPref}	WP reactive power reference or delta voltage reference, depending on WP control mode (x_{base})
x_{WPrefCom}	WP reactive power reference or delta voltage reference communicated to WP (x_{base})
x_{WTref}	WTT reactive power reference or delta voltage reference, depending on WT control mode (x_{base})
Z_{base}	impedance base value $Z_{\text{base}} = \dfrac{U_{\text{base}}^{2}}{S_{\text{base}}}$ (Ω)

5 Functional specification of models

5.1 General specifications

The models in this document have been developed with the following general specifications[4] in mind [13]:

– The models are modular in nature to allow for the potential of augmentation in case of future technologies being developed, or future supplemental controls features.

– The models are to be used primarily for power system stability studies and thus should represent all positive sequence dynamics affected and relevant during

- balanced short-circuits, including faults of varying impedance, on the transmission grid (external to the wind power plant, including voltage recovery),
- grid frequency disturbances[5],
- electromechanical modes of synchronous generator rotor oscillations (typically in the 0,2 Hz to 4 Hz range), and
- reference value changes.

– The models are for fundamental frequency positive sequence response[6].

– The models should be valid for typical power system frequency deviations (recommended ± 6 % from system nominal frequency).

– The models should be able to handle numerically the simulation of phase jumps.

– The models should be valid for steady state voltage deviations within the range from 0,85 p.u. to 1,15 p.u.

– The models should be valid for dynamic voltage phenomena (e.g. faults) where the voltage can dip temporarily close to zero[7]. The equipment suppliers shall establish the minimum voltage dip and/or system conditions for which the model is applicable for their specific equipment. A typical minimum voltage dip is 0,1[8].

– The typical dynamic simulation time frame of interest is from 10 s to 30 s. Wind speed is assumed to be constant during such a time frame.

– The models should work with integration time steps up to ¼ cycle[9]. As a consequence, the bandwidth of the models cannot be greater than 15 Hz[10].

– The models should initialise to a steady state from power flow solutions at full or partial nominal power.

– External conditions like wind speed should be taken into account implicitly through the available power.

---

4 The specifications are not performance requirements of the WPs or WTs, but requirements to the models.

5 The WT models do not include frequency control, but simulation of WP frequency control during grid frequency disturbances is possible using the WP power/frequency control model.

6 In general, positive sequence simulations are sufficient for bulk power system stability studies. Correct representation of the negative sequence and zero sequence components is cumbersome.

7 For very low voltages, the validity is also limited in the case of instability of the converter control [12].

8 For comparison, the minimum voltage dip test value in IEC 61400-21:2008 is 0,2.

9 The models can run stably with ½ cycle integration time steps, but some time constants may need to be modified to become minimum two times the integration time step. Such parameter modification will affect the model accuracy.

10 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 ¼ 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.

- The models should be numerically stable so that they can be applied in both high and low short-circuit systems. The equipment suppliers shall establish the minimum short-circuit ratio and/or system conditions for which the model is applicable for their specific equipment.
- The models should be clearly specified with block diagrams, explanation of non-linear components and equations in the models, and discussion of any unique initialisation issues to allow for any software vendor to implement the models. The standard will not describe the algorithms that are applied in the specific time series simulation tools, but only the linear, non-linear and differential relations that are modelled.
- The generic models will include generic modules for protection and control systems, which will inevitably deviate from specific manufacturer systems. The models should easily be parameterised to represent any manufacturer specific systems, which will be done by definition of distinct modules for protection and control. This modular structure will make it possible to replace the generic control and protection system modules with manufacturer specific modules.
- The generic models enables modelling of different control options depending on the specified control modes and other control parameters. The included set of control options is optional and specified by the manufacturer. For each of the included control option, the manufacturer shall specify the corresponding control parameters.

5.2 Wind turbine models

The WT models in this document have been developed with the following general specifications in mind:

- The specified wind turbine models can either be used in wind power plant models or to represent wind turbines without wind power plant relationships.
- The standard provides a formal specification of a set of generic simulation models covering the vast majority of existing WT types, and a structure to develop models for future WT types.
- The models span at least the existing four categories of currently developed WT technologies: conventional asynchronous generators, variable rotor resistance asynchronous generators, doubly-fed asynchronous generators and full-converter interface WTs.
- From the point of view of power system studies, existing WTs are generally divided into 4 types A-D [15] or 1-4 [16]. Using the NERC nomenclature 1-4, the 4 types have the following characteristics:
  - Type 1: WT with directly grid connected asynchronous generator with fixed rotor resistance (typically squirrel cage).
  - Type 2: WT with directly grid connected asynchronous generator with variable rotor resistance.
  - Type 3: WT with doubly-fed asynchronous generators (directly connected stator and rotor connected through power converter).
  - Type 4: WT connected to the grid through a full size power converter.
- Over/under frequency and over/under voltage protection should be modelled in order to allow a realistic representation of WT disconnection following grid disturbances.
- The turbine-generator inertia and first drive train torsional mode should be taken into account where it can have significant influence on the power swings[11].
- Dynamics of phase-locked loops are not included in the models[12].
- The model should include the reactive power capability of the WT.

---

[11] This is only possible if the eigenfrequency of the first drive train torsional mode is within the bandwidth of the model. However, this is the case for practically all WTs.

[12] Generally, dynamics associated with the PLL are one order of magnitude faster than those of the turbine power controller. The impact of PLL is therefore marginal from a bulk power system studies standpoint.

5.3 Wind power plant models

The WP models in this document have been developed with the following general specifications in mind:

– It is usually sufficient in power system stability studies to use a single aggregated model for all WTs in a WP. It is also possible to simulate a large WP using multiple aggregated models for WTs of the same or of different types. All WT models of the WP shall in this case receive the same reference values from the WP controller.

– The WP controller model measures voltage, frequency, active power and reactive power at the POC and calculates reference signals that are transmitted to the WT models.

– The WP includes two controllers: active power / frequency control and reactive power / voltage control.

– The WP model can control one single POC.

– Reactive power / voltage control is able to regulate power factor, reactive power or voltage. Reactive power and voltage controller models take the limited reactive power capability into account through the limitations in the WT models.

– Power / frequency control regulates active power at the POC as a function of frequency or as a reaction to an external reference change. Active power reference values calculated as a function of the frequency can be absolute (applied to nominal power) or relative (applied to available power). The power control model shall be able to represent the limitations in available power.

– The reactive power / voltage controller and the active power / frequency controller can receive reference values from outside the models as reference changes made by the user.

– Both controllers detect if voltage at POC dips below a threshold value. State variables are frozen if that occurs. Once voltage returns to normal operation band, the controller resumes operation starting from the frozen values or from another specified value.

– Voltage drop compensation shall be provided in the WP model.

– Coordination between WP controllers, OLTC, SVC or other auxiliary controllers at the wind farm level can be implemented in a supervisory controller using the external reference signals to the WP. The modelling of such supervisory controllers is out of the scope of this document.

6 Formal specification of modular structures of models

6.1 General

Clause 6 provides the formal specification of the modular structures of the generic WT, AUX and WP models. This is done in consistency with the functional specifications in Clause 5 and referring to the formal specifications of the modules in Clause 7.

Clause 6 specifies the structure of each generic model using block diagrams. The structure identifies the used modules and input/output variables which are transferred between the modules. The models shall be implemented in a modular way so that each module is available to the user through the input and output variables and the parameters used in each module. Giving access to inputs and outputs from modules makes it possible to use them as part of a modified model, e.g. a manufacturer specific model.

The WT models specified in 6.2 can either be used without an accompanying WP model or as an integral part of the WP model specified in 6.3. In either case, the WT model is intended to be used as an aggregated model representing multiple WTs, but it can also be used to represent a single WT.

6.2 Wind turbine models

6.2.1 General

The objective of 6.2 is to provide a formal specification for a set of generic WT simulation models covering the vast majority of existing WT types, and a generic structure suitable to develop models for future WT types.

This document uses the generic structure of the WT model shown in Figure 2. Whereas the arrows indicated that variables are transferred from one block to another, bold lines are used for the electrical system which will be specified using single line diagrams.

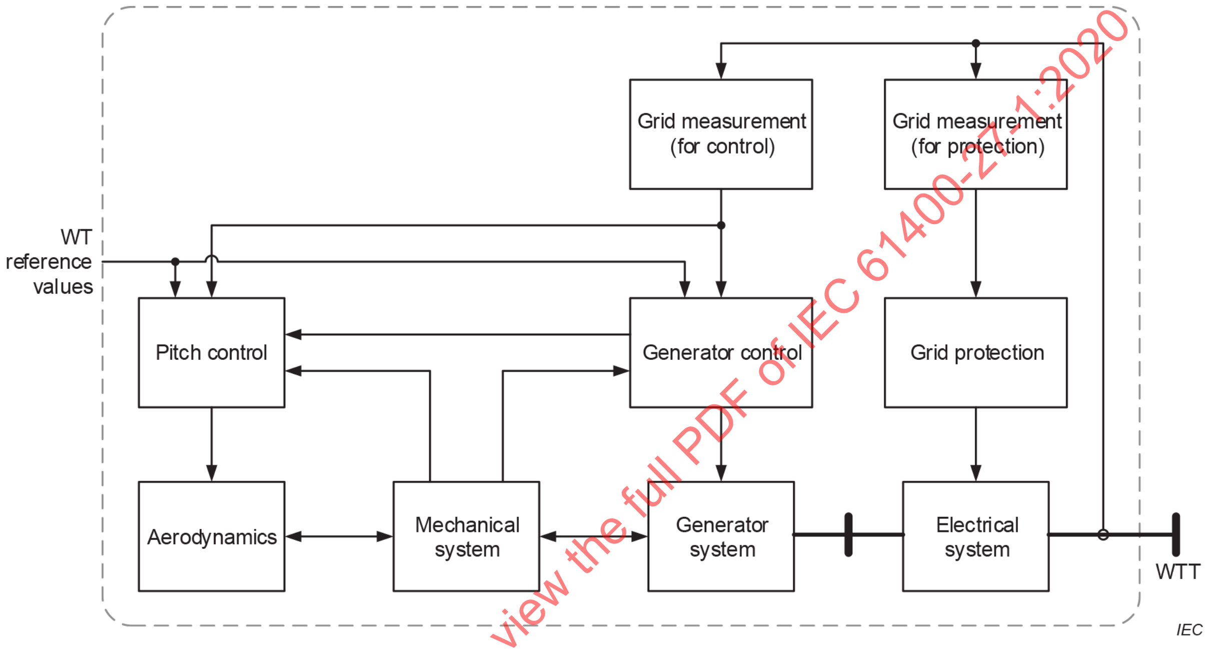


Figure 2 – Generic structure of WT models

The WT model can receive reference values from the WP control system model as in 6.3 or from other sources specified by the model user. The available set of WT reference values is different, depending on the WT type, the WT manufacturer and operation mode. The following reference values are considered in the generic WT models:

– active power reference value,
– reactive power reference value,
– voltage reference value.

Note that the WT models can also simulate power factor control mode, but in that case, it is assumed that the power factor reference value of the WP is constant throughout the simulation.

6.2.2 Type 1

6.2.2.1 Definition of type 1

The 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 not included in the type 1 models.

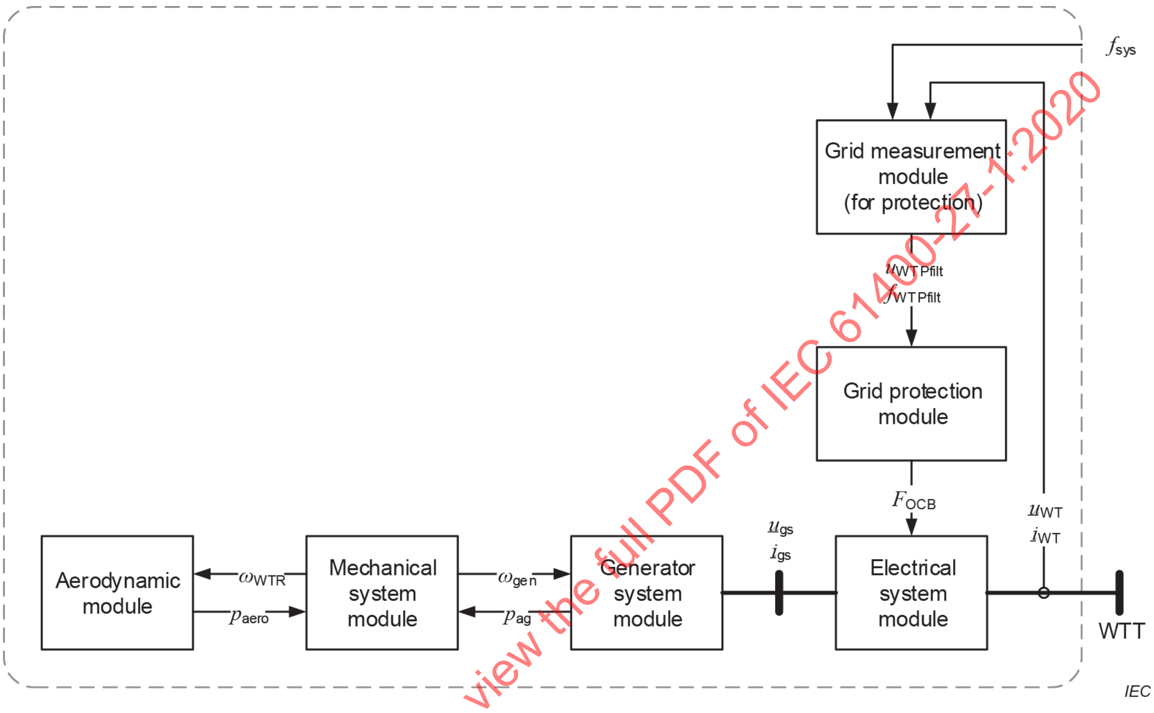
Type 1 WTs may have fixed blade pitch angles or pitch systems allowing the blades to be turned away from stall (positive pitch angle) or into stall (negative pitch angle, also denoted active power control or Combi Stall® power control). Pitch control is in some type 1 WTs used in active UVRT control [17].

Therefore, two type 1 models are specified in 6.2.2.2 and 6.2.2.3:

– Type 1A: WTs with fixed pitch angle,
– Type 1B: WTs with UVRT pitch control.

6.2.2.2 Modular structure of type 1A model

Figure 3 shows the modular structure of the type 1A WT model. This model assumes that the pitch angle is fixed.



NOTE The aerodynamic module is included in the figure, but it only represents a simplistic constant aerodynamics torque.

Figure 3 – Modular structure of the type 1A WT model

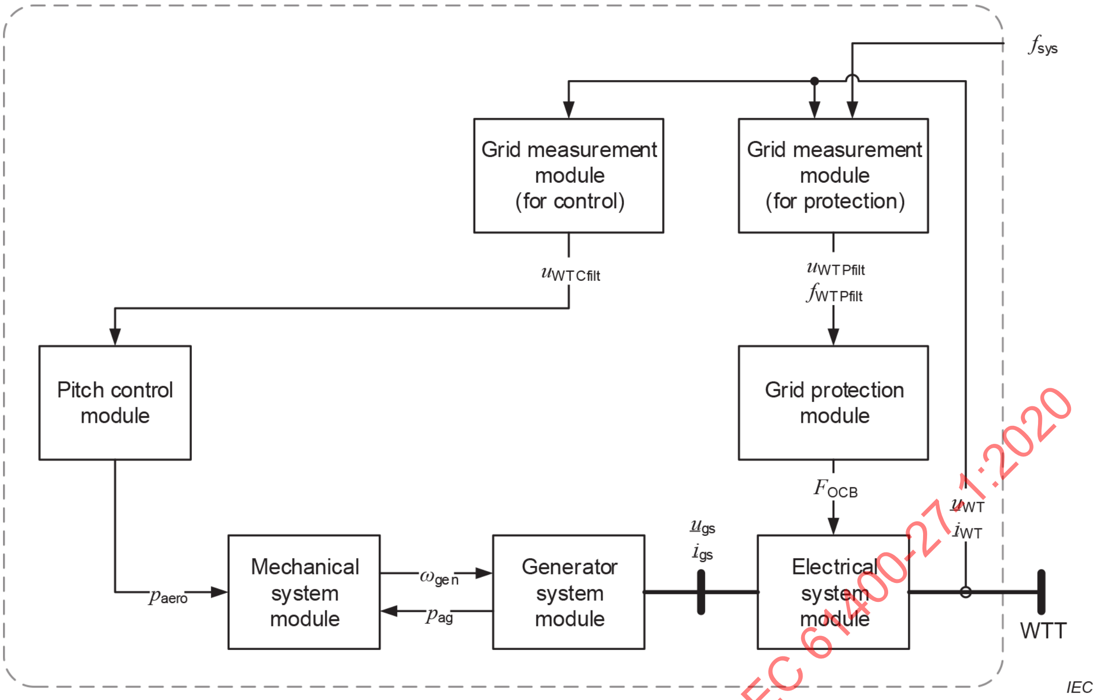
The modules used in the type 1A model are listed in Table 1, including references to the specifications of the modules in Clause 7.

Table 1 – Modules used in type 1A model

Module	Clause number	Clause title
Aerodynamic	7.2.1	"Constant aerodynamic torque "
Mechanical	7.3.1	"Two mass "
Generator system	7.4.1	"Asynchronous generator "
Electrical system	7.5.1	"Electrical systems gamma module"
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "

6.2.2.3 Modular structure of type 1B model

Figure 4 shows the modular structure of the type 1B WT model. This model includes UVRT pitch control.



NOTE The aerodynamic block is not included in the figure because the aerodynamic effects are embedded in the pitch control model.

Figure 4 – Modular structure of the type 1B WT model

The modules used in the type 1B model are listed in Table 2, including references to the specifications of the modules in Clause 7.

Table 2 – Modules used in type 1B model

Module	Clause number	Clause title
Aerodynamic	7.2.1	"Constant aerodynamic torque "
Mechanical	7.3.1	"Two mass "
Generator system	7.4.1	"Asynchronous generator "
Electrical system	7.5.1	"Electrical systems gamma module"
Pitch control	7.6.1	"Pitch control power "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

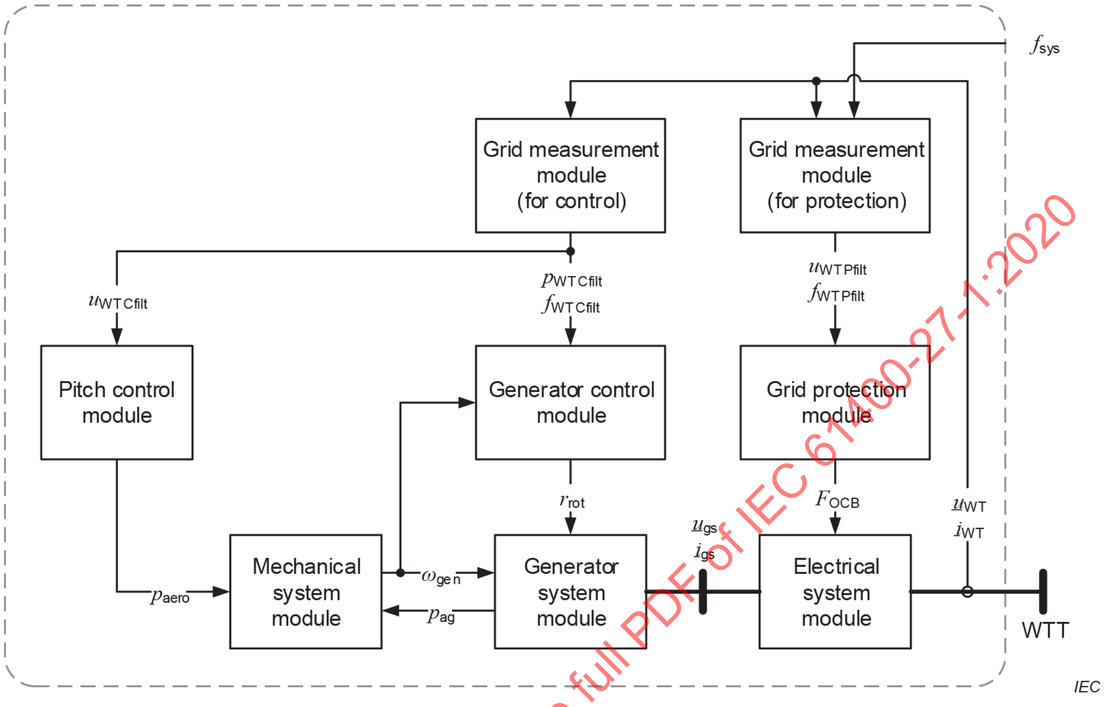
6.2.3 Type 2

6.2.3.1 Definition of type 2

A type 2 WT is similar to a type 1 WT in many aspects, but the type 2 asynchronous generator is equipped with a variable rotor resistance r_{rot}. Type 2 WTs are also normally equipped with pitch control.

6.2.3.2 Modular structure of type 2 model

The type 2 model specified in this document is based on the generic WT models specified by the IEEE / WECC working group and used in the 2nd generation WECC models [18]. The modular structure of the type 2 WT model is shown in Figure 5.



NOTE The aerodynamic block is not included in the figure because the aerodynamic effects are embedded in the pitch control model.

Figure 5 – Modular structure of the type 2 WT model

The modules used in the type 2 model are listed in Table 3, including references to the specifications of the modules in Clause 7.

Table 3 – Modules used in type 2 model

Module	**Clause number**	**Clause title**
Mechanical	7.3.1	"Two mass "
Generator system	7.4.1	"Asynchronous generator "
Electrical system	7.5.1	"Electrical systems gamma module"
Pitch control	7.6.1	"Pitch control power "
Generator control	7.7.1	"Rotor resistance control "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

6.2.4 Type 3

6.2.4.1 Definition of type 3

A type 3 WTs uses a doubly fed asynchronous generator, where the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter. Some type 3 WTs includes either a chopper or a crowbar for voltage ride-through without bypassing or disconnecting the converter. Type 3A model specified below represents type 3 wind turbines without crowbar while type 3B model represents type 3 wind turbines with crowbar.

6.2.4.2 Modular structure of type 3A and type 3B models

The generic type 3 model specified in this clause includes modules for the mechanical system as well as the aerodynamics. This level of detail is not always needed. In some cases, one of the generic type 4 models will be sufficient to simulate the behaviour at the WT terminals.

The modular structure of the type 3A and type 3B WT model is shown in Figure 6.

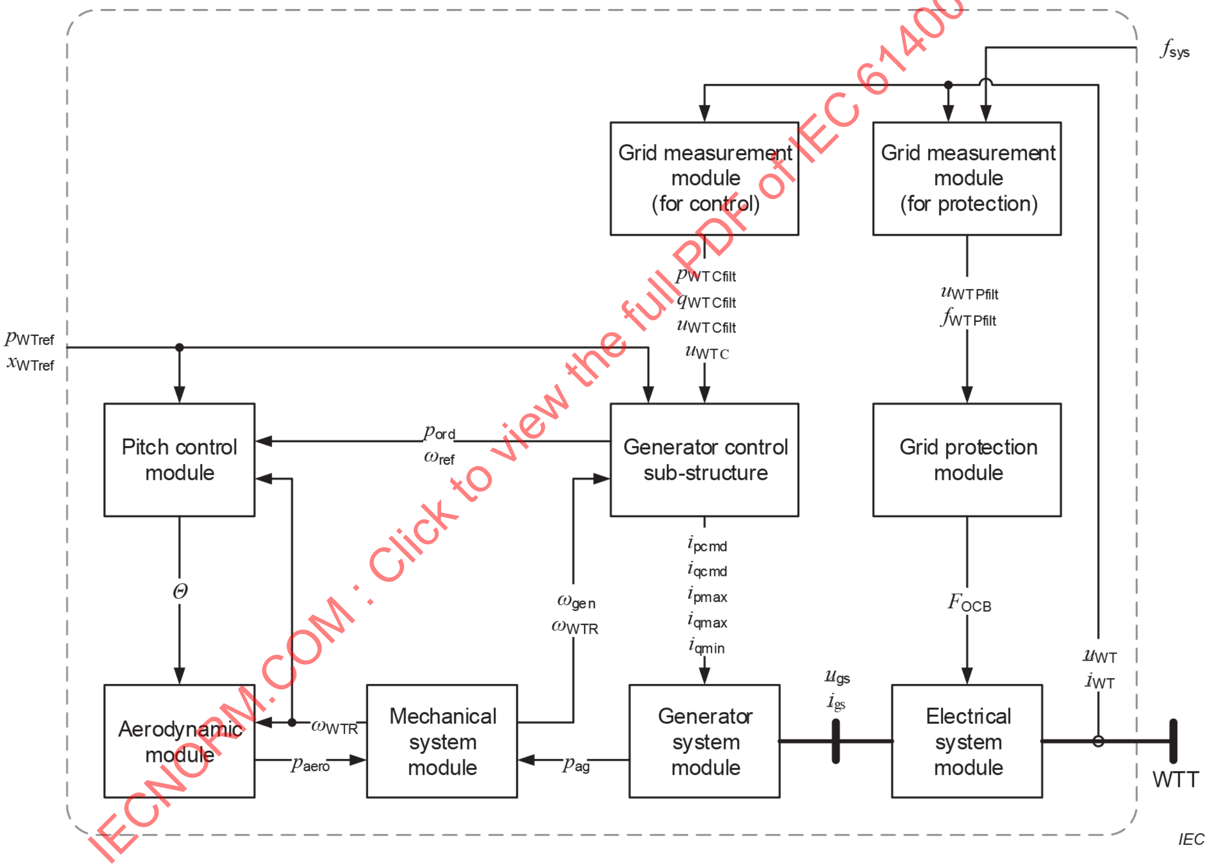


Figure 6 – Modular structure of the type 3A and type 3B WT models

Figure 7 shows the modular structure of the type 3 generator control models.

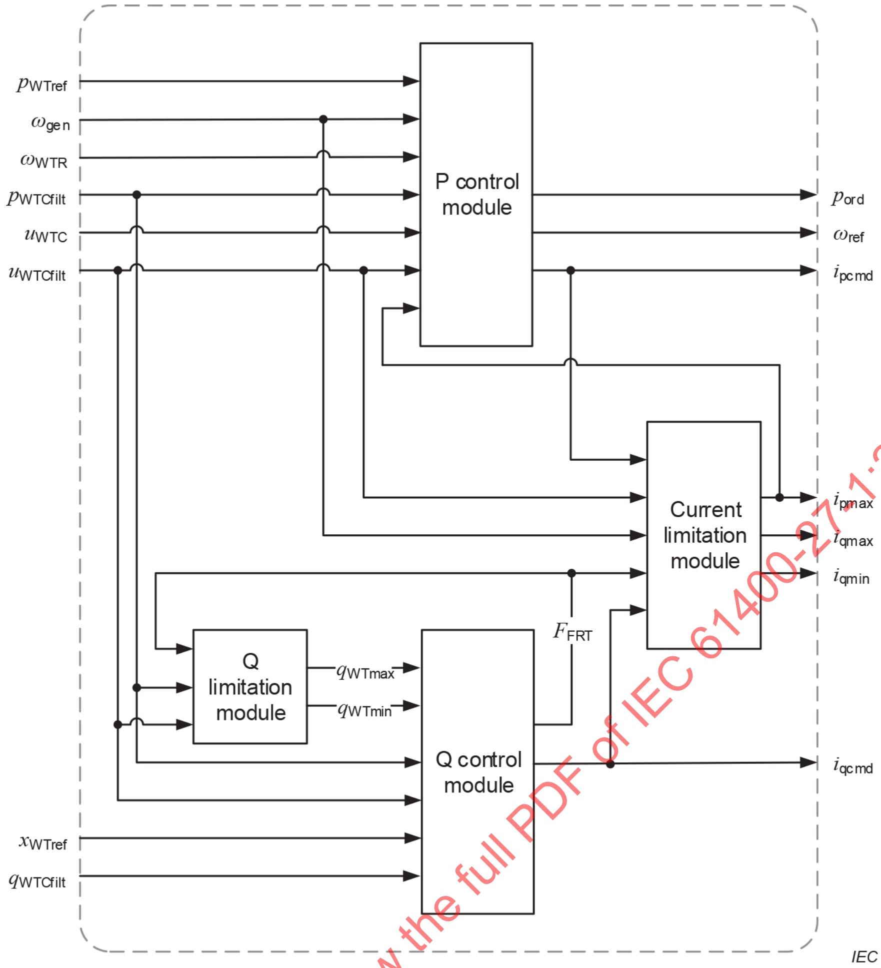


Figure 7 – Modular generator control sub-structure of the type 3A and type 3B models

The modules used in the type 3A model are listed in Table 4, including references to the specifications of the modules in Clause 7.

Table 4 – Modules used in type 3A model

Module	Clause number	Clause title
Aerodynamic	7.2.3 or 7.2.2	"Two-dimensional aerodynamic " or "One-dimensional aerodynamic "
Mechanical	7.3.1	"Two mass "
Generator system	7.4.2 or 7.4.3	"Type 3A generator system "
Electrical systems	7.5.1	"Electrical systems gamma module"
Pitch control	7.6.2	"Pitch angle control "
P control	7.7.2	"P control module type 3"
Q control	7.7.5	"Q control "
Current limitation	7.7.6	"Current limitation "
Q limitation	7.7.7 or 7.7.8	"Constant Q limitation " or "QP and QU limitation "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

The modules used in the type 3B model are listed in Table 5, including references to the specifications of the modules in Clause 7.

Table 5 – Modules used in type 3B model

Module	Clause number	Clause title
Aerodynamic	7.2.3 or 7.2.2	"Two-dimensional aerodynamic " or "One-dimensional aerodynamic "
Mechanical	7.3.1	"Two mass "
Generator system	7.4.2 or 7.4.3	"Type 3B generator system "
Electrical systems	7.5.1	"Electrical systems gamma module"
Pitch control	7.6.2	"Pitch angle control "
P control	7.7.2	"P control module type 3"
Q control	7.7.5	"Q control "
Current limitation	7.7.6	"Current limitation "
Q limitation	7.7.7 or 7.7.8	"Constant Q limitation " or "QP and QU limitation "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

6.2.5 Type 4

6.2.5.1 Definition of type 4

Type 4 WTs are WTs connected to the grid through a full scale power converter. Type 4 WTs use either synchronous generators or asynchronous generators. Some type 4 WTs use direct drive synchronous generators, and therefore have no gearbox.

Type 4 WTs with choppers on the converter DC link can normally be modelled neglecting the aerodynamic and mechanical parts of the WT. Type 4 WTs without choppers inject post-fault power oscillations due to damping of torsional oscillations. This is also the case for type 4 WTs with partially rated choppers. These oscillations are normally not affecting the power system stability, but the effect of torsional oscillation damping may be included using a two-mass mechanical model. If partially rated chopper is applied, then the damping coefficient in the two-mass model can be adjusted to match the rating of the chopper. The type 3A model may be used to simulate type 4 WTs, but simplified models are usually sufficient because of the converter decoupling of the drive train from the grid.

Therefore, two type 4 models are specified in 6.2.5.2 and 6.2.5.3:

– Type 4A: a model neglecting the aerodynamic and mechanical parts and thus not simulating any power oscillations,[13]

– Type 4B: a model including a 2-mass mechanical model to replicate the power oscillations but assuming constant aerodynamic torque.

[13] Neglecting the aerodynamic and mechanical parts, the type 4A model may also be applied to model PV plants.

6.2.5.2 Modular structure of type 4A model

The modular structure of the type 4A WT model is shown in Figure 8.

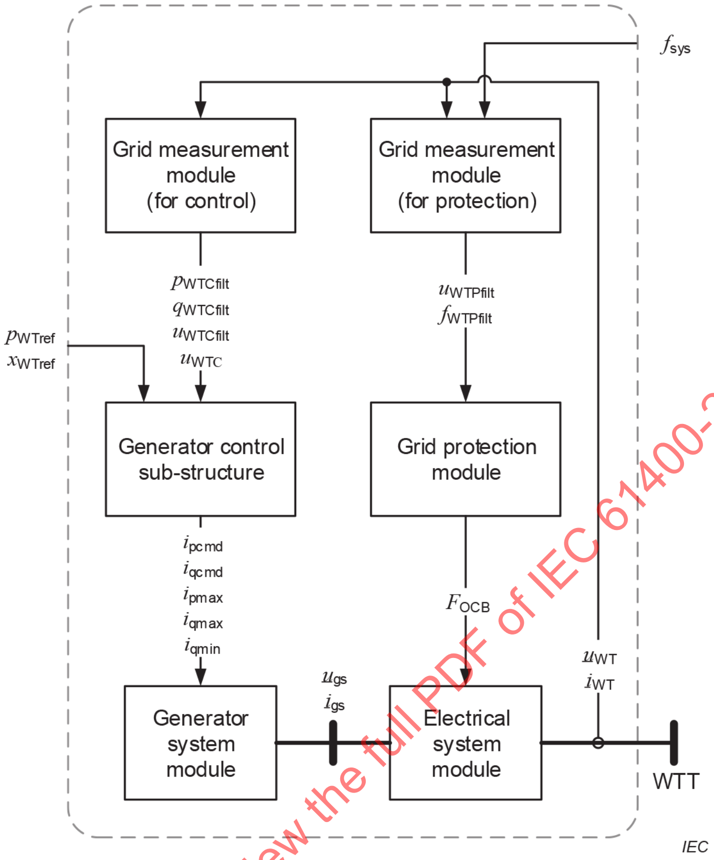


Figure 8 – Modular structure of the type 4A WT model

Figure 9 shows the modular structure of the type 4A generator control models.

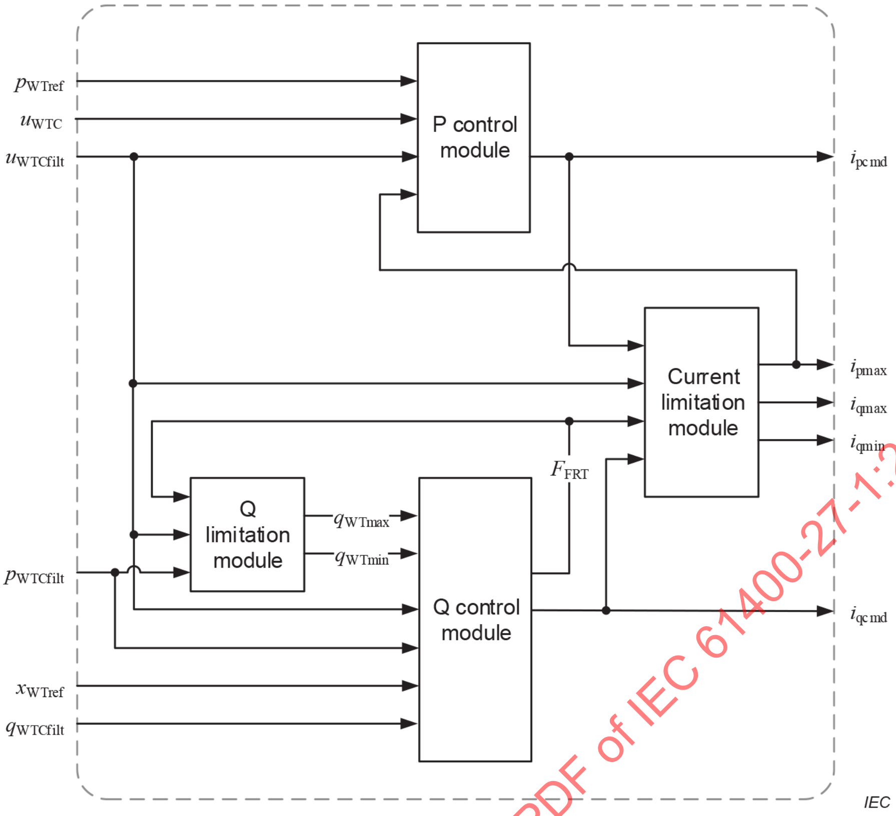


Figure 9 – Modular generator control sub-structure of the type 4A model

The modules used in the type 4A model are listed in Table 6, including references to the specifications of the modules in Clause 7.

Table 6 – Modules used in type 4A model

Module	Clause number	Clause title
Generator system	7.4.4 or 7.4.2	"Type 4 generator system " or "Type 3A generator system "[a]
Electrical system	7.5.1	"Electrical systems gamma module"
P control	7.7.3	"P control module type 4A"
Q control	7.7.5	"Q control "
Current limitation	7.7.6	"Current limitation "
Q limitation	7.7.7 or 7.7.8	"Constant Q limitation " or "QP and QU limitation "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

[a] The Type 3A generator system can be used in type 4 WT models, which will mitigate the reactive power spike appearing when the voltage recovers. This spike is mainly caused by numerical effects in the simulations.

6.2.5.3 Modular structure of type 4B model

The modular structure of the generic type 4B WT model is shown in Figure 10.

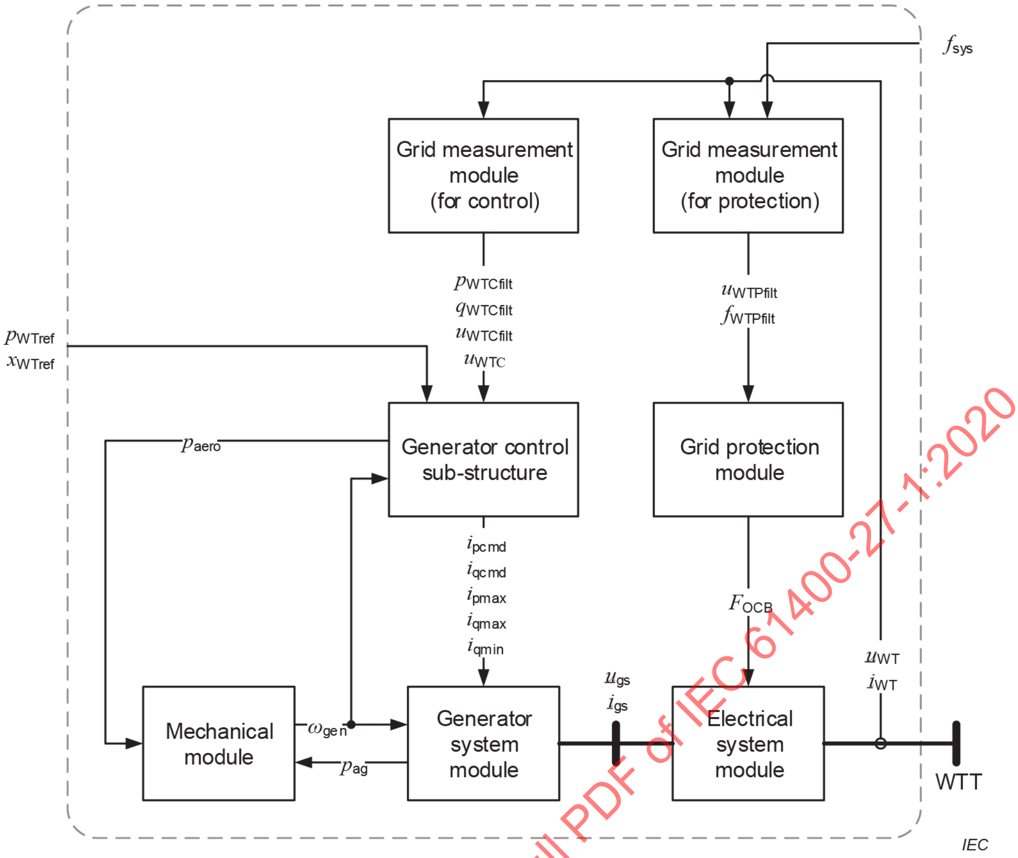


Figure 10 – Modular structure of the type 4B WT model

Figure 11 shows the modular structure of the type 4B generator control models.

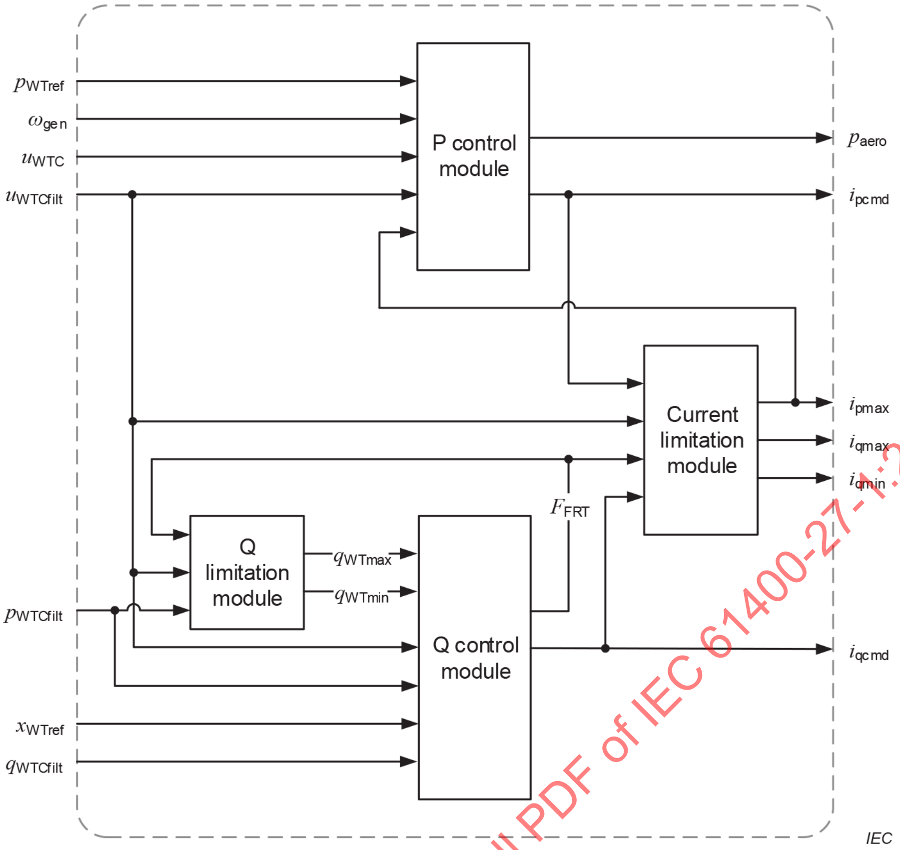


Figure 11 – Modular generator control sub-structure of the type 4B model

The modules used in the type 4B model are listed in Table 7, including references to the specifications of the modules in Clause 7.

Table 7 – Modules used in type 4B model

Module	Clause number	Clause title
Mechanical	7.3.1	"Two mass "
Generator system	7.4.4 or 7.4.2	"Type 4 generator system " or "Type 3A generator system " [a]
Electrical systems module	7.5.1	"Electrical systems gamma module"
P control	7.7.4	"P control module type 4B"
Q control	7.7.5	"Q control "
Current limitation	7.7.6	"Current limitation "
Q limitation	7.7.7 or 7.7.8	"Constant Q limitation " or "QP and QU limitation "
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

[a] The Type 3A generator system can be used in type 4 WT models, which will remove the reactive power spike appearing when the voltage recovers. This spike is mainly caused by numerical effects in the simulations.

6.3 Auxiliary equipment models

6.3.1 STATCOM

The modular structure of the STATCOM model is shown in Figure 12.

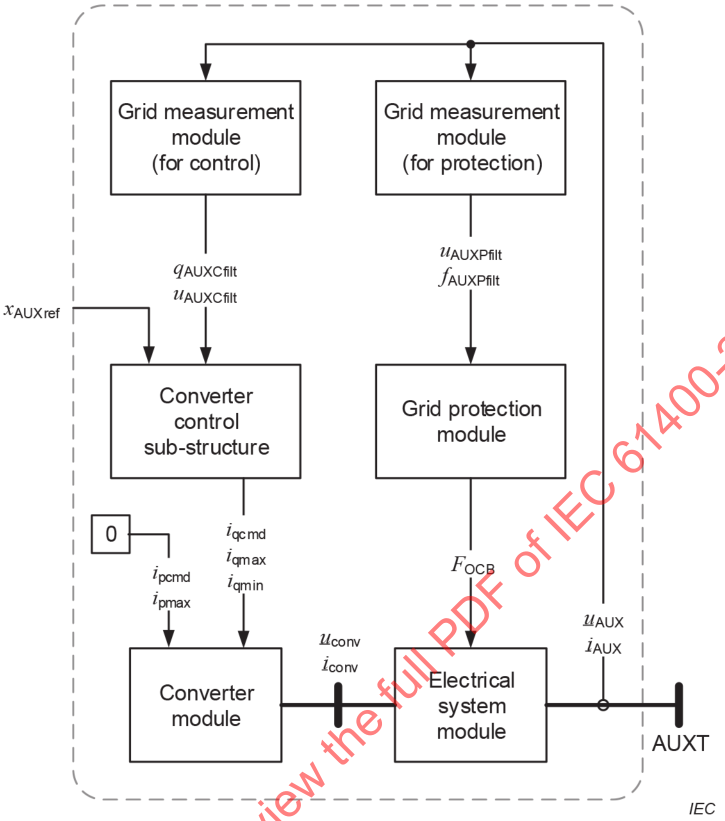


Figure 12 – Modular structure of STATCOM model

Figure 13 shows the modular structure of the STATCOM control models.

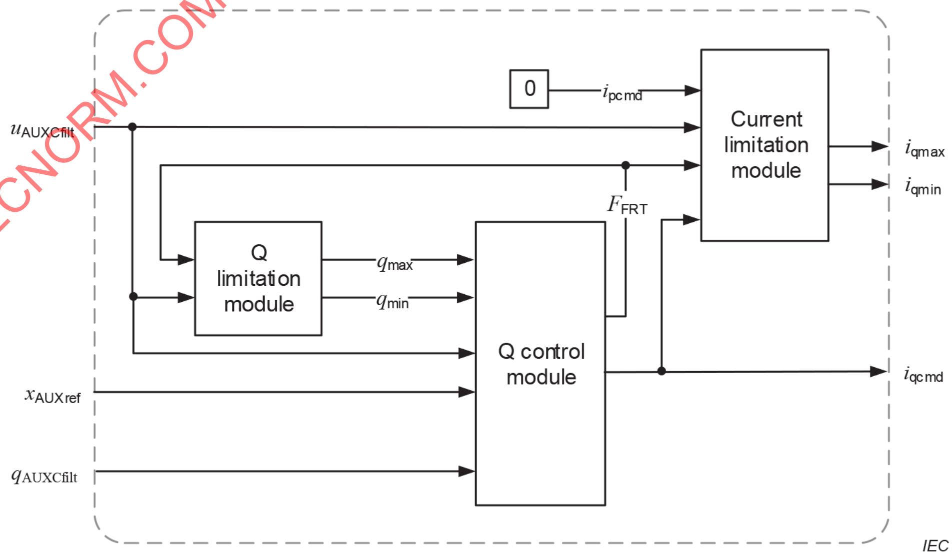


Figure 13 – Modular structure of the STATCOM control model

The modules used in the STATCOM model are listed in Table 8, including references to the specifications of the modules in Clause 7.

Table 8 – Modules used in STATCOM model

Module	Clause number	Clause title
Converter	7.4.4	"Type 4 generator system module"
Electrical system	7.5.1	"Electrical systems gamma module"
Q control	7.7.5	"Q control module" [a]
Current limitation	7.7.6	"Current limitation module"
Q limitation	7.7.7	"Constant Q limitation module"
Grid protection	7.8.1	"Grid protection module"
Grid measurement (for protection)	7.8.2	"Grid measurement "
Grid measurement (for control)	7.8.2	"Grid measurement "

[a] Note that the STATCOM model cannot use the power factor control modes M_{qG} = 3 and M_{qG} = 4 in the Q control module.

6.3.2 Other auxiliary equipment

Several other types of auxiliary equipment can be used in WPs:

– Shunt reactors which are often used in WPs to compensate reactive power injection,
– SVCs used for dynamic voltage control.

This document does not specify models for any of those types of auxiliary equipment. Standard models specified in IEC 61970-301 and IEC 61970-302 should be used if available. Alternatively, build in models in a chosen simulation tool can be used.

6.4 Wind power plant models

6.4.1 General

Wind power plants are wind farms with plant level control and communication [19], [20], and possible auxiliary equipment. The general structure of the WP model is illustrated in Figure 14. The power collection system model is implemented as part of the grid model. The PD (WT or AUX) models are connected to the power collection system model. Each PD model may receive reference values from the WP control and communication model.

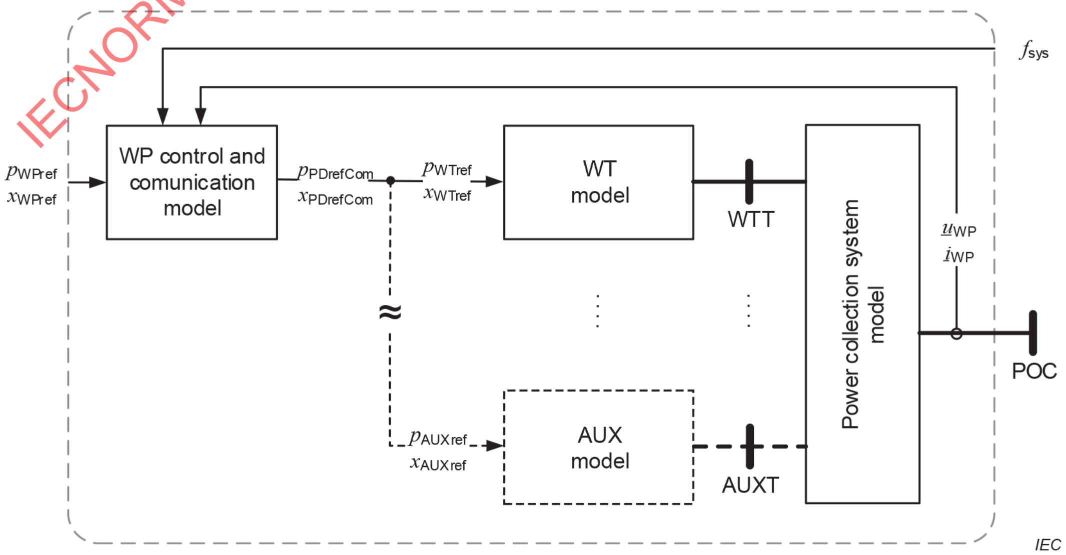


Figure 14 – General structure of WP model

The WP model can either be excited by an event in the grid model such as a short-circuit, or by a change in a WP reference value.

The WP model interacts with the grid in the POC of the WP. In some cases, different parts of a wind plant are connected to different points, e.g. to the primary side of parallel transformers. In such cases, a single POC should be defined in the model using a jumper, i.e. by joining the different points using connector(s) with zero impedance.

The WP model provides the reference values p_{PDref} and x_{PDref} to the WT/PD model(s) and interacts with the WT/PD model(s) at the individual WT/PD terminals.

The WP model can receive reference values p_{WPref} and x_{WPref} from sources specified by the model user. The available set of WP reference values is different, depending on the WP type, the WP manufacturer and operation mode. The following reference values are considered in the generic WP models:

– active power reference value,
– reactive power reference value,
– power factor value,
– voltage reference value.

Finally, the WP model can receive a system frequency from the power system simulation model providing the deviations from nominal frequency.

6.4.2 Wind power plant control and communication

Figure 15 shows the modular structure of the WP control and communication model.

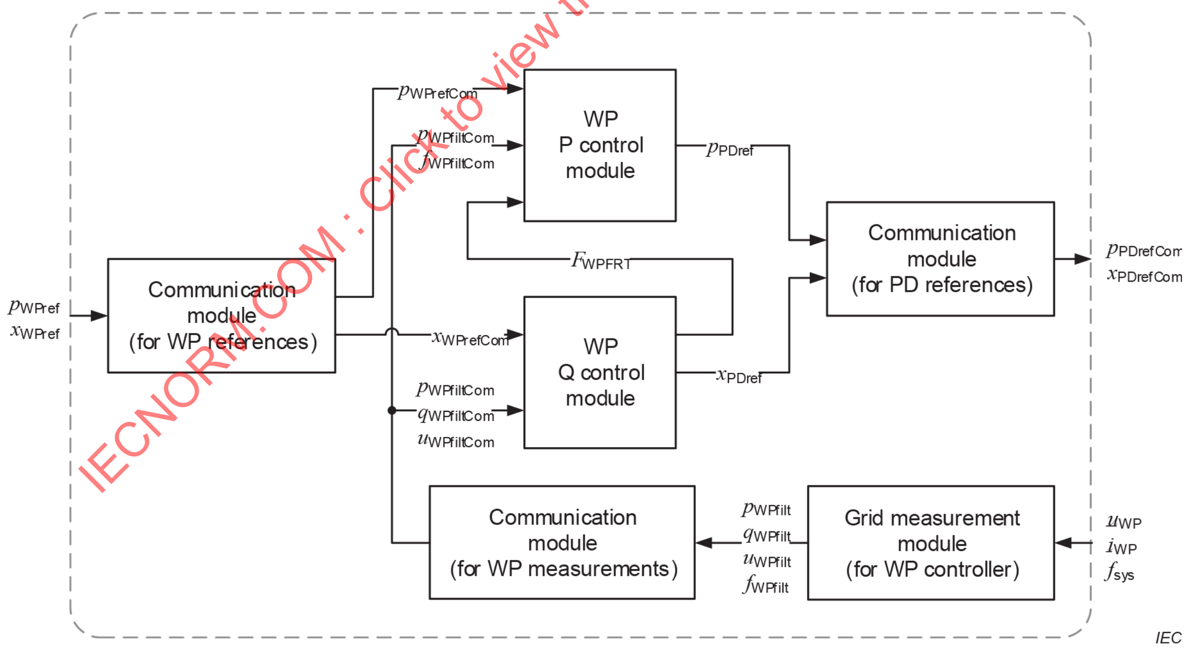


Figure 15 – General modular structure of WP control and communication block

Table 9 – Modules used in WP control and communication model

Block	Clause number	Clause title
WP P control	7.9.1	"WP P control "
WP Q control	7.9.2	"WP Q control "
Communication (for WP measurements)	7.10.2 or 7.10.3	"Communication delay " or "Linear communication " [a]
Communication (for WP references)	7.10.2 or 7.10.3	"Communication delay " or "Linear communication " [a]
Communication (for PD references)	7.10.2 or 7.10.3	"Communication delay " or "Linear communication " [a]
Grid measurement model (for WP controller)	7.8.2	"Grid measurement "

[a] The "Communication delay " should be applied for model validation purposes, but since delays may cause convergence problems in simulations of large power systems, the "Linear communication " may be used as an alternative in such cases.

The WP power collection system model is implemented as part of the grid model. It consists of standard models for the main grid components, i.e. transformers, cables and overhead lines. The power collection system model could be detailed including all the main grid components, but usually an aggregated model is used as described in Annex A.

6.4.3 Basic wind power plant

The simplest aggregated WP model is the basic model characterised by the single line diagram in Figure 16. This model is usually sufficient if the WP consists of one type of WTs and has no AUX.

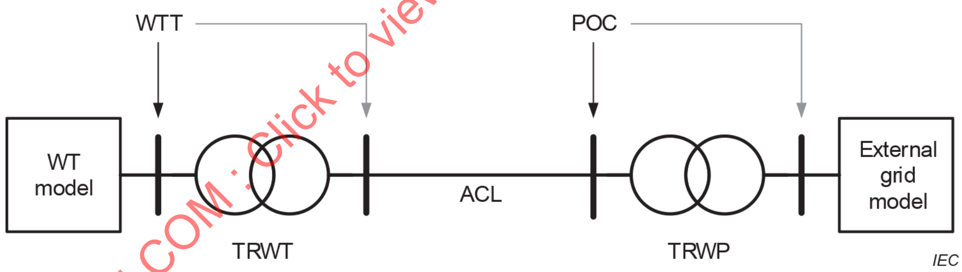


Figure 16 – Single line diagram for basic WP model

The models and additional modules used in the basic WP model are listed in Table 10, including references to the specifications of the modules in Clause 7.

Table 10 – Models and additional modules used in the basic WP model

Model / module	Clause number	Clause title
WT	6.2.4.2 or 6.2.5.2 or 6.2.5.3	"Modular structure of type 3A and type 3B models" or "Modular structure of type 4A model" or "Modular structure of type 4B model"
WP control and communication model	6.4.2	"Wind power plant control and communication"
WT transformer (TRWT) [a]	7.11.2	"Transformer "
Aggregated collector line (ACL)	7.11.1	"Line "
WP transformer (TRWP)	7.11.2	"Transformer "

[a] The WT transformer may be included in the WT electrical system model. In that case, it should not be duplicated as part of the power collection system.

6.4.4 Wind power plant with reactive power compensation

If the WP includes an AUX device, shunt capacitor and/or shunt reactor, then the power collection system model in Figure 17 is usually sufficient.

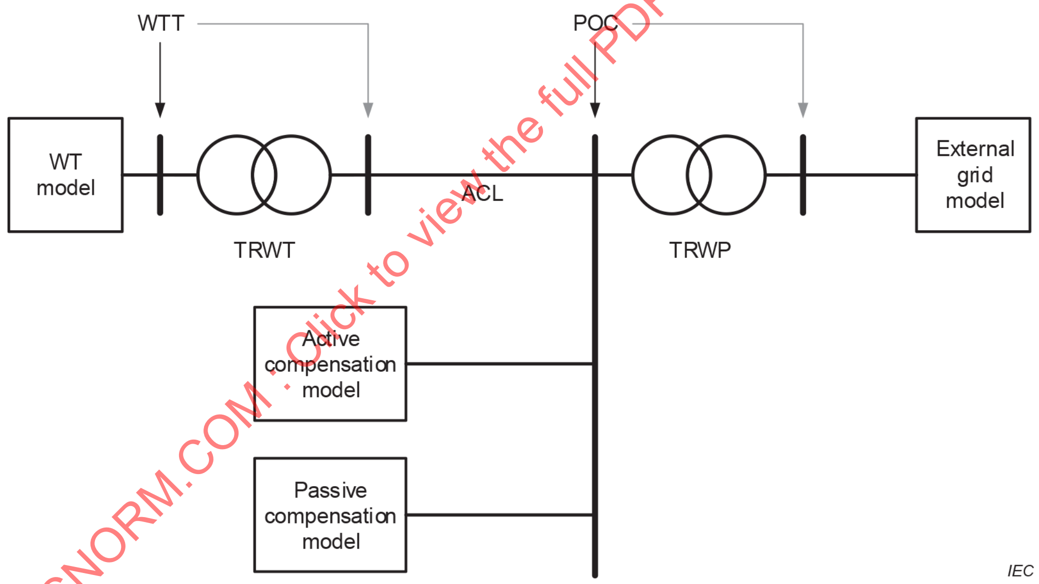


Figure 17 – Single line diagram for WP model with reactive power compensation

The models and additional modules used in the WP model with reactive power compensation are listed in Table 11, including references to the specifications of the modules in Clause 7.

Table 11 – Models and modules used in the WP model with reactive power compensation

Model / module	Clause number	Clause title
WT	6.2.4.2 or 6.2.5.2 or 6.2.5.3	"Modular structure of type 3A and type 3B models" or "Modular structure of type 4A model" or "Modular structure of type 4B model"
WP control and communication model	6.4.2	"Wind power plant control and communication"
Active compensation model	6.3.1 or 7.11.3	"STATCOM" or "Other electrical components "
Passive compensation model	7.11.3	"Other electrical components "
WT transformer (TRWT) [a]	7.11.2	"Transformer "
Aggregated collector line (ACL)	7.11.1	"Line "
WP transformer (TRWP)	7.11.2	"Transformer "

[a] The WT transformer may be included in the WT electrical system model. In that case, it should not be duplicated as part of the power collection system.

Depending on the number of WT types, AUX devices and the size of the power collection system, it may be relevant to use a more detailed model.

7 Formal specification of modules

7.1 General

Clause 7 provides the formal specification for the modules used by the WP and WT models specified in Clause 6.

Each module is specified in a figure. For most of the modules, the specifications are provided as block diagrams, but single line diagrams are also used for the electrical parts. The block diagrams use the symbols specified in Annex D.

The specification of the module is marked by a dashed frame in the figure, and all input variables to the module and all output variables from the module are drawn to this frame and the symbol for each input and output variable is given outside the frame.

For each of the modules, parameter lists are provided. Together with the global parameters listed in Table 12, those parameter lists include all the parameters which are needed to complete the model specification. The generic models shall be implemented so that the user can specify all parameters in the list.

Table 12 – Global model parameters

Symbol	Base unit	Description
f_n	Hz	Nominal frequency
T_s	s	Integration time step

The values for the module parameters are not specified in this document. The WT manufacturer and WP developer shall provide those parameters to complete the module specification. Manufacturer may provide different parameters sets for different control modes.

Each module parameter is categorised as either "Type", "Project" or "Use case" parameter. The category of each parameter is stated in the tables of parameters.

The three parameter categories are defined as follows:

– Type parameters are characteristic to the specific WT or WP type. This is typically the case for mechanical and electrical parameters.
– Project parameters are characteristic to the specific WP project, and may be different for a specific WT or WP type, depending on the specific project. This is typically the case for control parameters set according to specific grid code requirements.
– Use case parameters are characteristic to the specific simulation use case, and may vary depending on the specific steady state prior to the disturbance, e.g. depending on if the actual and/or possible power is nominal or partial. It is the responsibility of the WT manufacturer and WP developer to specify the application range of the provided use case parameters.

The WT manufacturer or WP developer may upgrade the category of a specific parameter whenever this is valid to the specific WT or WP type.

Each module parameter has a text name which is intended for software implementation. The text names are based on the parameter symbols but excludes subscripts, greek letters and other special characters so they can be used as parameter names in software implementation.

Some of the block diagrams include initialisation variables. Table 13 lists the initialisation variables which are included in the module block diagrams. Those variables shall be initialised by the load flow, and therefore they should not be specified as parameters.

Table 13 – Initialisation variable used in module block diagrams

Symbol	Base unit	Description
p_{init}	S_{base}	Initial power
τ_{init}	$\mathrm{T}_{\mathrm{base}}$	Initial torque
φ_{init}	deg	Initial phase angle

Some of the modules include hooks which are not used in the generic models specified in Clause 6. A hook is either an input to or an output from the module. An input hook shall be set to zero if it is not connected. If one or more hooks are used to extend the generic models specified in IEC 61400-27-1, the models are no longer generic and cannot be represented in CIM dynamics standard IEC 61970-302.

7.2 Aerodynamic modules

7.2.1 Constant aerodynamic torque module

The block diagram for the constant aerodynamic module is shown in Figure 18. The module requires no manufacturer supplied parameters. The initial torque τ_{init} shall be set by the load-flow.

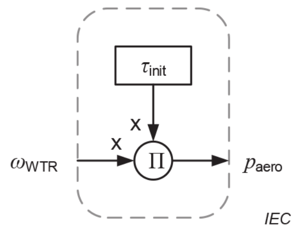


Figure 18 – Block diagram for constant aerodynamic torque module

7.2.2 One-dimensional aerodynamic module

This aerodynamic module corresponds to the one-dimensional model proposed in [21]. It includes the dependency on the pitch angle, but neglects the dependency on the rotor speed. The one-dimensional aerodynamic module parameters are given in Table 14, and the block diagram is given in Figure 19. The initial power p_{init} shall be set by the load-flow.

Table 14 – Parameter list for one-dimensional aerodynamic module

Symbol	Base unit	Description	Category	Text name
Θ_{w0}	deg	Initial pitch angle	Use case	Thetaw0
k_a	S_{base} / deg^2	Aerodynamic gain	Type	ka

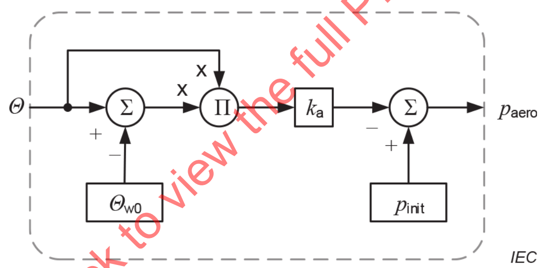


Figure 19 – Block diagram for one-dimensional aerodynamic module

7.2.3 Two-dimensional aerodynamic module

The two-dimensional aerodynamic module corresponds to the model proposed in [22]. The two-dimensional aerodynamic module parameters are given in Table 15, and the block diagram is given in Figure 20.

Table 15 – Parameter list for two-dimensional aerodynamic module

Symbol	Base unit	Description	Category	Text name
p_{avail}	S_{basey}	Available power [a]	Use case	Pavail
Θ_0	Deg	Pitch angle if the WT is not derated [b]	Use case	Theta0
ω_0	Ω_{base}	Rotor speed if the WT is not derated	Use case	omega0
dp_{Θ}	S_{base} / deg	Partial derivative of aerodynamic power with respect to changes in pitch angle [c]	Use case	dpTheta
$dp_{\omega 0}$	S_{base} / Ω_{base}	Constant term of partial derivative of aerodynamic power with respect to changes in WTR speed	Use case	dpomega0
$dp_{\omega\Theta}$	S_{base} / Ω_{base} / deg	Pitch dependent term of partial derivative of aerodynamic power with respect to changes in WTR speed	Type	dpomegaTheta

a The available power allows modelling of derated operation for the integration with wind power plant power controller in order to allow the WT to increase active power if there is enough available power. The aerodynamic power cannot be greater than p_{avail}.

b The pitch angle should normally be zero for p_{avail} <1 and greater than zero if p_{avail} = 1 or if the initial value of p_{aero} is less that p_{avail}.

c The partial derivative dp_{Θ} is usually negative.

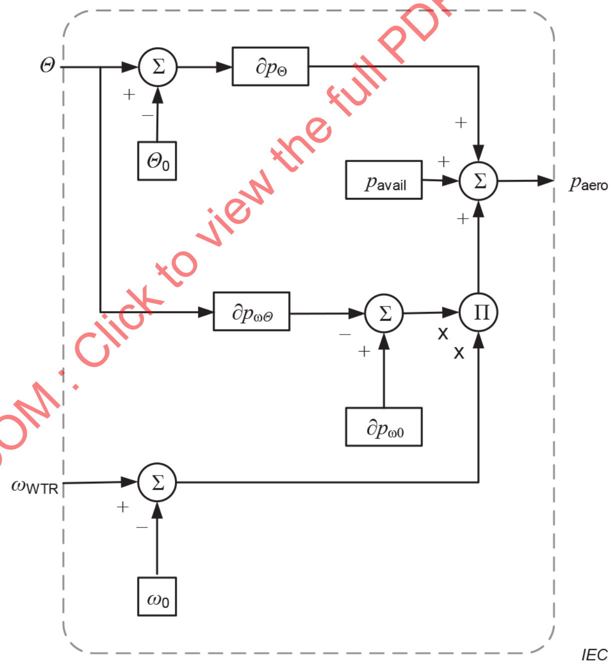


Figure 20 – Block diagram for two-dimensional aerodynamic module

Annex B describes the background for the two-dimensional aerodynamic module, including a guideline to the WT manufacturer for determination of the case dependent module parameters and for the software vendor how to calculate the initialisation if the necessary parameters are provided by the manufacturer.

7.3 Mechanical modules

7.3.1 Two mass module

The module parameters are given in Table 16, and the block diagram is given in Figure 21.[14]

Table 16 – Parameter list for two-mass module

Symbol	Base unit	Description	Category	Text name
H_{WTR}	s	Inertia time constant[a] of WT rotor	Type	HWTR
H_{gen}	s	Inertia time constant[a] of generator	Type	Hgen
k_{drt}	T_{base}	Drive train stiffness	Type	kdtr
c_{drt}	$T_{\text{base}}/\Omega_{\text{base}}$	Drive train damping	Type	cdtr

[a] The inertia constant H is defined as $H = \frac{1}{2} J \frac{\Omega_{\text{base}}^2}{P_{\text{WTn}}}$.

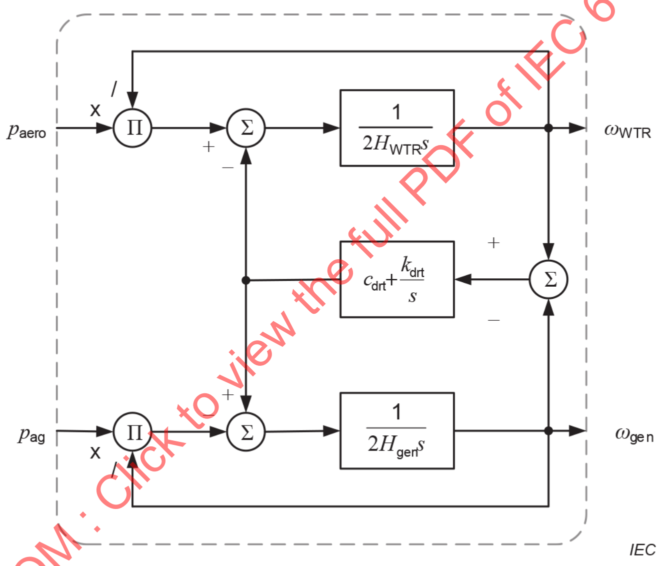


Figure 21 – Block diagram for two mass module

7.3.2 Other mechanical modules

One and three mass modules have been proposed in literature. However, this document does not specify other generic mechanical modules.

7.4 Generator and converter system modules

7.4.1 Asynchronous generator module

This document does not specify a module for the asynchronous generator. A standard asynchronous machine module specified in IEC 61970-301 and IEC 61970-302 should be used. Alternatively, a build in asynchronous generator module in a chosen simulation tool can be used.

---

[14] Some software tools include the generator inertia in the built-in generator model. In this case, the additional mechanical model should interface with the generator shaft instead of the generator air gap, and consequently not include the generator inertia. The complete mechanical model will then still be a two mass model as described in 7.3.1.

7.4.2 Type 3A generator system module

The module parameters are given in Table 17, and the block diagram is given in Figure 22 (for background information see [22], [23]). The output of the generator module is a current, injected through a current source. However, in some power system simulation software, the current source needs a parallel impedance to improve the convergence behaviour of the simulation as suggested in [23] and described in Annex C.

The losses in the generator system are neglected setting the generator air gap power p_{ag} equal to the WT terminal power.

Table 17 – Parameter list for type 3A generator system module

Symbol	Base unit	Description	Category	Text name
K_{Pc}	-	Current PI controller proportional gain	Type	KPc
T_{Ic}	s	Current PI controller integration time constant	Type	TIc
x_{eqv}	Z_{base}	Transient reactance [a]	Type	xeqv
di_{pmax}	I_{base}/s	Maximum active current ramp rate	Project	dipmax
di_{qmax}	I_{base}/s	Maximum reactive current ramp rate	Project	diqmax

[a] The transient reactance should be calculated from the transient inductance as defined in [23].

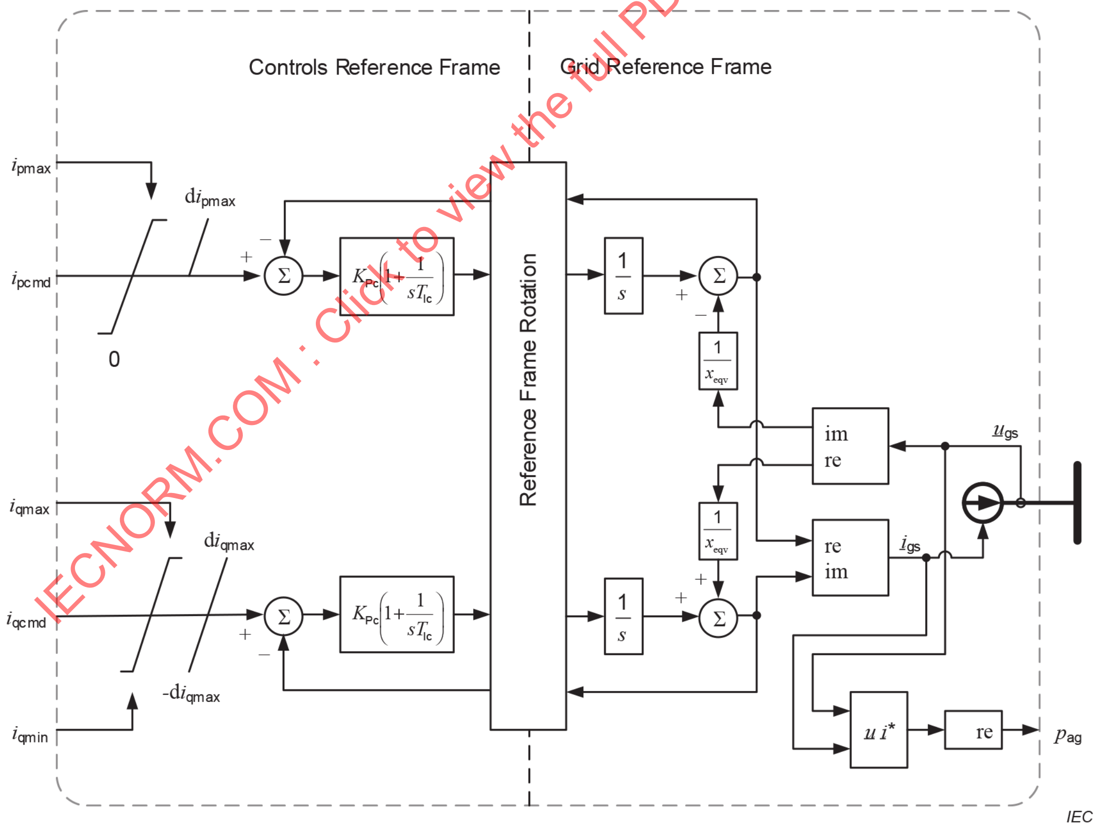


Figure 22 – Block diagram for type 3A generator system module

7.4.3 Type 3B generator system module

The module parameters are given in Table 18, and the block diagram is given in Figure 23. This type 3B generator system module is the state-of-the-art simplification of the 3A generator system module with addition of a crowbar model [24]. The output of the generator module is a current, injected through a current source. However, in some power system simulation software, the current source needs a parallel impedance to improve the convergence behaviour of the simulation as suggested in [23] and described in Annex C.

Table 18 – Parameter list for type 3B generator system module

Symbol	Base unit	Description	Category	Text name
T_g	s	Current generation time constant	Type	Tg
di_{pmax}	I_{base}/s	Maximum active current ramp rate	Project	dipmax
di_{qmax}	I_{base}/s	Maximum reactive current ramp rate	Project	diqmax
x_{eqv}	Z_{base}	Transient reactance	Type	xeqv
$T_{CRB}(du)$	s(U_{base})	Crowbar duration versus voltage variation look-up table	Use case	TCRB(duTCRB)
T_{wo}	s	Time constant for crowbar washout filter	Use case	Two
M_{CRB}	-	Crowbar control mode	Use case	MCRB

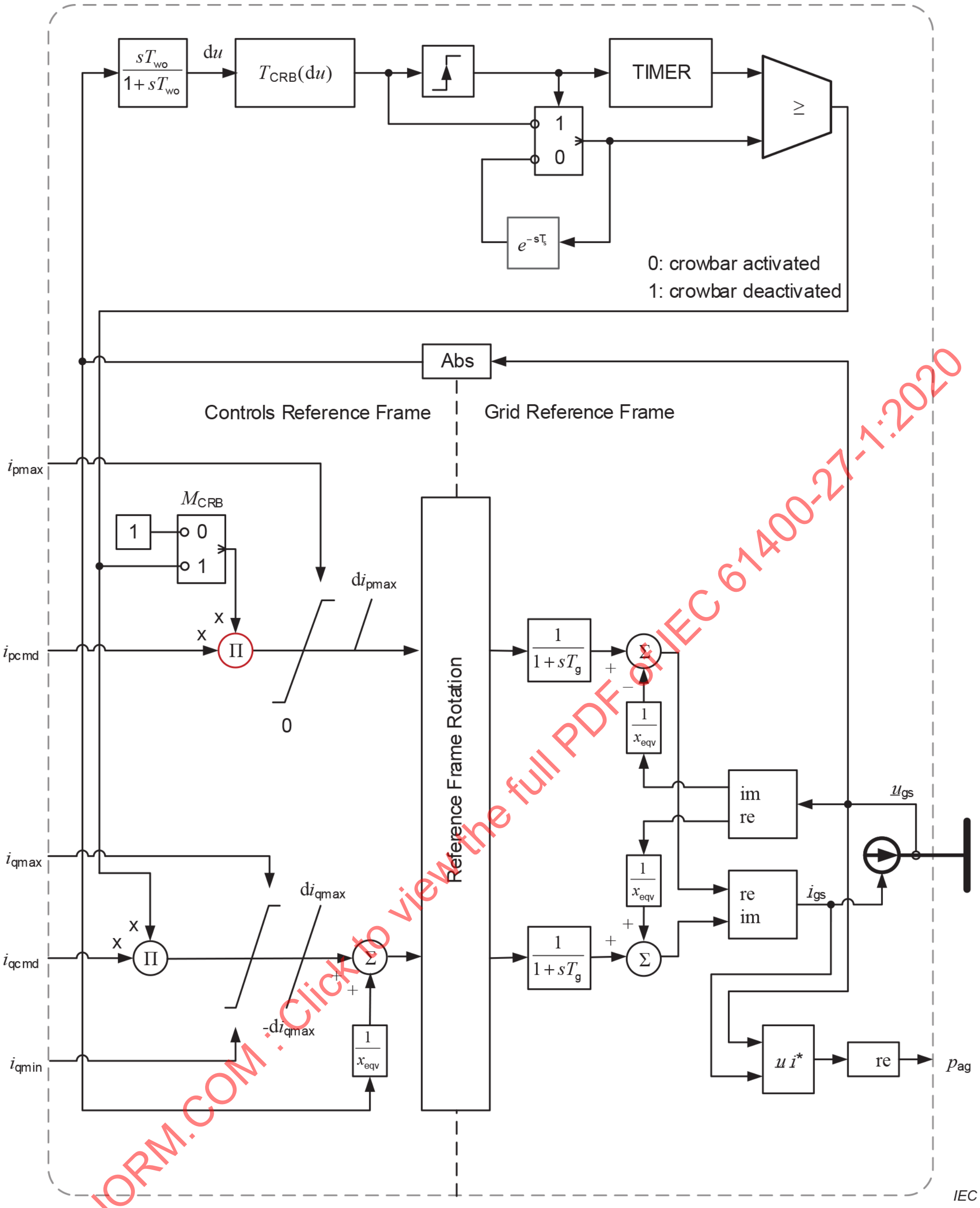


Figure 23 – Block diagram for type 3B generator system module

7.4.4 Type 4 generator system module

The module parameters for the type 4 generator module are given in Table 19, and the block diagram is given in Figure 24. The output of the generator module is a current, injected through a current source. However, in some power system simulation software, the current source needs a parallel impedance to improve the convergence behaviour of the simulation as described in Annex C.

Table 19 – Parameter list for type 4 generator system module

Symbol	Base unit	Description	Category	Text name
T_g	s	Time constant	Type	Tg
di_{pmax}	I_{base}/s	Maximum active current ramp rate	Project	dipmax
di_{qmax}	I_{base}/s	Maximum reactive current ramp rate	Project	diqmax
di_{qmin}	I_{base}/s	Minimum reactive current ramp rate	Project	diqmin

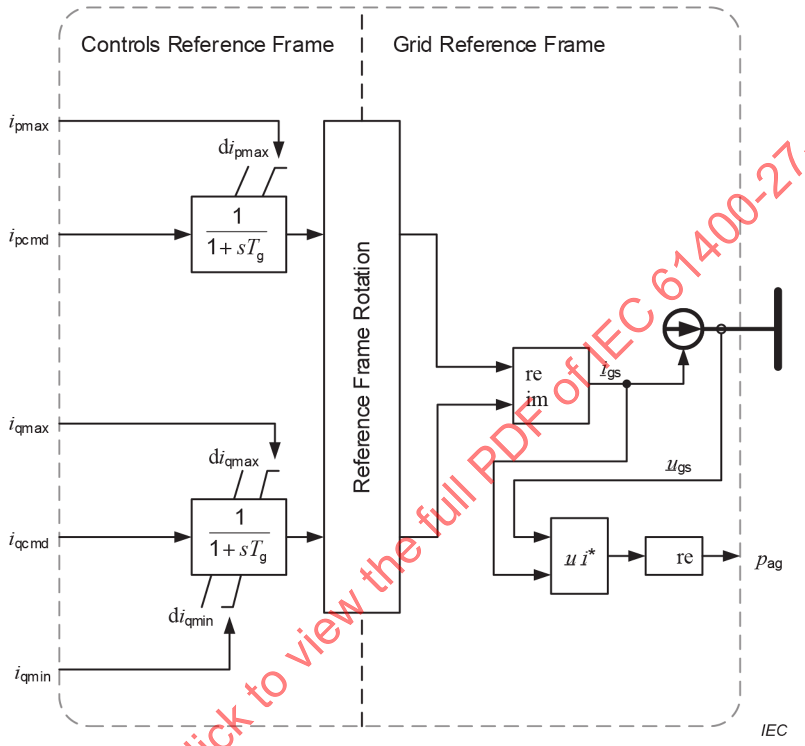


Figure 24 – Block diagram for type 4 generator system module

7.4.5 Reference frame rotation module

The module parameters for the reference frame rotation module are given in Table 20, and the block diagram is given in Figure 25.

Table 20 – Parameter list for reference frame rotation module

Symbol	Base unit	Description	Category	Text name
T_{PLL}	s	Time constant for PLL first order filter model	Type	TPLL
u_{PLL1}	U_{base}	Voltage below which the angle of the voltage is filtered and possibly also frozen[a]	Type	uPLL1
u_{PLL2}	U_{base}	Voltage below which the angle of the voltage is frozen if $u_{PLL2} \leq u_{PLL1}$[b]	Type	uPLL2

[a] Angle is filtered and/or frozen to avoid instabilities due to lack of voltage reference.

[b] The value of u_{PLL2} should be coordinated with the value of u_{PLL1}. Usually, $u_{PLL2} \leq u_{PLL1}$. u_{PLL2} is employed to avoid numerical problems when voltage is close to zero and then angle is not numerically valid.

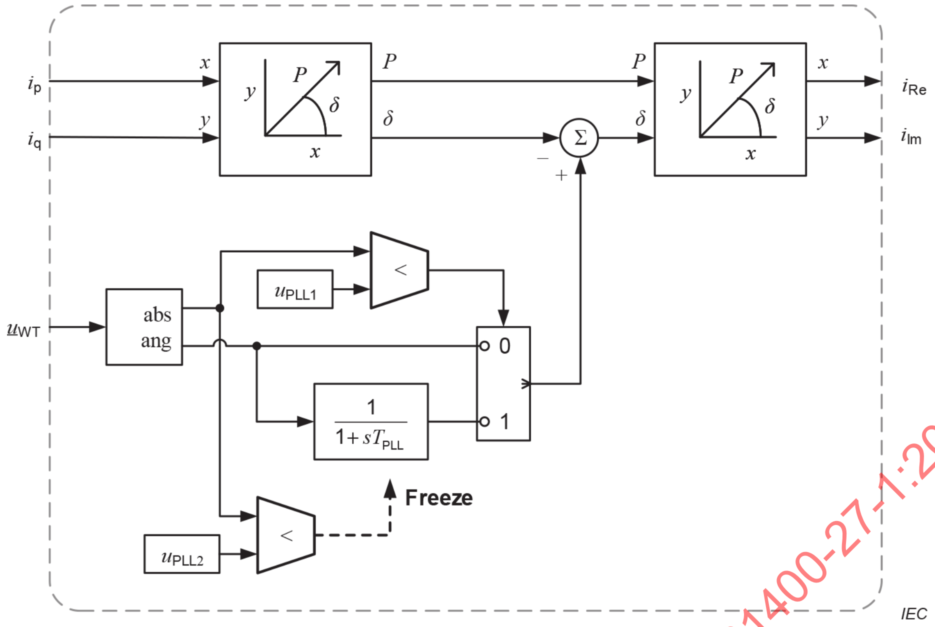


Figure 25 – Block diagram for the reference frame rotation module

7.5 Electrical systems modules

7.5.1 Electrical systems gamma module

The electrical systems gamma module includes a circuit breaker activated by the grid protection of the WT or STATCOM. The module can also be used to include transformer, capacitor bank, harmonic filter and other electrical components in the WT model or STATCOM model.

The module parameters are given in Table 21, and the single line diagram is given in Figure 26. Normally the WTT is identified to the low-voltage side of the WT transformer, and therefore the WT transformer is not included in the generic WT models but as a part of the WP model as part of the power collection systems. If the transformer is included in the WP model and other electrical components are neglected, then the serial impedance and the shunt admittance are zero, implying that the electrical systems simplifies to only include the circuit breaker.

Table 21 – Parameter list for electrical systems gamma module

Symbol	Base unit	Description	Category	Text name
r_{es}	Z_{base}	Serial resistance	Type	res
x_{es}	Z_{base}	Serial reactance	Type	xes
g_{es}	$1/Z_{base}$	Shunt conductance	Type	ges
b_{es}	$1/Z_{base}$	Shunt susceptance	Type	bes

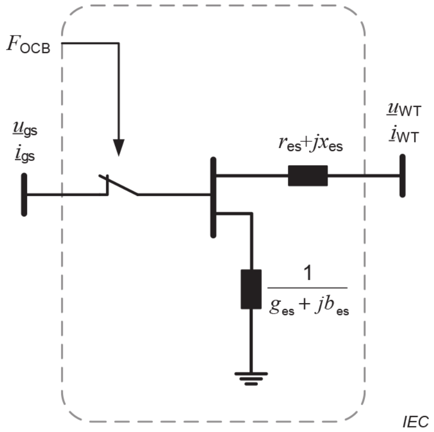


Figure 26 – Single line diagram for electrical systems gamma module

7.5.2 Other electrical systems modules

This document does not specify other generic electrical systems modules.

7.6 Pitch control modules

7.6.1 Pitch control power module

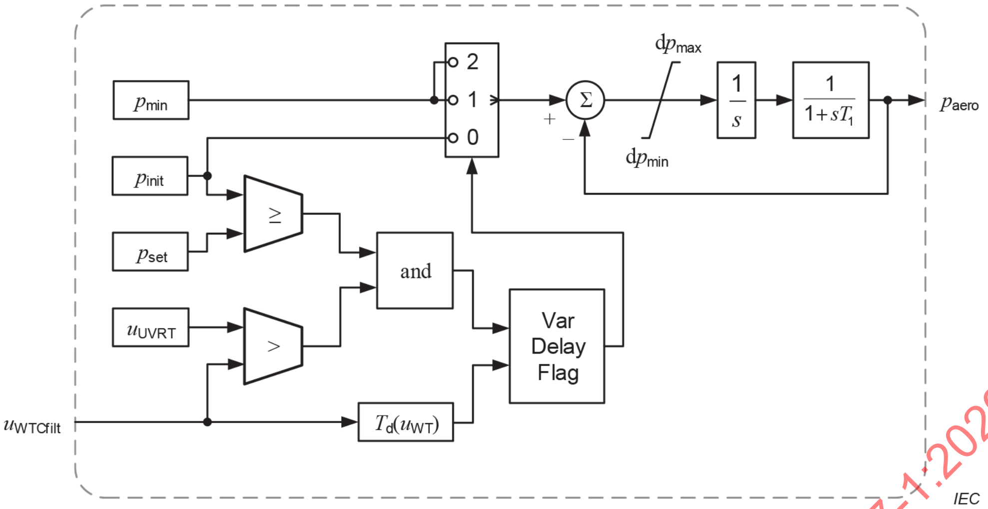
This module corresponds to the type 1 and type 2 WT pitch controller proposed for the 2nd generation WECC models [18]. The module parameters are given in Table 22, and the block diagram is given in Figure 27.

Table 22 – Parameter list for pitch control power module

Symbol	Base unit	Description	Category	Text name
dp_{max}	S_{base}	Rate limit for increasing power	Type	dpmax
dp_{min}	S_{base}	Rate limit for decreasing power	Type	dpmin
T_1	s	Lag time constant	Type	T1
p_{min}	S_{base}	Minimum power setting	Type	pmin
p_{set}	S_{base}	If $p_{init} < p_{set}$ then power will be ramped down to p_{min}	Type	pset
$T_d(u_{WT})$	s(U_{base})	Lookup table to determine the duration of the power reduction after a voltage dip, depending on the size of the voltage dip [a]	Type	Td(uWTTd)
u_{UVRT}	U_{base}	Dip detection threshold [b]	Type	uUVRT

[a] Note that for the WECC models, this lookup table is defined as steps between four points.

[b] Note that for the WECC models, u_{UVRT} is equal to the highest voltage in $T_d(u_{WT})$.



NOTE The initial power p_{init} is set by the load flow.

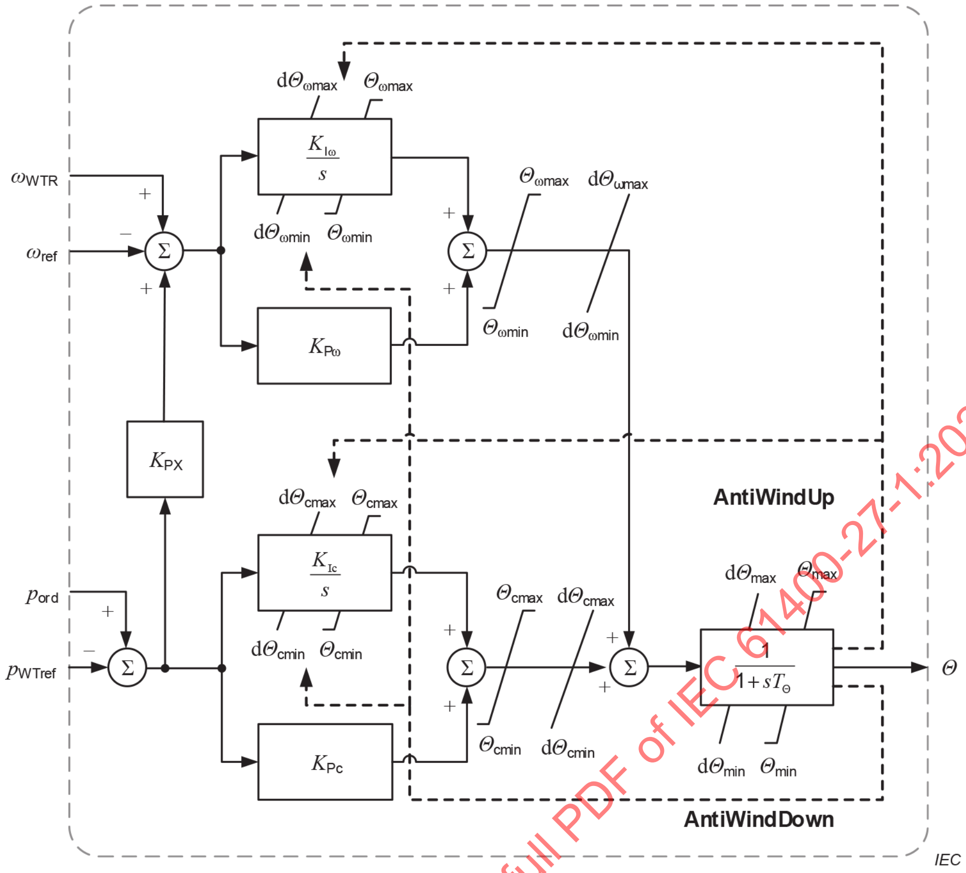
Figure 27 – Block diagram for pitch control power module

7.6.2 Pitch angle control module

The module parameters are given in Table 23, and the block diagram is given in Figure 28.

Table 23 – Parameter list for pitch angle control module

Symbol	Base unit	Description	Category	Text name
$K_{P\omega}$	deg/Ω_{base}	Speed PI controller proportional gain	Type	KPomega
$K_{I\omega}$	deg/Ω_{base}/s	Speed PI controller integration gain	Type	KIomega
K_{Pc}	deg/S_{base}	Power PI controller proportional gain	Type	KPc
K_{Ic}	deg/S_{base}/s	Power PI controller integration gain	Type	KIc
K_{PX}	Ω_{base}/S_{base}	Pitch cross coupling gain	Type	KPX
$\Theta_{\omega max}$	deg	Maximum pitch angle of speed PI controller	Type	Thetaomegamax
$\Theta_{\omega min}$	deg	Minimum pitch angle of speed PI controller	Type	Thetaomegamin
$d\Theta_{\omega max}$	deg/s	Maximum pitch positive ramp rate of speed PI controller	Type	dThetaomegamax
$d\Theta_{\omega min}$	deg/s	Maximum pitch negative ramp rate of speed PI controller	Type	dThetaomegamin
Θ_{cmax}	deg	Maximum pitch angle of power PI controller	Type	Thetacmax
Θ_{cmin}	deg	Minimum pitch angle of power PI controller	Type	Thetacmin
$d\Theta_{cmax}$	deg/s	Maximum pitch positive ramp rate of power PI controller	Type	dThetacmax
$d\Theta_{cmin}$	deg/s	Maximum pitch negative ramp rate of power PI controller	Type	dThetacmin
Θ_{max}	deg	Maximum pitch angle	Type	Thetamax
Θ_{min}	deg	Minimum pitch angle	Type	Thetamin
$d\Theta_{max}$	deg/s	Maximum pitch positive ramp rate	Type	dThetamax
$d\Theta_{min}$	deg/s	Maximum pitch negative ramp rate	Type	dThetamin
T_{Θ}	s	Pitch time constant	Type	TTheta



NOTE The block diagram uses the anti windup integrator described in Clause D.9 and the first order filter with limitation detection described in Clause D.11.

Figure 28 – Block diagram for pitch angle control module

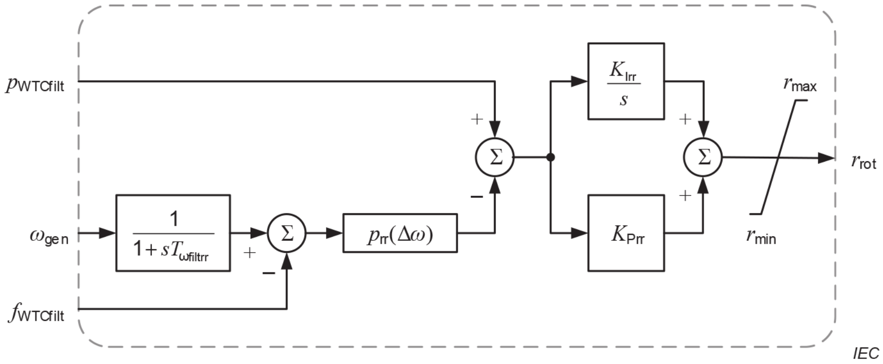
7.7 Generator and converter control modules

7.7.1 Rotor resistance control module

The module parameters are given in Table 24, and the block diagram is given in Figure 29.

Table 24 – Parameter list for rotor resistance control module

Symbol	Base unit	Description	Category	Text name
$T_{\omega filtrr}$	s	Filter time constant for generator speed measurement	Type	Tomegafiltrr
$p_{rr}(\Delta\omega)$	S_{base} (Ω_{base})	Power versus speed change (negative slip) lookup table	Type	prr(Deltaomegaprr)
K_{Prr}	Z_{base}/S_{base}	Proportional gain in rotor resistance PI controller	Type	KPrr
K_{Irr}	Z_{base}/S_{base}/s	Integral gain in rotor resistance PI controller	Type	KIrr
r_{max}	Z_{base}	Maximum rotor resistance	Type	rmax
r_{min}	Z_{base}	Minimum rotor resistance	Type	rmin



NOTE The module is similar to the IEEE / WECC model, but there are some formal differences. Firstly, the original IEEE / WECC model uses motor sign convention for power and slip in accordance with text book models for asynchronous machines, whereas this document uses generator sign convention, and therefore the PI controller input sign is reversed compared to the signs in the original IEEE / WECC model. Secondly, the measurement filter gains in the original IEEE / WECC models are removed as measurement filter gains are not considered in this document. Thirdly, the frequency filter is removed from this block as it is included in the measurement block.

Figure 29 – Block diagram for rotor resistance control module

7.7.2 P control module type 3

The module parameters are given in Table 25, and the block diagrams are given in Figure 30 and Figure 31.

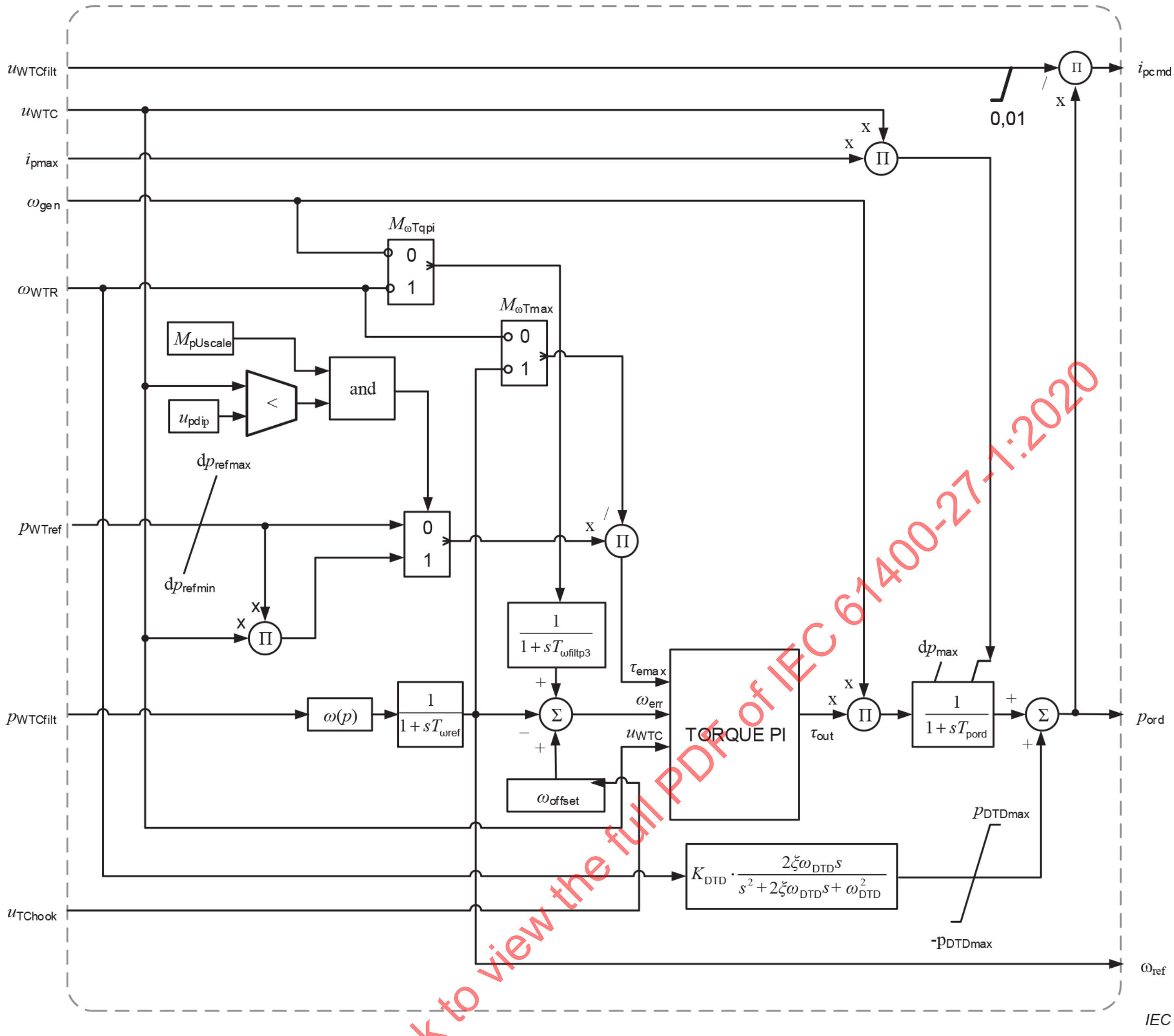
Table 25 – Parameter list for P control module type 3

Symbol	Base unit	Description	Category	Text name
ω_{offset}	Ω_{base}	Offset to reference value that limits controller action during rotor speed changes	Use case	omegaoffset
$\omega(p)$	$\Omega_{base}(S_{base})$	Power vs. speed lookup table	Type	omega(pomega)
K_{Pp}	T_{base}/Ω_{base}	PI controller proportional gain	Type	KPp
K_{Ip}	T_{base}/Ω_{base}/s	PI controller integration parameter	Type	KIp
$T_{\omega ref}$	s	Time constant in speed reference filter	Type	Tomegaref
$T_{\omega filtp3}$	s	Filter time constant for generator speed measurement	Type	Tomegafiltp3
K_{DTD}	S_{base}/Ω_{base}	Gain for active drive train damping	Type	KDTD
p_{DTDmax}	S_{base}	Maximum active drive train damping power	Type	pDTDmax
ζ	-	Coefficient for active drive train damping	Type	zeta
ω_{DTD}	Ω_{base}	Active drive train damping frequency, can be calculated from two mass module parameters in Table 16: $\omega_{DTD}=\sqrt{k_{drt}\cdot\left(\frac{1}{2\cdot H_{WTR}}+\frac{1}{2\cdot H_{gen}}\right)}$	Type	omegaDTD
T_{pord}	s	Time constant in power order lag	Type	Tpord
dp_{max}	S_{base}/s	Maximum WT power ramp rate	Type [a]	dpmax
dp_{refmax}	S_{base}/s	Maximum ramp rate of WT reference power	Project	dprefmax
dp_{refmin}	S_{base}/s	Minimum ramp rate of WT reference power	Project	dprefmin
u_{pdip}	U_{base}	Voltage dip threshold for P control. Part of turbine control, often different (e.g. 0,8) from converter thresholds	Project	updip

Symbol	Base unit	Description	Category	Text name
$d\tau_{max}$	T_{base}/s	Ramp limitation of torque, required in some grid codes	Project [a]	dtaumax
τ_{emin}	T_{base}	Minimum electrical generator torque	Type	tauemin
τ_{uscale}	T_{base}/U_{base}	Voltage scaling factor of reset-torque	Project	tauuscale
$M_{\omega Tqpi}$	-	Rotational speed source mode for torque PI controller error (0: ω_{gen} – 1: ω_{WTR}) [b]	Project	MomegaTqpi
$M_{\omega Tmax}$	-	Rotational speed source mode for maximum torque calculation (0: ω_{WTR} – 1: ω_{ref})	Project	MomegaTmax
M_{pUVRT}	-	Enable UVRT power control mode (0: reactive power control – 1: voltage control)	Project	MpUVRT
$d\tau_{maxUVRT}$	T_{base} /s	Limitation of torque rise rate during UVRT	Project	dtaumaxUVRT
u_{DVS}	U_{base}	Voltage limit for hold UVRT status after deep voltage dips	Project	uDVS
T_{DVS}	s	Time delay after deep voltage dips	Project	TDVS
$M_{pUscale}$	-	Voltage scaling for power reference during voltage dip (0: no scaling – 1: u scaling)	Project	MpUscale
u_{pdip}	U_{base}	Voltage dip threshold for P control. Part of WT control, often different from converter thresholds	Project	updip

[a] Note that grid codes often specify ramp rates for torque and power in s. In cases where it is not allowed to ramp faster than specified in s, the user may want to adjust the ramp rates dependent on the voltage dip depth. In such cases, the ramp rates are considered use case parameters.

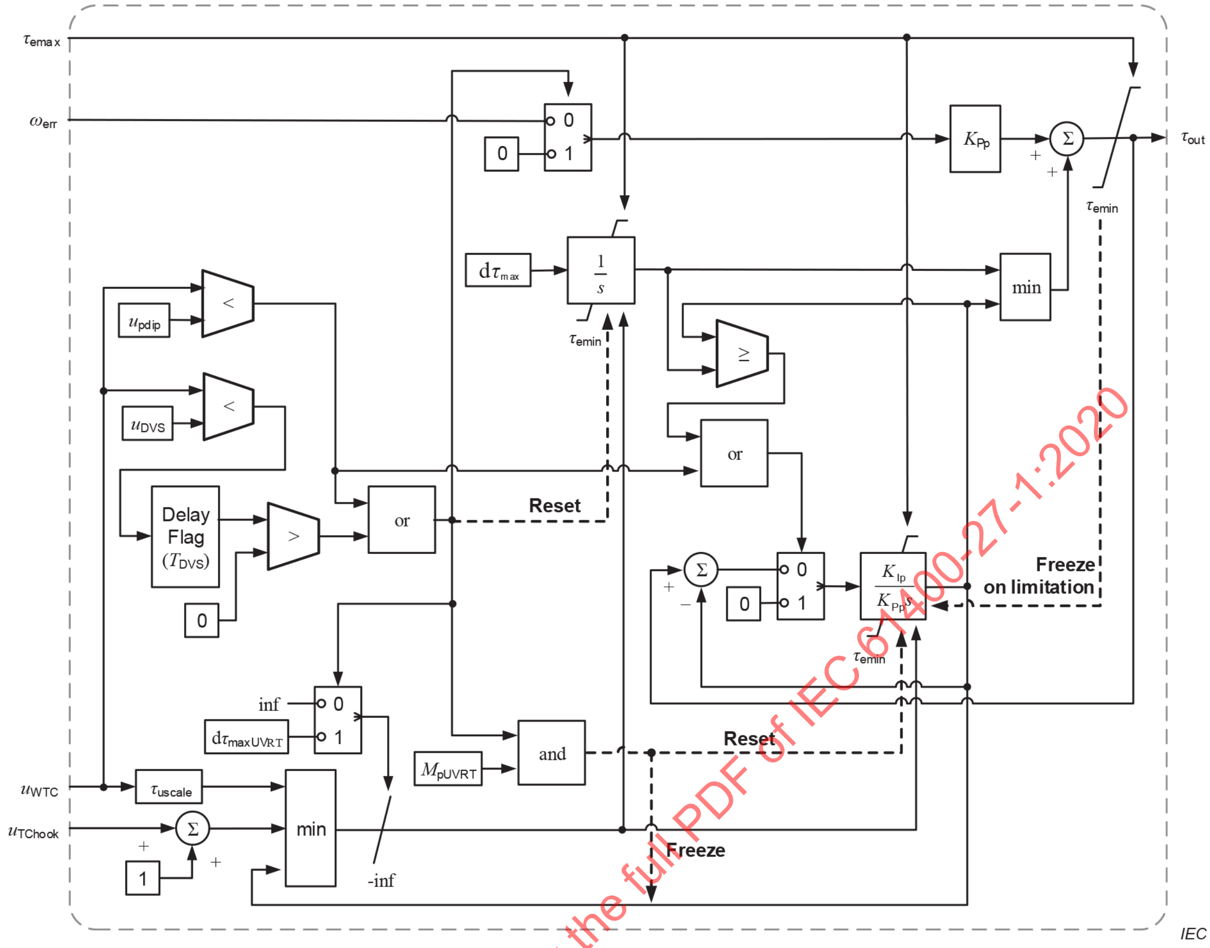
[b] Note that setting $M_{\omega Tqpi}$ = 1 (using rotor speed instead of generator speed) is an efficient way to filter the speed.



NOTE 1 The hook u_{TChook} is not used by the models specified in Clause 6.

NOTE 2 The TORQUE PI block is detailed in Figure 31.

Figure 30 – Block diagram for type 3 P control module



NOTE 1 The hook u_{TChook} is not used by the models specified in Clause 6.

NOTE 2 The Freeze function is detailed in Clause D.5, i.e. using Figure D.7 without limitations.

Figure 31 – Block diagram for type 3 torque PI

7.7.3 P control module type 4A

The module parameters are given in Table 26, and the block diagram is given in Figure 32.

Table 26 – Parameter list for P control module type 4A

Symbol	Base unit	Description	Category	Text name
$T_{pordp4A}$	s	Time constant in power order lag	Type	Tpordp4A
dp_{maxp4A}	S_{base}/s	Maximum WT power ramp rate	Project	dpmaxp4A
$T_{pWTref4A}$	s	Time constant in reference power order lag	Type	TpWTref4A
$dp_{refmaxp4A}$	S_{base}/s	Maximum WT reference power ramp rate	Project	dprefmaxp4A
$dp_{refmin4A}$	S_{base}/s	Minimum WT reference power ramp rate	Project	dprefmin4A
$M_{pUScale}$	-	Voltage scaling for power reference during voltage dip (0: no scaling – 1: u scaling)	Project	MpUscale
u_{pdip}	U_{base}	Voltage dip threshold for P control. Part of WT control, often different from converter thresholds	Project	updip

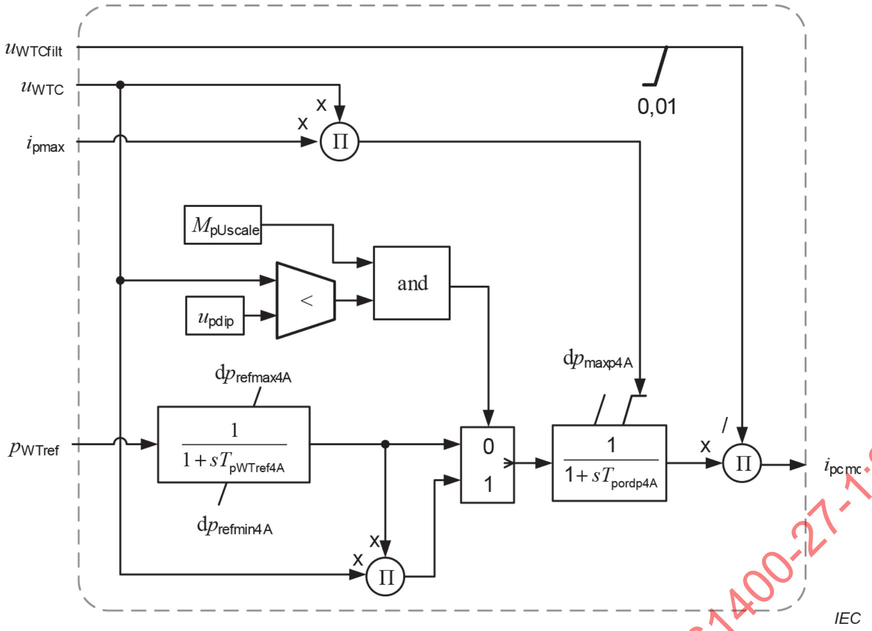


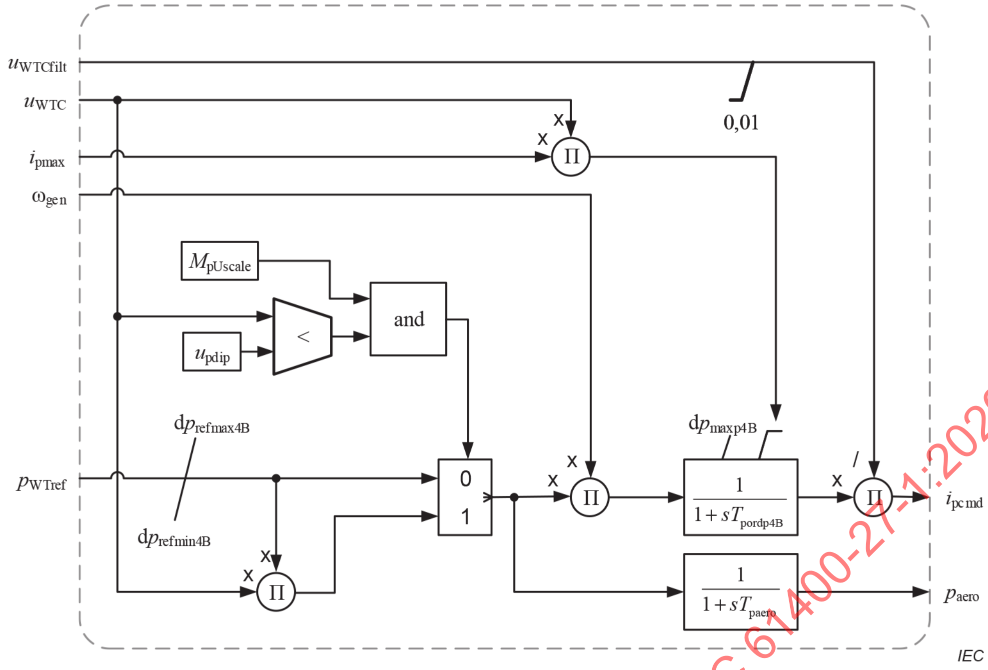
Figure 32 – Block diagram for type 4A P control module

7.7.4 P control module type 4B

The module parameters are given in Table 27, and the block diagram is given in Figure 33.

Table 27 – Parameter list for P control module type 4B

Symbol	Base unit	Description	Category	
T_{pordp4B}	s	Time constant in power order lag	Type	Tpordp4B
T_{paero}	s	Time constant in aerodynamic power response	Type	Tpaero
$\mathrm{d}p_{\text{maxp4B}}$	S_{base}/s	Maximum WT power ramp rate	Project	dpmaxp4B
$\mathrm{d}p_{\text{refmaxp4B}}$	S_{base}/s	Maximum WT reference power ramp rate	Project	dprefmaxp4B
$\mathrm{d}p_{\text{refmin4B}}$	S_{base}/s	Minimum WT reference power ramp rate	Project	dprefmin4B
M_{pUscale}	-	Voltage scaling for power reference during voltage dip (0: no scaling – 1: u scaling)	Project	MpUscale
u_{pdip}	U_{base}	Voltage dip threshold for P control. Part of WT control, often different from converter thresholds	Project	updip



NOTE The type 4B P control module assumes that $\tau_{init} = p_{init}$, i.e. the initial value of ω_{gen} is 1.

Figure 33 – Block diagram for type 4B P control module

7.7.5 Q control module

The Q control module supports the 5 different general Q control modes M_{qG} listed in Table 28.

Table 28 – General WT Q control modes M_{qG}

M_{qG}	Description
0	Voltage control
1	Reactive power control
2	Open loop reactive power control (only used with closed loop at plant level)
3	Power factor control
4	Open loop power factor control

The Q control module supports the three specific and one user defined FRT Q control modes M_{qFRT} listed in Table 29. The control modes specify the reactive current injection during the voltage dip, and in an optional post-fault period.

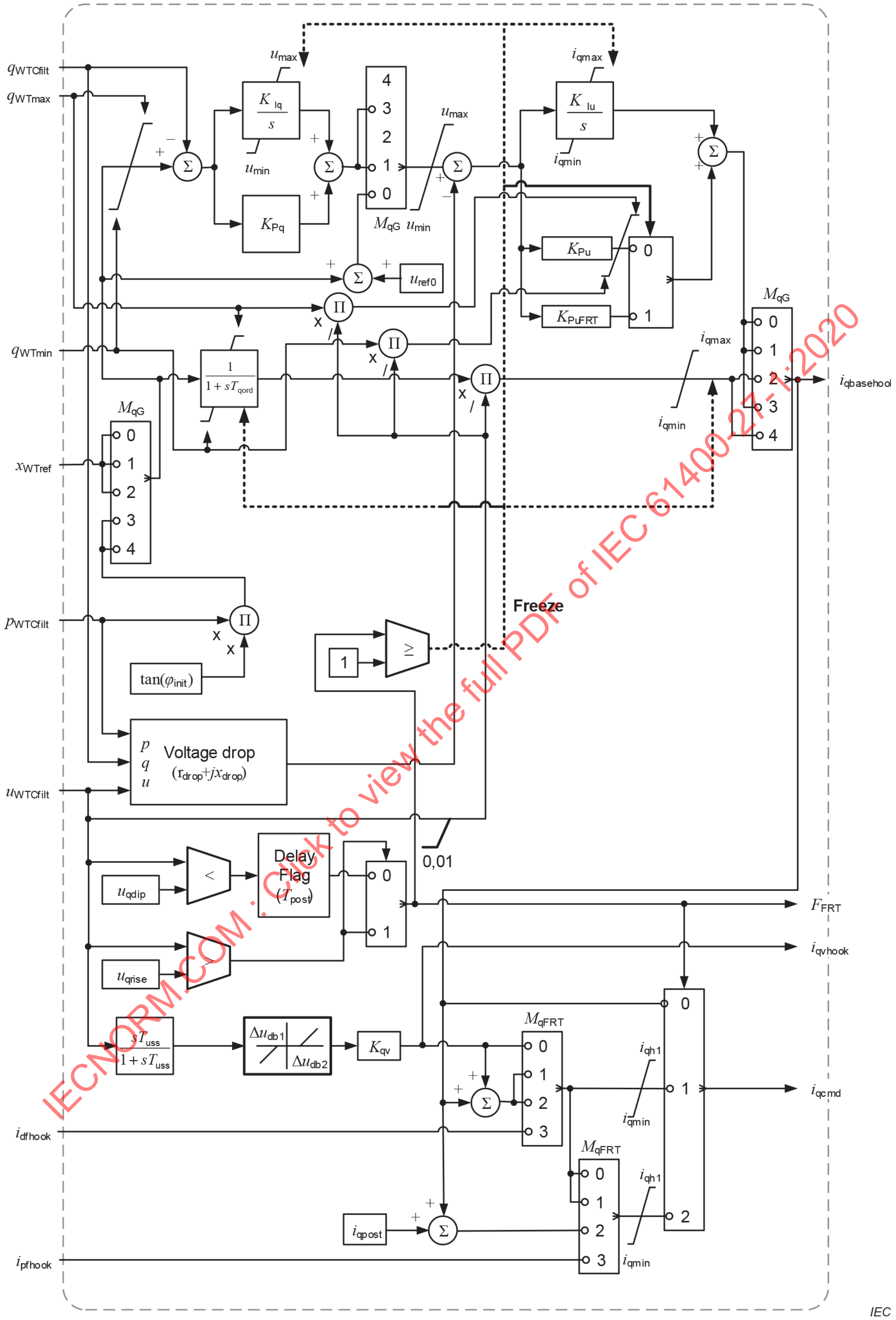
Table 29 – Reactive current injection for each FRT Q control modes M_{qFRT}

M_{qFRT}	During fault	Post fault
0	A function of the voltage change compared to the pre-fault voltage	Same function as during fault
1	Pre-fault current plus a term depending on the voltage change compared to the pre-fault voltage	Same function as during fault
2	Pre-fault current plus a term depending on the voltage change compared to the pre-fault voltage	Pre-fault current plus a constant
3	User defined	User defined

The module parameters for the Q control module are given in Table 30, and the block diagram is given in Figure 34.

Table 30 – Parameter list for Q control module

Symbol	Base unit	Description	Category	
M_{qG}	-	General Q control mode (see Table 28)	Project	MqG
M_{qFRT}	-	FRT Q control modes (see Table 29)	Project	MqFRT
K_{Pq}	U_{base}/S_{base}	Reactive power PI controller proportional gain	Type	KPq
K_{Iq}	$U_{base}/S_{base}/s$	Reactive power PI controller integration gain	Type	KIq
K_{Pu}	I_{base}/U_{base}	Voltage PI controller proportional gain	Type	KPu
K_{PuFRT}	I_{base}/U_{base}	Voltage PI controller proportional gain during FRT	Type	KPuFRT
K_{Iu}	$I_{base}/U_{base}/s$	Voltage PI controller integration gain	Type	KIu
Δu_{db1}	U_{base}	Voltage change dead band lower limit (typically negative)	Type	Δudb1
Δu_{db2}	U_{base}	Voltage change dead band upper limit (typically positive)	Type	Δudb2
T_{uss}	s	Time constant of steady state voltage filter	Type	Tuss
K_{qv}	I_{base}/U_{base}	Voltage scaling factor for FRT current	Project	Kqv
u_{max}	U_{base}	Maximum voltage in voltage PI controller integral term	Type	umax
u_{min}	U_{base}	Minimum voltage in voltage PI controller integral term	Type	umin
u_{ref0}	U_{base}	User defined bias in voltage reference $u_{WTref} = u_{ref0}+\Delta u_{WTref}$ (used when M_{qG} = 0).	Use case	uref0
u_{qdip}	U_{base}	Voltage threshold for UVRT detection in Q control	Type	uqdip
u_{qrise}	U_{base}	Voltage threshold for OVRT detection in Q control	Type	uqrise
T_{qord}	s	Time constant in reactive power order lag	Type	Tqord
T_{post}	s	Length of time period where post fault reactive power is injected	Project	Tpost
i_{qmax}	I_{base}	Maximum reactive current injection	Type	iqmax
i_{qmin}	I_{base}	Minimum reactive current injection	Type	iqmin
i_{qh1}	I_{base}	Maximum reactive current injection during dip	Type	iqh1
i_{qpost}	I_{base}	Post fault reactive current injection	Project	iqpost
r_{drop}	Z_{base}	Resistive component of voltage drop impedance	Project	rdrop
x_{drop}	Z_{base}	Inductive component of voltage drop impedance	Project	xdrop
Extreme care should be taken in coordinating the parameters u_{db1}, u_{db2} and u_{qdip} so as not to have an unintentional response from the reactive power injection control loop.				



NOTE 1 The implementation of the "Freeze" function is described in Clause D.5.

NOTE 2 tan(φ_{init}) is initialised by the load flow through q_{WTC} and $p_{WTCfilt}$. In cases where the load flow $p_{WTCfilt}$ is zero, tan(φ_{init}) is initialised to zero.

Figure 34 – Block diagram for Q control module

The external reference $\underline{x}_{\text{WTref}}$ can either be a reactive power or delta voltage command from the park controller, depending on the Q control mode. If no park controller module is applied, this signal is initialised as a constant input.

The "Delay Flag" block outputs the F_{FRT} flag in 1 of 3 stages described in Table 31.

Table 31 – Description of F_{FRT} flag values

F_{FRT}	Description
0	Normal operation ($u_{\text{qdip}} < u_{\text{WTCfilt}} < u_{\text{qrise}}$)
1	During fault ($u_{\text{WTCfilt}} \leq u_{\text{dip}}$ or $u_{\text{WTCfilt}} \geq u_{\text{qrise}}$)
2	Post fault ($u_{\text{qdip}} < u_{\text{WTCfilt}} < u_{\text{qrise}}$) stays F_{FRT} = 2 for $t = T_{\text{post}}$

The "Voltage drop" block shall calculate the voltage in a point which is located with the serial impedance distance $r+jx$ from WTT (typically a transformer), i.e.

$$u = \sqrt{\left(u_{\text{WT}} - r_{\text{drop}}\frac{p_{\text{WT}}}{u_{\text{WT}}} - x_{\text{drop}}\frac{q_{\text{WT}}}{u_{\text{WT}}}\right)^2 + \left(x_{\text{drop}}\frac{p_{\text{WT}}}{u_{\text{WT}}} - r_{\text{drop}}\frac{q_{\text{WT}}}{u_{\text{WT}}}\right)^2} \quad (1)$$

7.7.6 Current limitation module

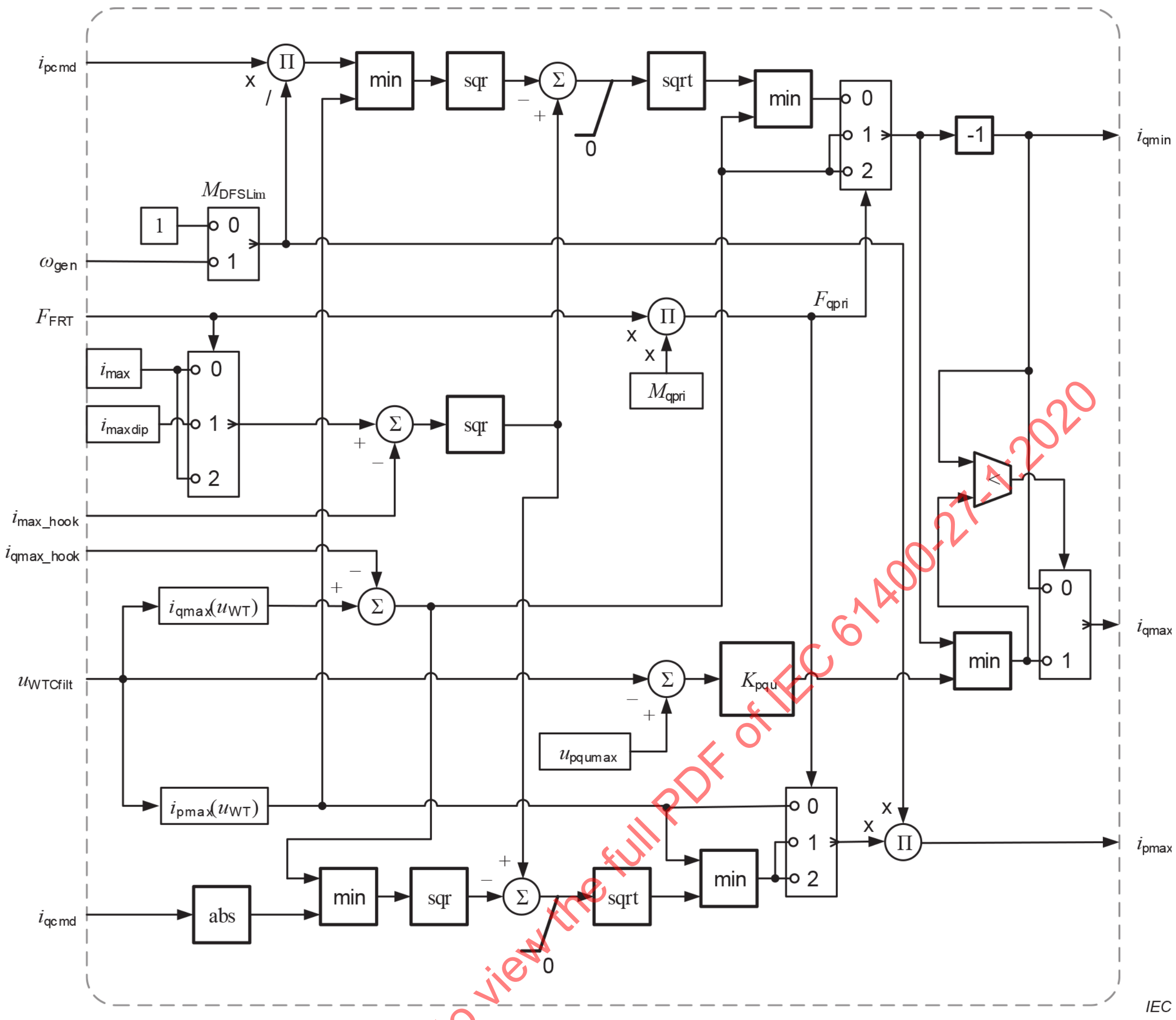
The current limitation module combines the physical limits and the control limits.

The module parameters are given in Table 32, and the block diagram is given in Figure 35.

Table 32 – Parameter list for current limiter module

Symbol	Base unit	Description	Category	Text name
i_{max}	I_{base}	Maximum continuous current at the WT terminals	Type	imax
i_{maxdip}	I_{base}	Maximum current during voltage dip at the WT terminals	Project	imaxdip
M_{DFSLim} [a]	-	Limitation of type 3 stator current (0: total current limitation, 1: stator current limitation)	Type	MDFSLim
M_{qpri}	-	Prioritisation of reactive power during FRT (0: active power priority – 1: reactive power priority)	Project	Mqpri
$i_{\text{pmax}}(u_{\text{WT}})$	I_{base} (U_{base})	Lookup table for voltage dependency of active current limits	Project	ipmax(uWTipmax)
$i_{\text{qmax}}(u_{\text{WT}})$	I_{base} (U_{base})	Lookup table for voltage dependency of reactive current limits	Project	iqmax(uWTiqmax)
u_{pqumax}	U_{base}	WT voltage in the operation point where zero reactive current can be delivered	Type	upqumax
K_{pqu}	I_{base} / U_{base}	Partial derivative of reactive current limit vs. voltage	Type	Kpqu

[a] M_{DFSLim} = 1 for type 4 WTs.



NOTE 1 The hooks i_{max_hook} and i_{qmax_hook} are not used by the models specified in Clause 6.

NOTE 2 ω_{gen} input is not used for type 4 which is ensured by setting M_{DFSLim} = 0.

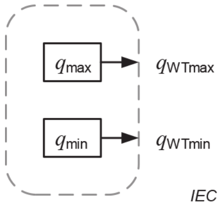
Figure 35 – Block diagram for current limiter

7.7.7 Constant Q limitation module

The module parameters are given in Table 33, and the block diagram is given in Figure 36.

Table 33 – Parameter list for constant Q limitation module

Symbol	Base unit	Description	Category	Text name
q_{max}	S_{base}	Maximum reactive power	Type	qmax
q_{min}	S_{base}	Minimum reactive power	Type	qmin



NOTE The constant Q limitation module is not using the Q limitation module inputs F_{FRT}, $u_{WTCfilt}$ and $p_{WTCfilt}$.

Figure 36 – Block diagram for constant Q limitation module

7.7.8 QP and QU limitation module

The module parameters are given in Table 34, and the block diagram is given in Figure 37.

Table 34 – Parameter list for QP and QU limitation module

Symbol	Base unit	Description	Category	Text name
$q_{maxp}(p)$	S_{base} (S_{base})	Lookup table for active power dependency of reactive power maximum limit	Type	qmaxp(pqmaxp)
$q_{minp}(p)$	S_{base} (S_{base})	Lookup table for active power dependency of reactive power minimum limit	Type	qminp(pqminp)
$q_{maxu}(u)$	S_{base} (U_{base})	Lookup table for voltage dependency of reactive power maximum limit	Type	qmaxu(uqmaxu)
$q_{minu}(u)$	S_{base} (U_{base})	Lookup table for voltage dependency of reactive power minimum limit	Type	qminu(uqminu)

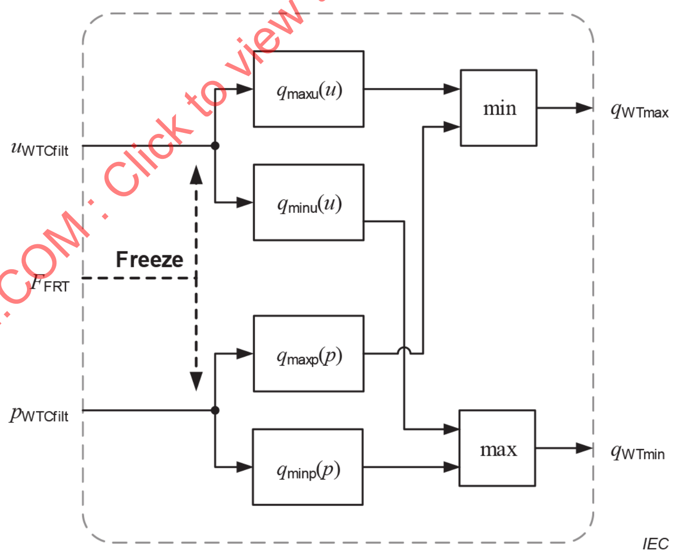


Figure 37 – Block diagram for QP and QU limitation module

7.8 Grid interfacing modules

7.8.1 Grid protection module

The grid protection module includes protection against over and under voltage, and against over and under frequency. The definite time grid protection is characterized by a set of protection levels and a corresponding set of disconnection times as defined and tested in IEC 61400-21-1[15]. User-definable curves may be entered to model specific tripping profiles by defining a set of voltage/time or frequency/time co-ordinates. Interpolation between points is used to provide a smooth trip characteristic.

The module parameters are given in Table 35, and the block diagrams are given in Figure 38.

Table 35 – Parameter list for grid protection module

Symbol	Base unit	Description	Category	Text name
u_{over}	U_{base}	WT over voltage protection activation threshold	Project	uover
$T_{uover}(u_{WT})$	s (U_{base})	Disconnection time versus over voltage lookup table	Project	Tuover(uWTTuover)
u_{under}	U_{base}	WT under voltage protection activation threshold	Project	uunder
$T_{uunder}(u_{WT})$	s (U_{base})	Disconnection time versus under voltage lookup table	Project	Tuunder(uWTTuunder)
f_{over}	f_n	WT over frequency protection activation threshold	Project	fover
$T_{fover}(f_{WT})$	s (f_n)	Disconnection time versus over frequency lookup table	Project	Tfover(fWTTfover)
f_{under}	f_n	WT under frequency protection activation threshold	Project	funder
$T_{funder}(f_{WT})$	s (f_n)	Disconnection time versus under frequency lookup table	Project	Tfunder(fWTTfunder)

15 Industry normally models protection conservatively, so that model tripping always occurs when one of the voltage or frequency levels exceed the corresponding protection level thresholds. Actual equipment may exceed these minimum ride-through protection level thresholds without tripping the WT.

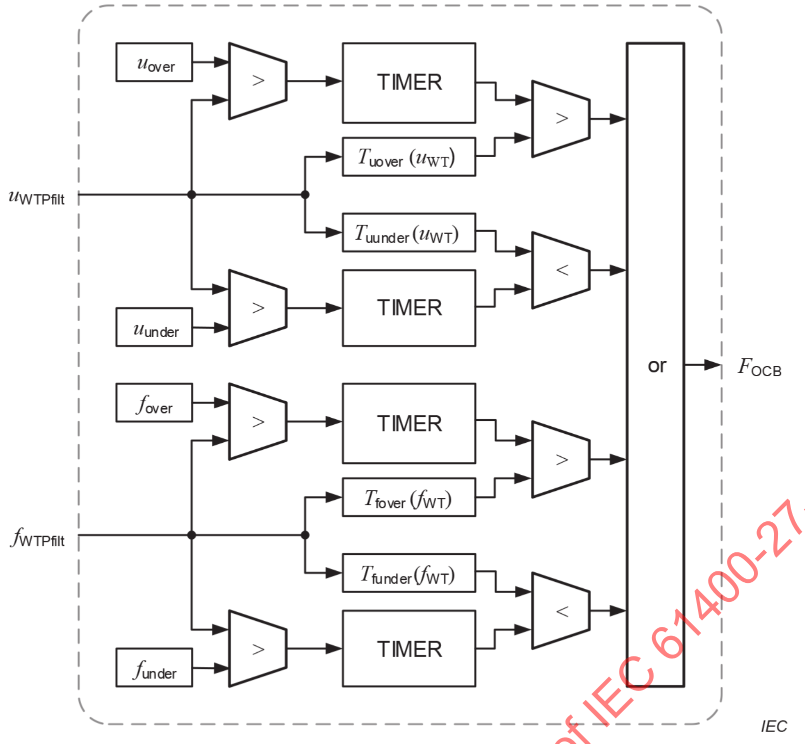


Figure 38 – Block diagram for grid protection system

For each individual pair of protection level and disconnection times, the module trips the WT if the corresponding variable has exceeded the corresponding protection level continuously during the corresponding disconnection time. The module does not include any reconnection of a tripped WT.

To use a definite – time relay module, a single pair of co-ordinates can be defined in lookup tables. To use specific tripping profiles, the user can enter as many pairs of co-ordinates as required in lookup tables.

7.8.2 Grid measurement module

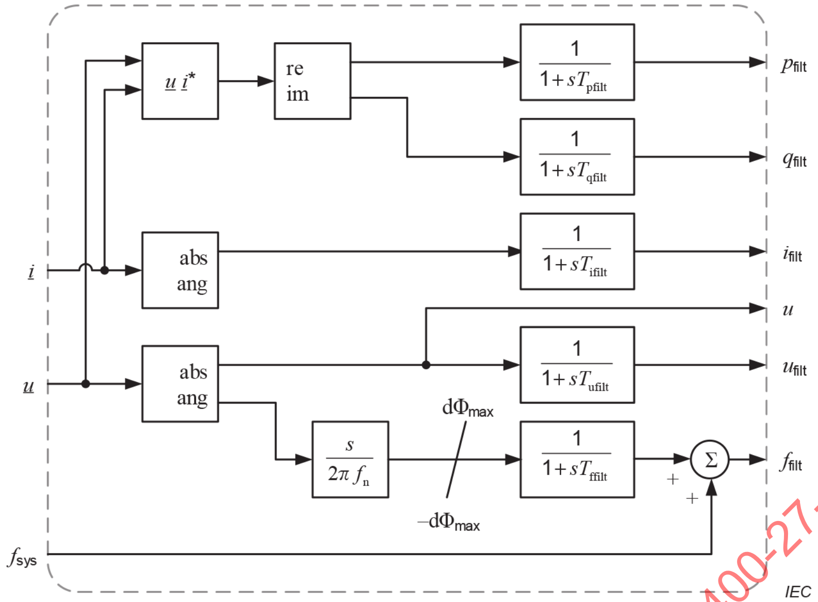
The parameters for the grid measurement module are given in Table 36 and the block diagram is given in Figure 39.

Table 36 – Parameter list for grid measurement module

Symbol	Base unit	Description	Category	Text name
$d\Phi_{max}$	f_n/s	Maximum rate of change of frequency[a]	Type	dPhimax
T_{ufilt}	s	Time constant in voltage measurement filter	Type	Tufilt
T_{ifilt}	s	Time constant in current measurement filter	Type	Tifilt
T_{pfilt}	s	Time constant in power measurement filter	Type	Tpfilt
T_{qfilt}	s	Time constant in reactive power measurement filter	Type	Tqfilt
T_{ffilt}	s	Time constant in frequency measurement filter[b]	Type	Tffilt

[a] $d\Phi_{max}$ should be greater than any ROCOF protection activation threshold in the power system. Presently, 0,5 Hz/s is reported in some grid codes, and 2,5 Hz/s proposed, so it is recommended to use $d\Phi_{max}$ = 5 Hz/s.

[b] Typical values for protection equipment are 3 to 5 line periods.



NOTE The module parameter f_n is included in the global parameter list Table 12.

Figure 39 – Block diagram for u-f measurement

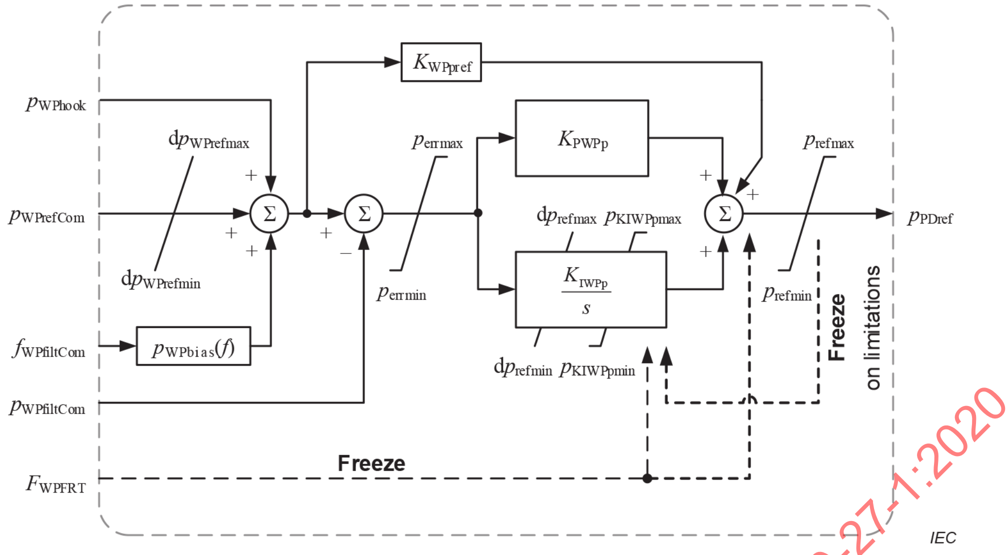
7.9 Wind power plant control modules

7.9.1 WP P control module

The module parameters are given in Table 37, and the block diagram is given in Figure 40.

Table 37 – Parameter list for power/frequency control module

Symbol	Base unit	Description	Category	
$p_{\mathrm{WPbias}}(f)$	$S_{\mathrm{base}}(f_{\mathrm{N}})$	Look up table for defining power variation versus frequency	Use case	pWPbias(fpWPbias)
dp_{WPrefmax}	S_{base}/ s	Maximum positive ramp rate for WP power reference	Project	dpWPrefmax
dp_{WPrefmin}	S_{base}/ s	Minimum negative ramp rate for WP power reference	Project	dpWPrefmin
p_{errmax}	S_{base}	Maximum control error for power PI controller	Project	perrmax
p_{errmin}	S_{base}	Minimum negative control error for power PI controller	Project	perrmin
K_{WPpref}	-	Power reference gain	Project	KWPpref
K_{PWPp}	-	Power PI controller proportional gain	Project	KPWPp
K_{IWPp}	s^{-1}	Power PI controller integration gain	Project	KIWPp
p_{KIWPpmax}	S_{base}	Maximum active power reference from integration	Project	pKIWPpmax
p_{KIWPpmin}	S_{base}	Minimum active power reference from integration	Project	pKIWPpmin
p_{refmax}	S_{base}	Maximum PD power reference	Use case	prefmax
p_{refmin}	S_{base}	Minimum PD power reference	Project	prefmin
dp_{refmax}	S_{base}/ s	Maximum positive ramp rate for PD power reference	Project	dprefmax
dp_{refmin}	S_{base}/ s	Minimum negative ramp rate for PD power reference	Project	dprefmin



NOTE The hook p_{WPhook} is not used by the models specified in Clause 6.

Figure 40 – Block diagram for WP power/frequency control module

7.9.2 WP Q control module

The module parameters are given in Table 38, and the block diagram is given in Figure 41.

Table 38 – Parameter list for reactive power/voltage control module

Symbol	Base unit	Description	Category	
$q_{\text{WP}}(u_{\text{err}})$	S_{base} (U_{base})	Look up table for the UQ static mode	Project	qWP(uerrqWP)
T_{uqfilt}	s	Time constant for the UQ static mode	Project	Tuqfilt
u_{WPqdip}	U_{base}	Voltage threshold for UVRT detection	Project	uWPqdip
u_{WPqrise}	U_{base}	Voltage threshold for OVRT detection	Project	uWPqrise
K_{WPqu}		Voltage controller cross coupling gain	Project	KWPqu
K_{WPqref}	-	Reactive power reference gain	Project	KWPqref
K_{PWPx}	-	Reactive power/voltage PI controller proportional gain	Project	KPWPx
K_{IWPx}	s^{-1}	Reactive power/voltage PI controller integral gain	Project	KIWPx
x_{KIWPxmax}	x_{base}	Maximum reactive Power/voltage reference from integration	Project	xKIWPxmax
x_{KIWPxmax}	x_{base}	Minimum reactive Power/voltage reference from integration	Project	xKIWPxmax
x_{refmax}	x_{base}	Maximum WT reactive power/voltage reference	Use case	xrefmax
x_{refmin}	x_{base}	Minimum WT reactive power/voltage reference	Project	xrefmin
dx_{refmax}	x_{base}/ s	Maximum positive ramp rate for WT reactive power/voltage reference	Project	dxrefmax
dx_{refmin}	x_{base}/ s	Minimum negative ramp rate for WT reactive power/voltage reference	Project	dxrefmin
M_{WPqmode}		Reactive power/voltage control mode (0 –reactive power reference, 1- power	Use case	MWPqmode

Symbol	Base unit	Description	Category	
		factor reference, 2- UQ static, 3 voltage control)		
r_{WPdrop}	Z_{base}	Resistive component of WP voltage drop impedance	Project	rWPdrop
x_{WPdrop}	Z_{base}	Inductive component of WP voltage drop impedance	Project	xWPdrop
x_{errmax}	x_{base}	Maximum reactive power error (or voltage error if M_{WPqmode} = 2) input to PI controller	Project	xerrmax
x_{errmin}	x_{base}	Minimum reactive power error (or voltage error if M_{WPqmode} = 2) input to PI controller	Project	xerrmin
$q_{\text{WPmax}}(p_{\text{WP}})$	S_{base} (S_{base})	Power dependent reactive power maximum limit	Project	qWPmax(pWPqWPmax)
$q_{\text{WPmin}}(p_{\text{WP}})$	S_{base} (S_{base})	Power dependent reactive power minimum limit	Project	qWPmin(pWPqWPmin)

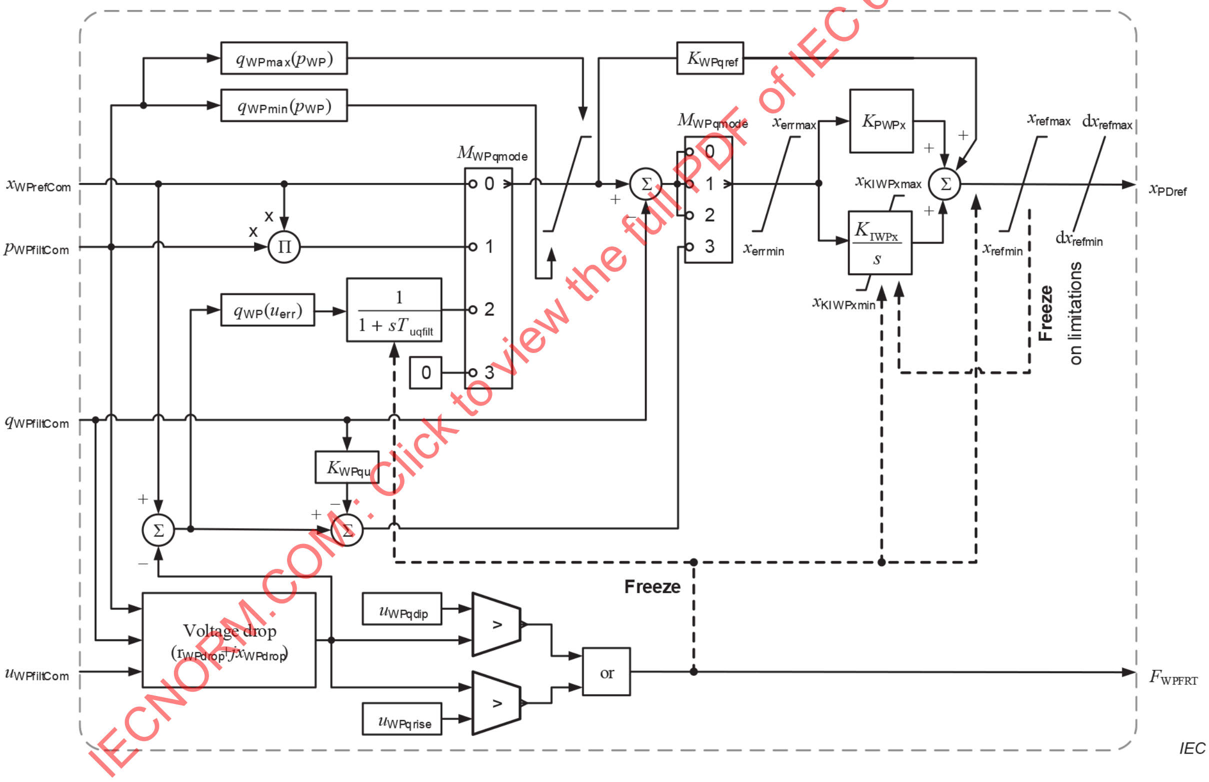


Figure 41 – Block diagram for WP reactive power/voltage control module

The external reference x_{WPrefCom} can either be a reactive power, voltage or power factor command communicated by the operator, depending on the reactive power/voltage control mode M_{WPqmode}.

7.10 Communication modules

7.10.1 General

Two different communications are specified below: the communication delay module and the linear communication module. The communication delay module is recommended if accurate modelling of the communication delay is required, but this module slows down computer simulation time, especially in cases where many WPs are simulated in large system studies. In such cases, it is recommended to use the linear communication module.

7.10.2 Communication delay module

The module parameters are given in Table 39, and the block diagram for an example with N communication variables is given in Figure 42.

Table 39 – Parameter list for communication delay module

Symbol	Base unit	Description	Category	Text name
T_d	s	Communication delay time	Project	Td

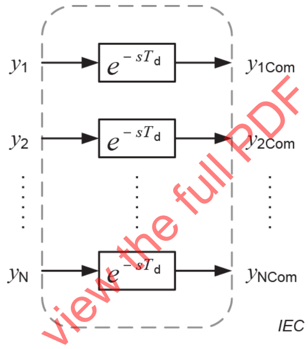


Figure 42 – Block diagram for communication delay module

7.10.3 Linear communication module

The module parameters are given in Table 40, and the block diagram for an example with N communication variables is given in Figure 43.

Table 40 – Parameter list for linear communication module

Symbol	Base unit	Description	Category	Text name
T_{lead}	s	Communication lead time constant	Project	Tlead
T_{lag}	s	Communication lag time constant	Project	Tlag

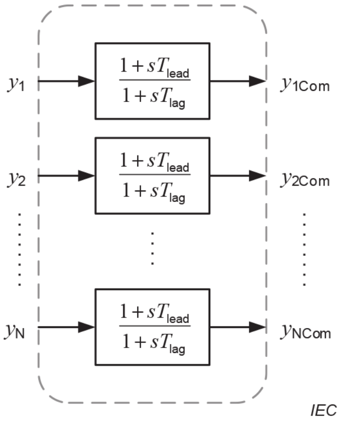


Figure 43 – Block diagram for linear communication module for an example with N communication variables

7.11 Electrical components modules

7.11.1 Line module

This document does not specify a line module. A standard line module specified in IEC 61970-301 should be used. Alternatively, a build-in line module in a chosen simulation tool can be used.

7.11.2 Transformer module

This document does not specify a transformer module. A standard transformer module specified in IEC 61970-301 should be used. Alternatively, a build-in transformer module in a chosen simulation tool can be used.

7.11.3 Other electrical components modules

This document does not specify standard electrical components modules. Standard modules specified in IEC 61970-301 should be used. Alternatively, build-in modules in a chosen simulation tool can be used.

Annex A
(informative)

Estimation of parameters for single branch power collection system model

A.1 General

Annex A specifies a method for estimation of the parameters of the single branch power collection system model shown in Figure 16. The estimation is based on a method described in [25]. The applied method is based on the following assumptions:

– All WTs can be represented by the same model.
– All WTs inject the same active and reactive currents.
– The impact of other assets than WTs connected to the power collection system is disregarded.
– The power collection system is radial, i.e. one possible power flow path from each WT to WP POC.
– The method is based on DC power flow assuming same per-unit voltage in all points.
– The active and reactive power losses are approximately the same in the aggregated collection system model as in the detailed collection system model.

A.2 Description of method

A.2.1 General

The aggregation is done using per-unit parameters at the WP level.

Assuming that the active and reactive losses are preserved by the aggregation, a number N_{ser} of serial impedances z_i can be aggregatet into a single serial impedance z_{agg} determined as

$$z_{\text{agg}} = \sum_{i=1}^{N_{\text{ser}}} \left(\frac{n_i}{N_{\text{WT}}} \right)^2 z_i \qquad \text{(A.1)}$$

where n_i is the number of wind turbines feeding through z_i and N_{WT} is the total number of wind turbines in the wind plant.

Assuming that the active and reactive losses are preserved by the aggregation, a number N_{shunt} of shunt admittances y_i can be aggregatet into a single shunt admittance y_{agg} determined as

$$y_{\text{agg}} = \sum_{i=1}^{N_{\text{shunt}}} y_i \qquad \text{(A.2)}$$

A.2.2 Lines aggregation

The physical lines in the power collection system are aggregated into a single aggregated collector line denoted ACL.

Following the general method in A.2.1, the physical lines are represented by the per-unit parameters at the WP level.

Using Formula (A.1), the serial impedance z_{ACL} of ACL is determined as

$$z_{\mathrm{ACL}} = \sum_{i=1}^{N_{\mathrm{L}}} \left(\frac{n_i}{N_{\mathrm{WT}}} \right)^2 z_i \tag{A.3}$$

where N_{L} is the total number of lines in the power collection system, z_i is the serial impedance of line i, n_i is the number of wind turbines feeding through line i and N_{WT} is the total number of WTs in the WP.

Using Formula (A.2), the shunt susceptance b_{ACL} of ACL is calculated according to

$$b_{\mathrm{ACL}} = \sum_{i=1}^{N_L} b_i \tag{A.4}$$

where b_i is the shunt susceptance of line i.

A.2.3 Wind turbine transformers aggregation

The physical WT transformers are aggregated into a single aggregated transformer denoted TRWT.

Following the general method in A.2.1, the physical WT transformers are represented by the per-unit parameters at the WP level. However, data for the physical WT transformers are usually given as per-unit parameters at the WT level. Therefore, it is necessary to convert the WT level transformer parameters to WP level before they are aggregated.

The per-unit value at WT level of a single WT transformer serial impedence $z_{\mathrm{1TR@WT}}$ is converted to physical value $Z_{\mathrm{1TR\ @WP}}$ at the WP voltage level U_{WPn} (high voltage side of the WT transformer) according to

$$Z_{\mathrm{1TR@WP}} = z_{\mathrm{1TR@WT}} \cdot \frac{{U_{\mathrm{WPn}}}^2}{P_{\mathrm{WTn}}} \tag{A.5}$$

The physical value $Z_{\mathrm{1TR\ @WP}}$ at the WP level is converted to per-unit value $z_{\mathrm{1TR\ @WP}}$ at the WP level according to

$$z_{\mathrm{1TR@WP}} = Z_{\mathrm{1TR@WP}} \Big/ \frac{{U_{\mathrm{WPn}}}^2}{P_{\mathrm{WPn}}} = Z_{\mathrm{1TR@WP}} \cdot \frac{P_{\mathrm{WPn}}}{{U_{\mathrm{WPn}}}^2} \tag{A.6}$$

The WP nominal power P_{WPn} is calculated as the sum of WT nominal powers. If the WP consists of N_{WT} WTs each with nominal power P_{WTn} then

$$P_{\mathrm{WPn}} = N_{\mathrm{WT}} P_{\mathrm{WTn}} \tag{A.7}$$

Inserting Formulae (A.5) and (A.7) in Formula (A.6) yields

$$z_{\mathrm{1TR@WP}} = N_{\mathrm{WT}} z_{\mathrm{1TR@WT}} \tag{A.8}$$

The impedance z_{TRWT} of the aggregating WT transformer TRWT is calculated according to Formula (A.1).

$$z_{\mathrm{TRWT}} = \sum_{i=1}^{N_{\mathrm{WT}}} \left(\frac{1}{N_{\mathrm{WT}}} \right)^2 z_{\mathrm{1TR@WP}} \tag{A.9}$$

Inserting Formula (A.8), Formula (A.9) yields

$$z_{\mathrm{TRWT}} = z_{\mathrm{1TR@WT}} \tag{A.10}$$

Formula (A.10) shows that the per-unit value of the aggregated TRWT serial impedance in WP base is equal to the serial impedances of a single WT transformer in WT base. In other words, the per-unit values from the WT model can be applied directly in the WP model. Thus, the WT transformer serial impedance parameters r_{TR1}, x_{TR1}, r_{TR2} and x_{TR2} can be used for TRWT. It can also be shown that the WT shunt parameter x_{TRM} can be used for TRWT.

NOTE Also the WT model can be applied directly in the aggregation changing only the power base according to Formula (A.7).

A.3 Numerical example

An example power collection system is shown in Figure A.1.

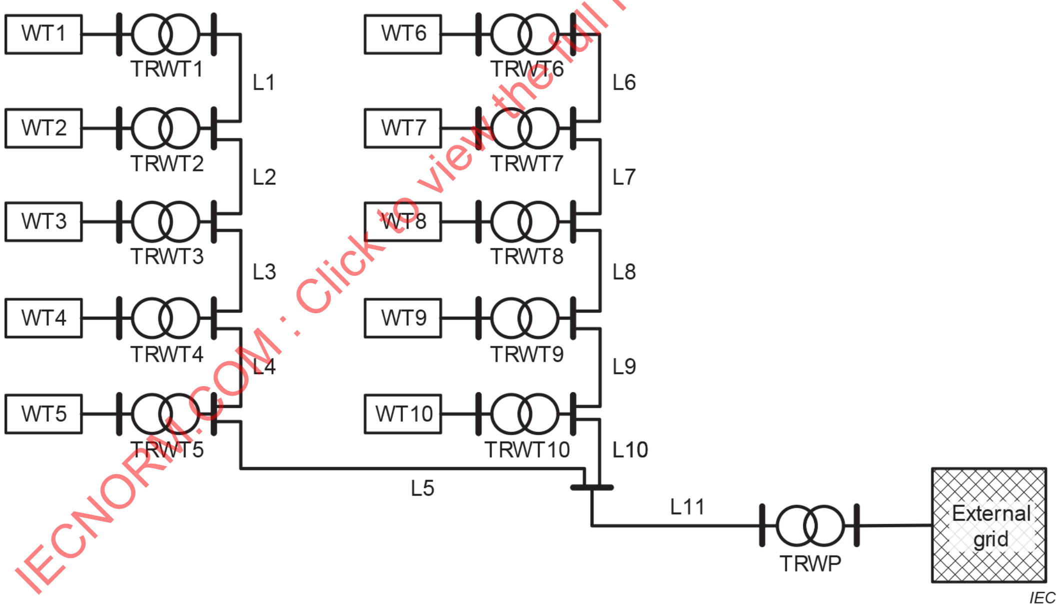


Figure A.1 – WP power collection system example

Line parameters for each of the lines are given in Table A.1 together with calculated values for the aggregated collection line (last row in table).

Table A.1 – Lines parameters and aggregation calculations. The data is in per-units using WP base values

Line name	i	r_i	x_i	b_i	n_i	$\left(\frac{n_i}{N_{WT}}\right)^2 r_i$	$\left(\frac{n_i}{N_{WT}}\right)^2 x_i$
L1	1	0,000 3	0,000 3	0,0371	1	0,000 0	0,000 0
L2	2	0,000 3	0,000 3	0,0385	2	0,000 0	0,000 0
L3	3	0,000 4	0,000 3	0,0432	3	0,000 0	0,000 0
L4	4	0,000 8	0,000 7	0,0873	4	0,000 1	0,000 1
L5	5	0,000 6	0,000 8	0,079	5	0,000 2	0,000 2
L6	6	0,000 5	0,000 4	0,0581	1	0,000 0	0,000 0
L7	7	0,000 5	0,000 4	0,0559	2	0,000 0	0,000 0
L8	8	0,000 6	0,000 5	0,0639	3	0,000 1	0,000 0
L9	9	0,000 4	0,000 4	0,0464	4	0,000 1	0,000 1
L10	10	0,000 4	0,000 5	0,0556	5	0,000 1	0,000 1
L11	11	0,000 4	0,000 6	0,0601	10	0,000 4	0,000 6
ACL	-	-	-	**0,625 1**	-	**0,001 0**	**0,001 1**

The WT transformers are assumed to be identical. The parameters for the WT transformers in WT base per-unit values and the parameters for the WP transformer in WP base per-unit values are given in Table A.2.

Table A.2 – Transformers parameters

Transformer	per-unit base	r_1	x_1	r_2	x_2	x_M
TRWT	Z_{base}	0,004 4	0,050 0	0,004 4	0,050 0	1 960
TRWP	Z_{base}	0,000 7	0,031 5	0,000 7	0,031 5	1 350