Prof. Poul Sørensen, convener of IEC 61400-27

Standards for modelling of wind in power system studies

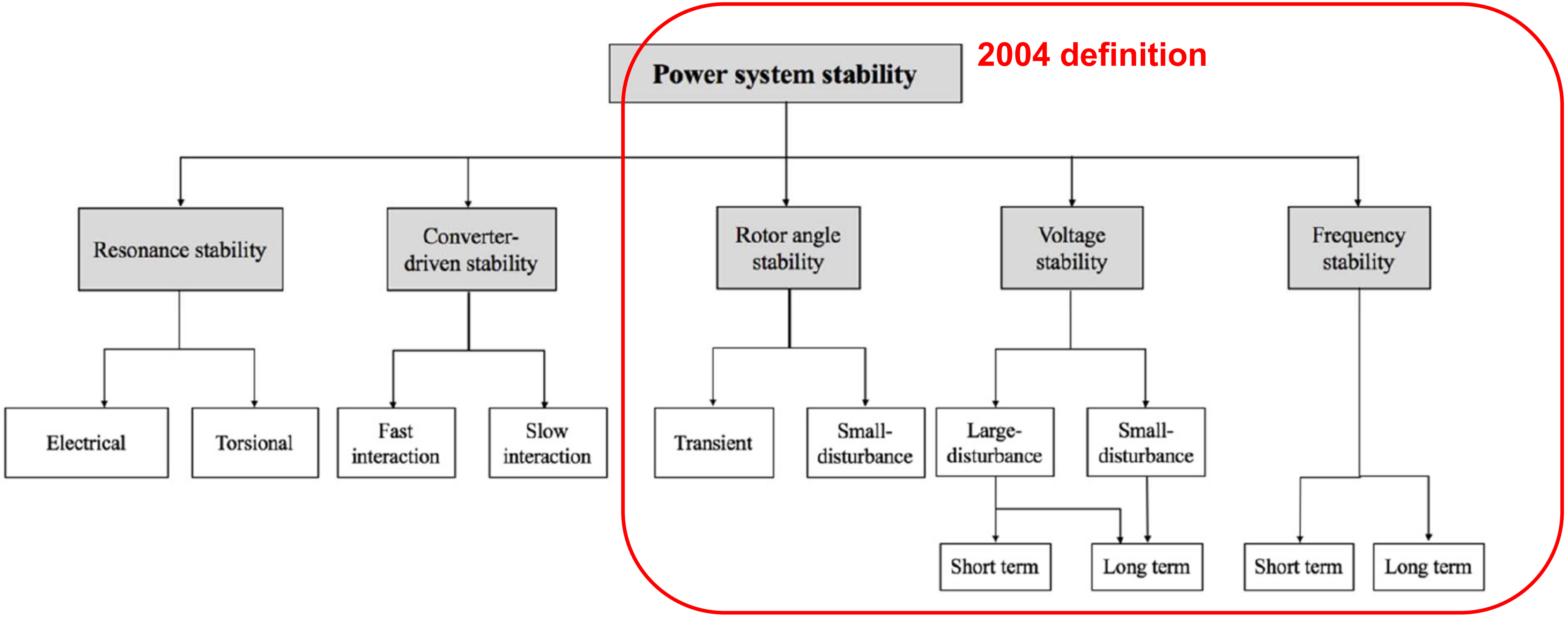
Outline

- Introduction
  - Power system stability definition
  - Types of models used in power system studies
  - Why generic models
  - Standards and best practices (-27, WECC, CIM, -21-3, CIGRE)
- Generic fundamental frequency (RMS) models
  - IEC 61400-27-1
  - WECC
- Validation of fundamental frequency (RMS) models
  - IEC 61400-27-2

Introduction

- Power system stability definition
- Types of models used in power system stability studies
- Why generic models
- Standards and best practices (-27, WECC, CIM, -21-3, CIGRE)

Power system stability definition(s)



Source:

Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies

IEEE Power & Energy Society TECHNICAL REPORT PES-TR77 April 2020

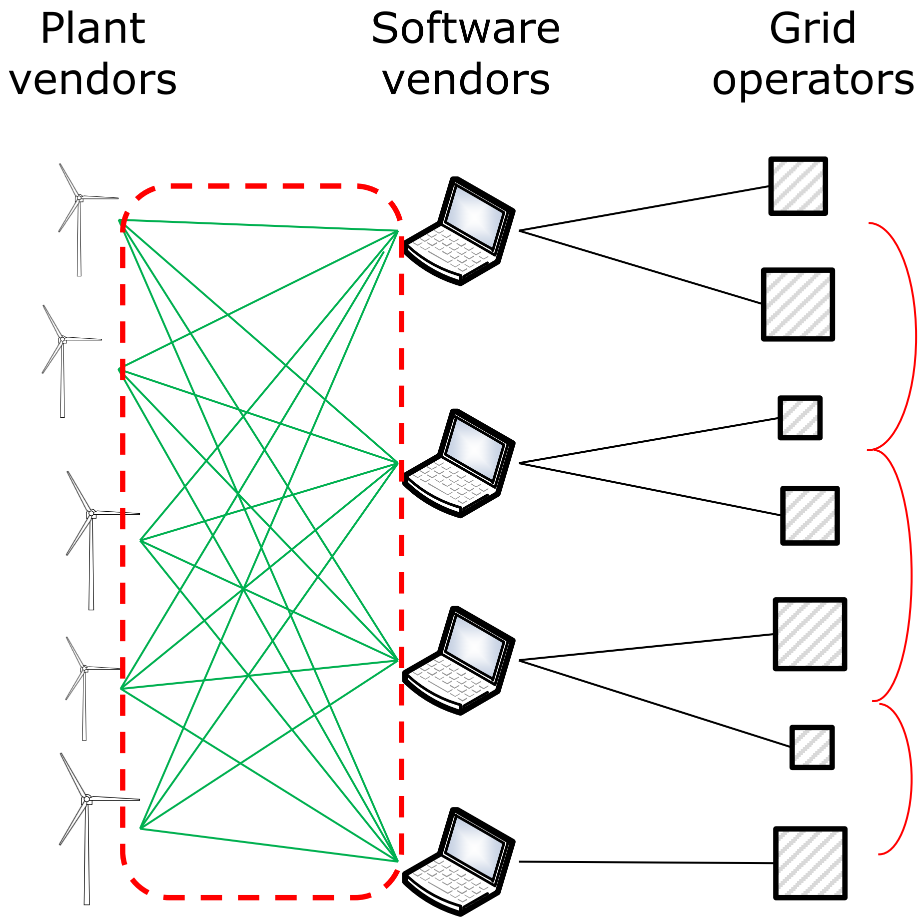
Types of models used in power system stability studies

- CENELEC CLC/TS 50654-1:2018 distinguishes between the following 7 types of models:
  1. Load flow models
  2. Short-circuit models
  3. Protection system models
  4. Insulation coordination related models
  5. Electromechanical transient models
  6. Electromagnetic transient models
  7. Power quality models

- TSO & developer questionnaire in EU PROMOTioN project found that this sub-division of models does not exactly reflect used types of models
- One reply specified :
  – Load flow models
  – Short-circuit and protection system models
  – Electromechanical transient models (often denoted RMS models or fundamental frequency models)
  – EMT models both for EMT studies and insulation coordination studies
  – Models for harmonic / power quality studies

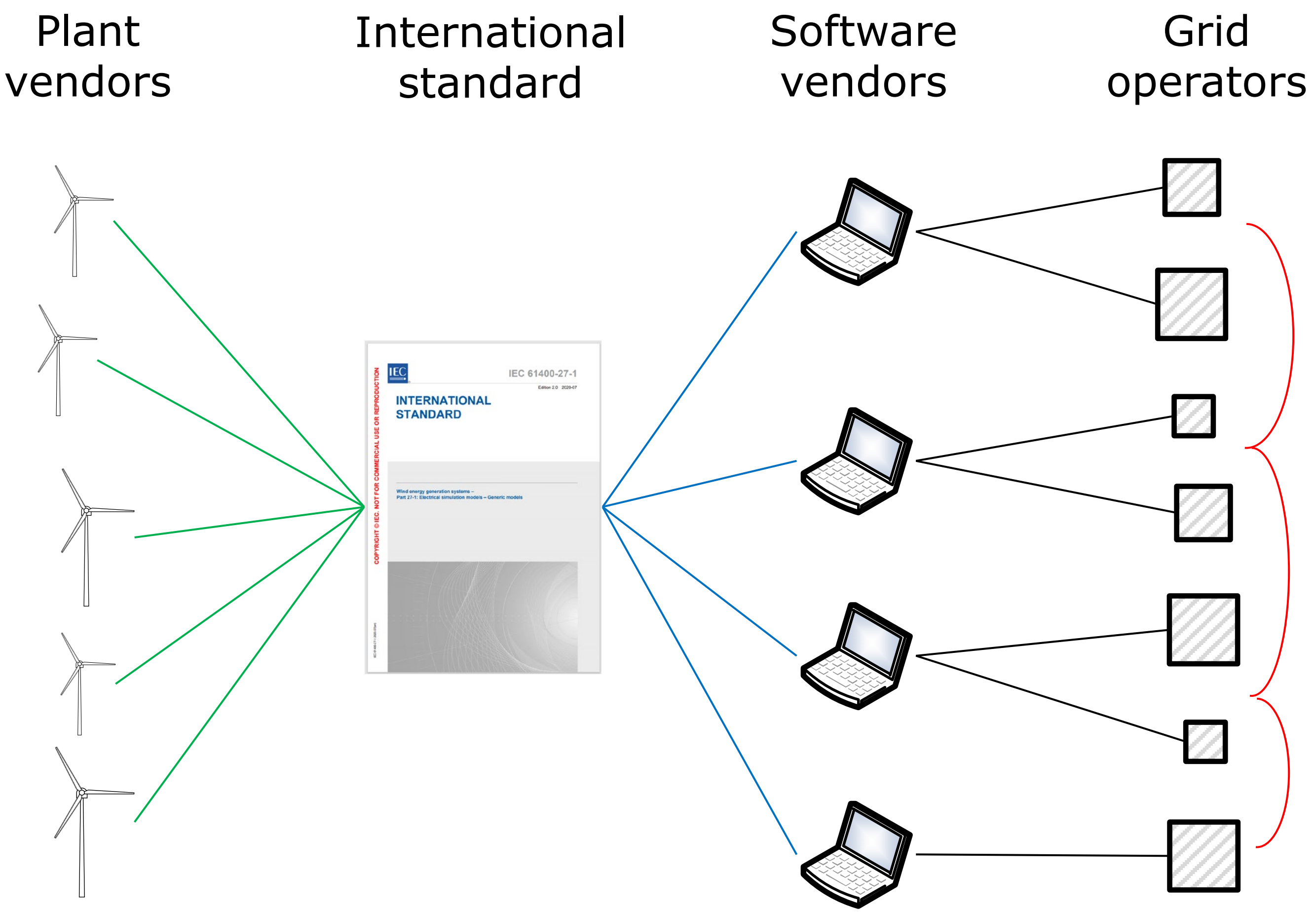
Why generic models?

- Different grid operators use different software
- In order to connect to a system operator grid, plant vendors need to supply models in the software used by that system operator
- This model development and model validation requires extensive work from plant vendors
- Interconnected grid operators also have difficulties exchanging models if they use different software



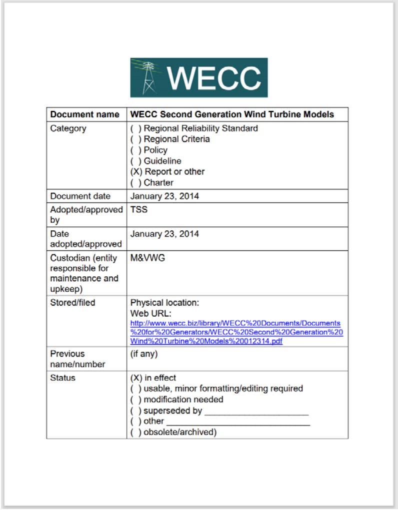
Why generic models?

- Advantages of standard generic models:
  - Less implementation and validation work
  - Software vendors implement models
  - Eases model exchange
- Challenges:
  - Different vendor hardware and control
  - Competitive advantages of leading plant vendors



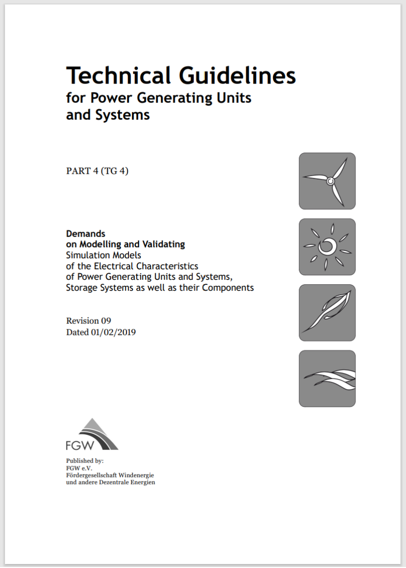
Fundamental frequency models

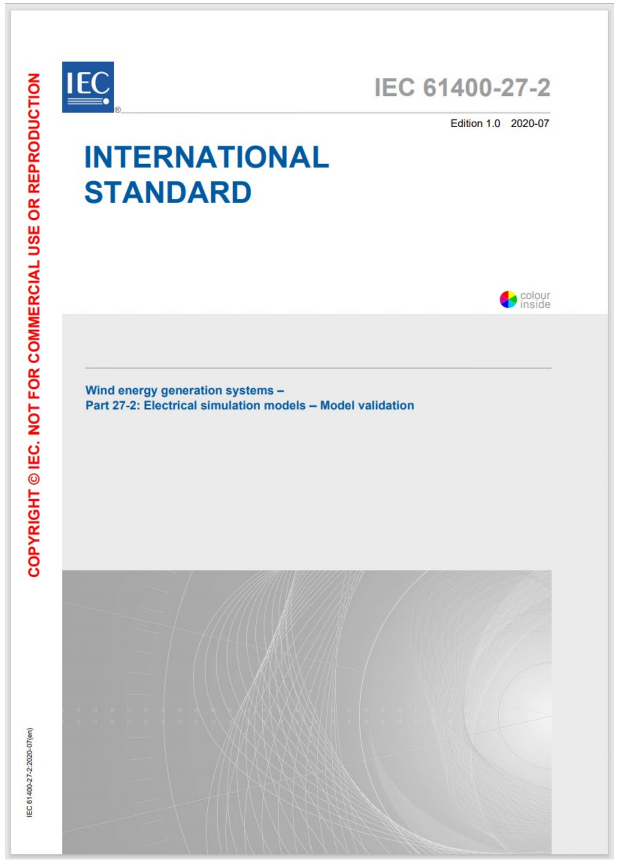
Generic models: WECC and IEC



Document name	WECC Second Generation Wind Turbine Models
Category	( ) Regional Reliability Standard ( ) Regional Criteria ( ) Policy ( ) Guideline (X) Report or other ( ) Charter
Document date	January 23, 2014
Adopted/approved by	TSS
Date adopted/approved	January 23, 2014
Custodian (entity responsible for maintenance and upkeep)	M&VWG
Stored/filed	Physical location: Web URL: http://www.wecc.biz/library/WECC%20Documents/Documents%20for%20Generators/WECC%20Second%20Generation%20Wind%20Turbine%20Models%20012314.pdf
Previous name/number	(if any)
Status	(X) in effect ( ) usable, minor formatting/editing required ( ) modification needed ( ) superseded by ____________ ( ) other ____________ ( ) obsolete/archived)

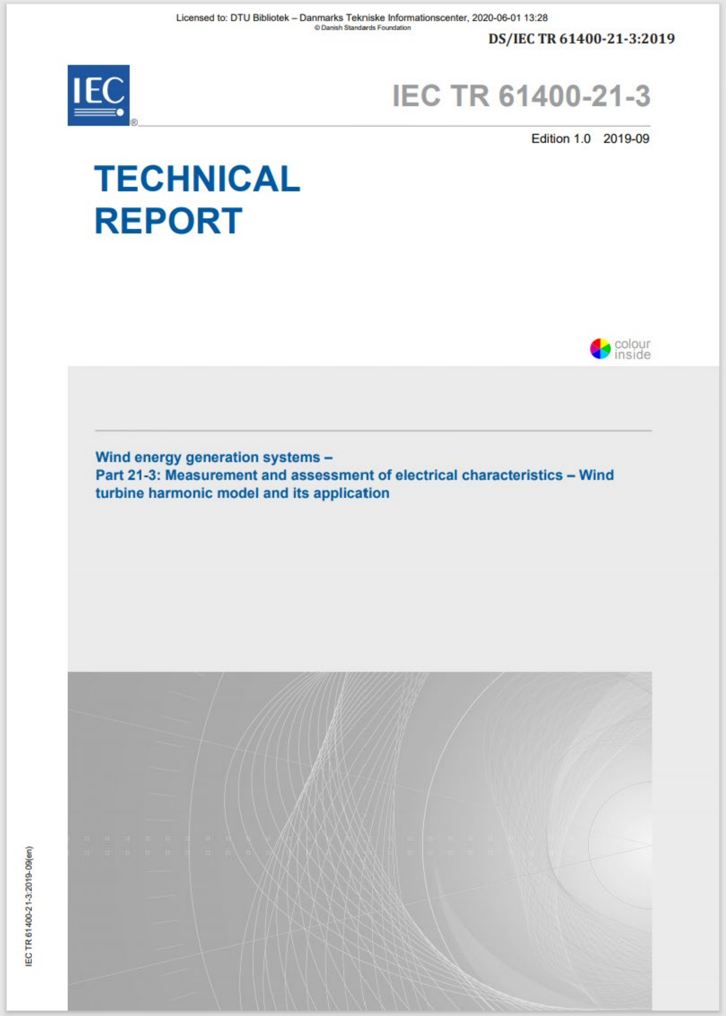
Model validation: German and IEC

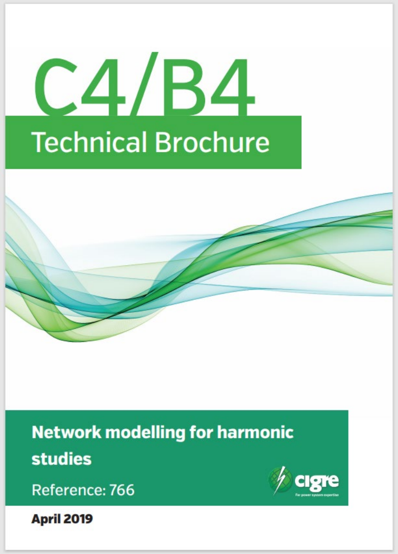




Best practices for multifrequency (harmonics) modelling

- IEC 61400-21-3 (2019)
  - Technical report – not standard
  - Content:
    - Norton or Thevenin equivalent representation for type 3 and type 4 wind turbines
    - Model validation case definitions
- Cigre TB 776 (2019)
  - Network modelling
- Cigre WG C4.49: Multi-frequency stability of converter-based modern power systems (2021-06)
  - Linear modelling for small system stability studies, time domain simulations, frequency and sequence coupling
  - Mitigation (stability requirements, resonance studies, active damping…)
- Cigre WG C4.65: Specification, Validation and Application of Harmonic Models of Inverter Based Resources (2021-Q3)
- IEC New work item proposal (NWIP) under preparation





EMT modelling

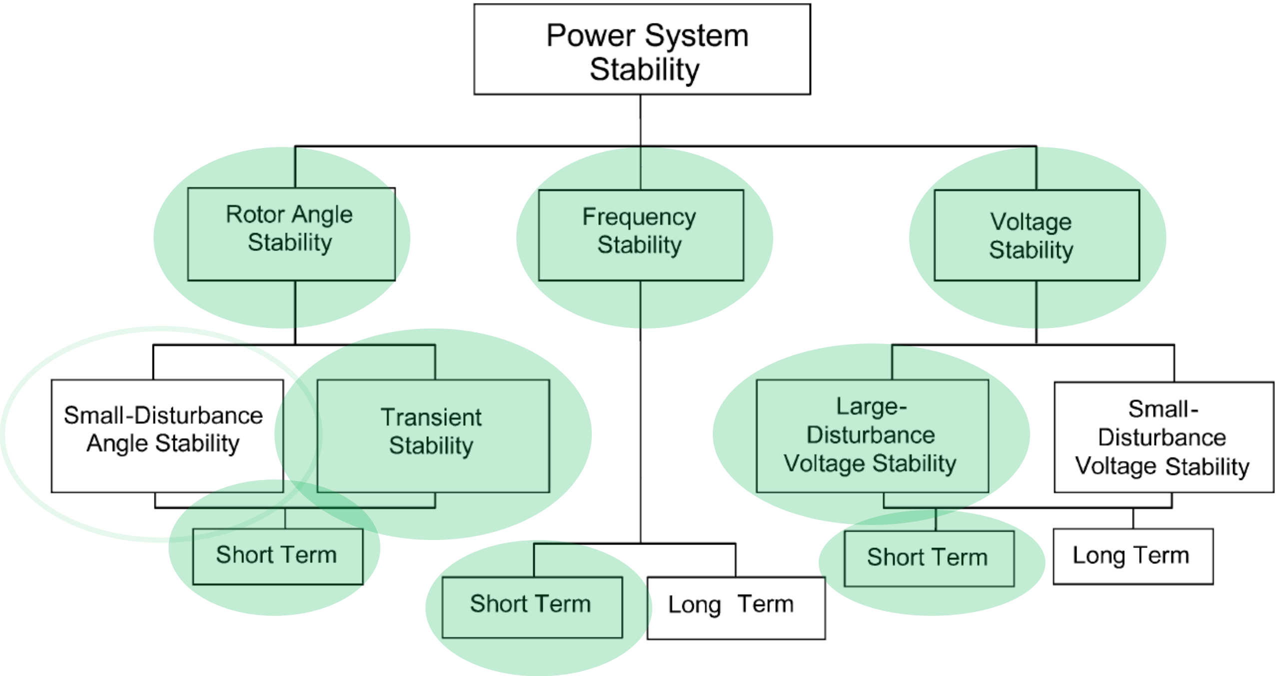
- Informative annex in IEC 61400-27-2 on specification of generic model interface
- Cigre WG B4.82 / IEEE: Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and Inverter based generators in Power Systems Analysis (2019-09)
  - Specify necessary parameters
  - Comparison of “real-code” (OEM) models to generic models
- IEC New work item proposal (NWIP) under preparation

Generic fundamental frequency ("RMS") models

- IEC 61400-27-1: Wind energy generation systems – Electrical simulation models – Generic models
- WECC Second Generation Wind Turbine Models
- IEC 61970-302: Common information model (CIM) dynamics.

Scope of IEC 61400-27 – general

- IEEE/CIGRE Joint Task Force on Stability Terms and Definitions has categorized power system stability
- IEC 61400-27 generic models are intended for short term stability studies
- Models simulate fundamental frequency positive sequence



Classification of power system stability according to IEEE/CIGRE Joint Task Force on Stability Terms and Definitions. (© IEEE 2004)

Scope of IEC 61400-27 models
– 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.
- Linearisation for *eigenvalue analysis* is not trivial nor necessarily appropriate based on these simplified models.
- This standard does not address the specifics of *short-circuit calculations*.
- The models are not applicable to studies of *extremely weak systems* including situations where wind turbines are islanded without other synchronous generation as well as cases with extremely low short-circuit ratios.
- Models do not include *negative and zero sequences*

Scope of IEC 61400-27 – Potential users

- ***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 turbine manufacturers*** will typically provide the wind turbine models to the owner,
- ***Wind plant owners*** are typically responsible to provide the wind power plant models to TSO and/or DSO prior to plant commissioning,
- ***Developers of power system simulation software*** will use the standard to implement standard wind power models as part of the software library, and
- ***Certification*** companies will use standard to verify simulation models
- ***Education and research*** communities, who can also benefit from the generic models, as the manufacturer specific models are typically confidential.

IEC 61400-27-1 Edition 2.0 (2020-07)

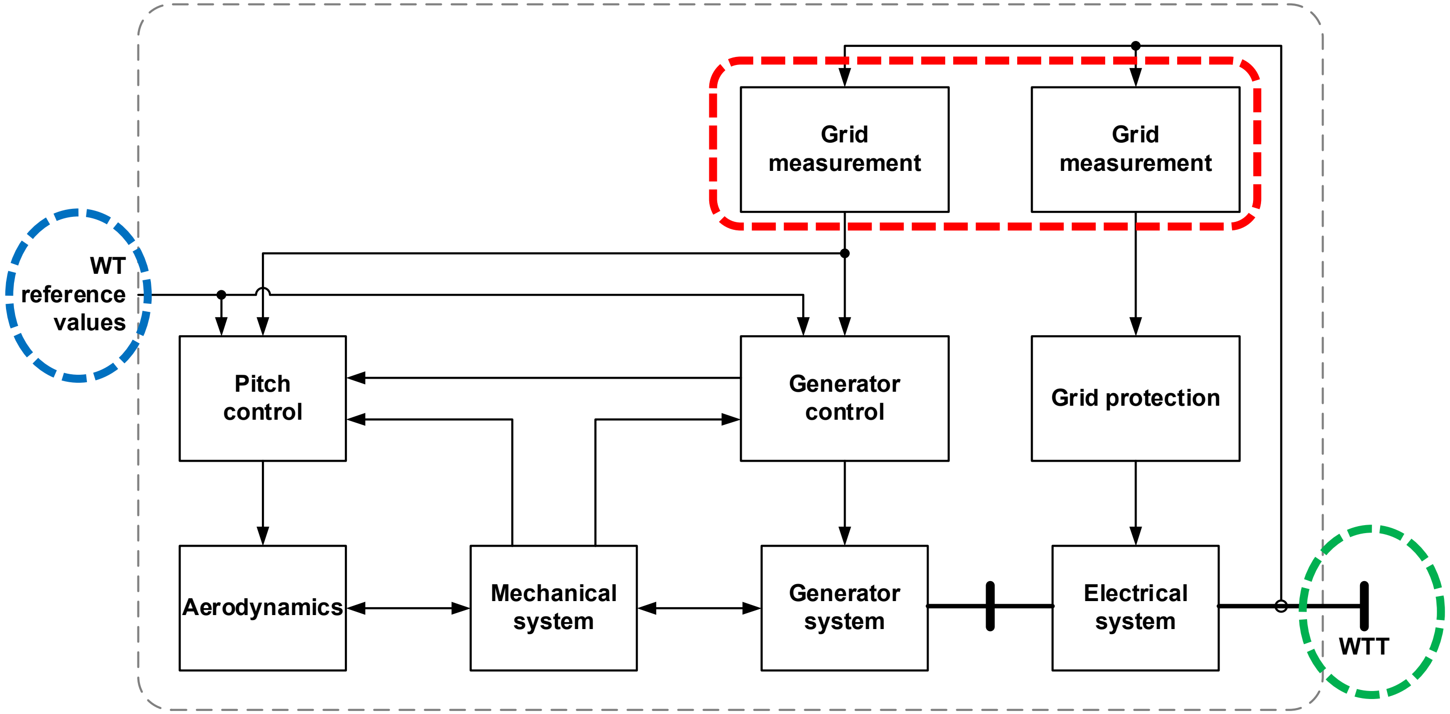
- Wind energy generation systems – Electrical simulation models – Generic models
  - – Scope
  - – References and definitions
  - – Functional specification of models
  - – Formal specification of
    - Modular structure of models
    - Modules
  - – Includes models for
    - Wind turbine types 1-4
    - Auxciliary equipment
    - Wind power plants

Modular structure

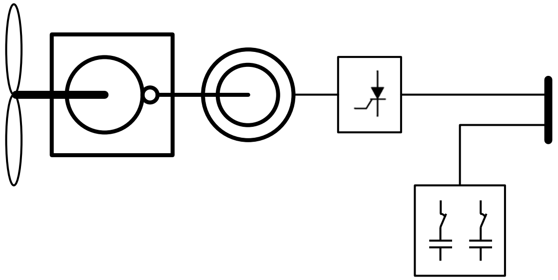
- Modular struture was introduced in IEC 61400-27-1 Edition 1.0:
  - *Sørensen, Poul Ejnar • Andresen, Bjørn • Fortmann, Jens • Pourbeik, Pouyan*. Modular structure of wind turbine models in IEC 61400-27-1. **IEEE Power & Energy Society General Meeting, Vancouver 2013**
  - Flexible structure supporting
    - ***needs for revisions*** of future generic models
    - ***share of modules*** between different wind turbine types (e.g. mechanical module) and between wind tubines and wind power plants (e.g. grid measurement module)
    - ***expansion of models with non-generic features*** (e.g. manufacutrer specific models or new control features)

Modular structure of WT models – Edition 2.0 (tbc)

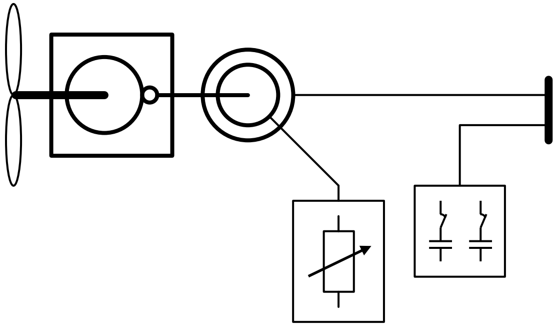
- WT model refers to the wind turbine terminal (WTT)
- Can receive external reference values
- Uses software built-in models for ”electrical system” module
- Grid measurement block is used twice (one formal specification but different parameters)



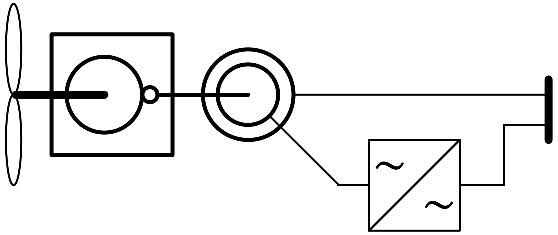
Wind turbine types



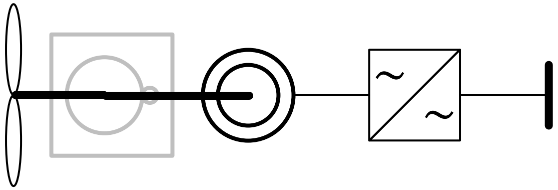
Type 1



Type 2



Type 3

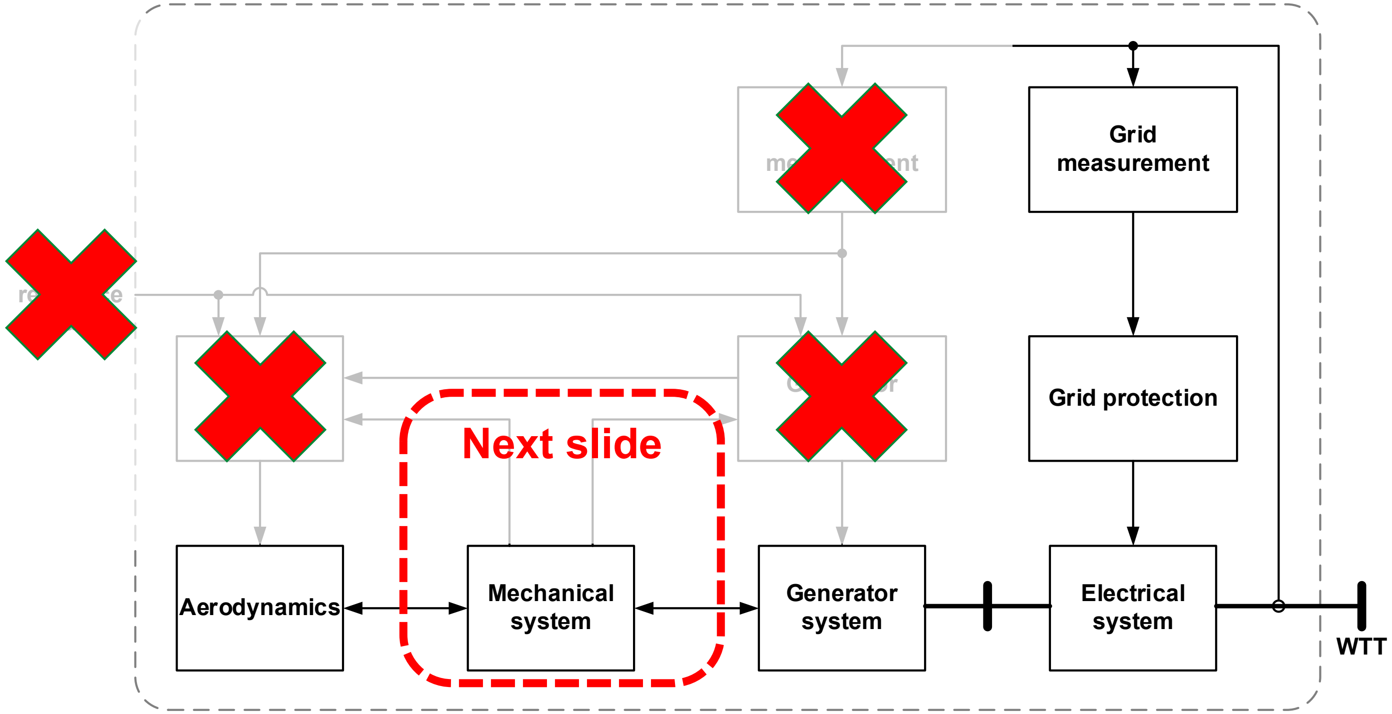


Type 4

Type 1A modular structure

- Two type 1 models:
  - 1A: fixed pitch angle
  - 1B: UVRT pitch control

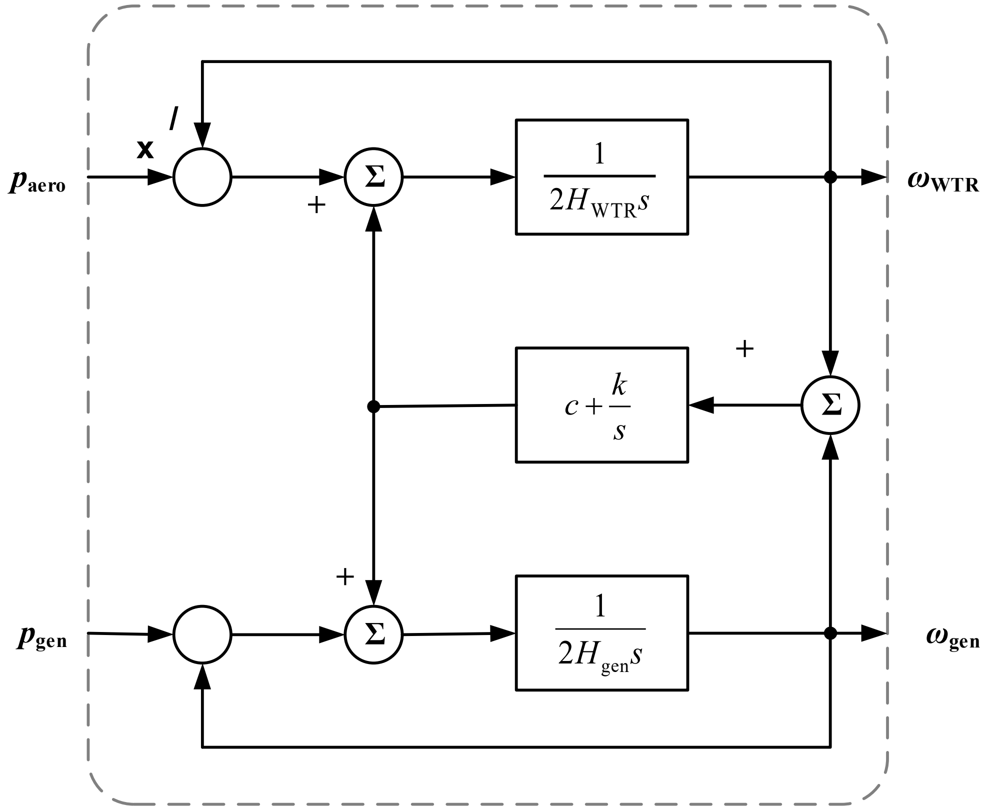
- Type 1: Directly connected induction generator:
  - No WT reference values
  - No generator control
- Subtype 1A:
  - No pitch control



Module specification example – mechanical module

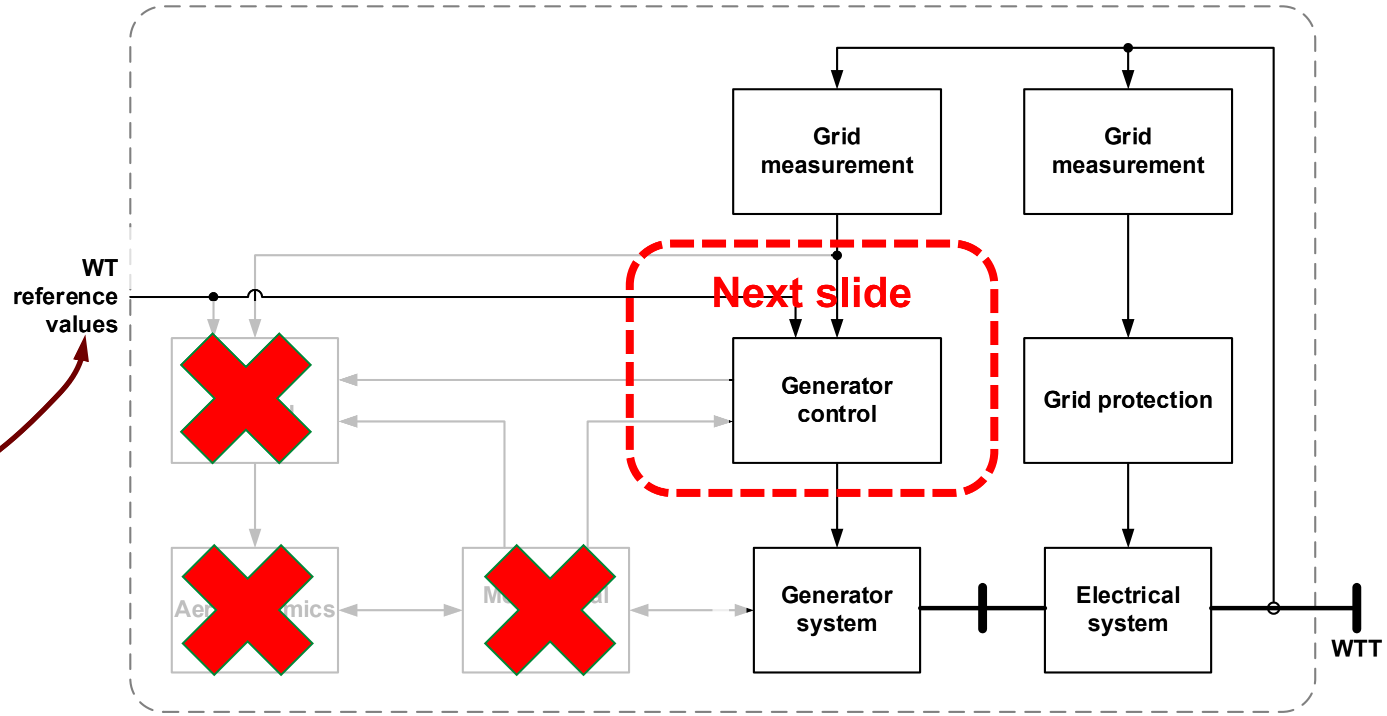
- Power input chosen (could have been torque instead)
- All modules are specified by a block diagram and a parameter list
- Models are in per-unit (no gear ratio)
- All model parameters are listed:

Symbol	Base unit	Description	Category
H_{WTR}	s	Inertia time constant of WT rotor	Type
H_{gen}	s	Inertia time constant of generator	Type
k	$\mathrm{T}_{\mathrm{base}}$	Drive train stiffness	Type
c	$\mathrm{T}_{\mathrm{base}}/\Omega_{\mathrm{base}}$	Drive train damping	Type



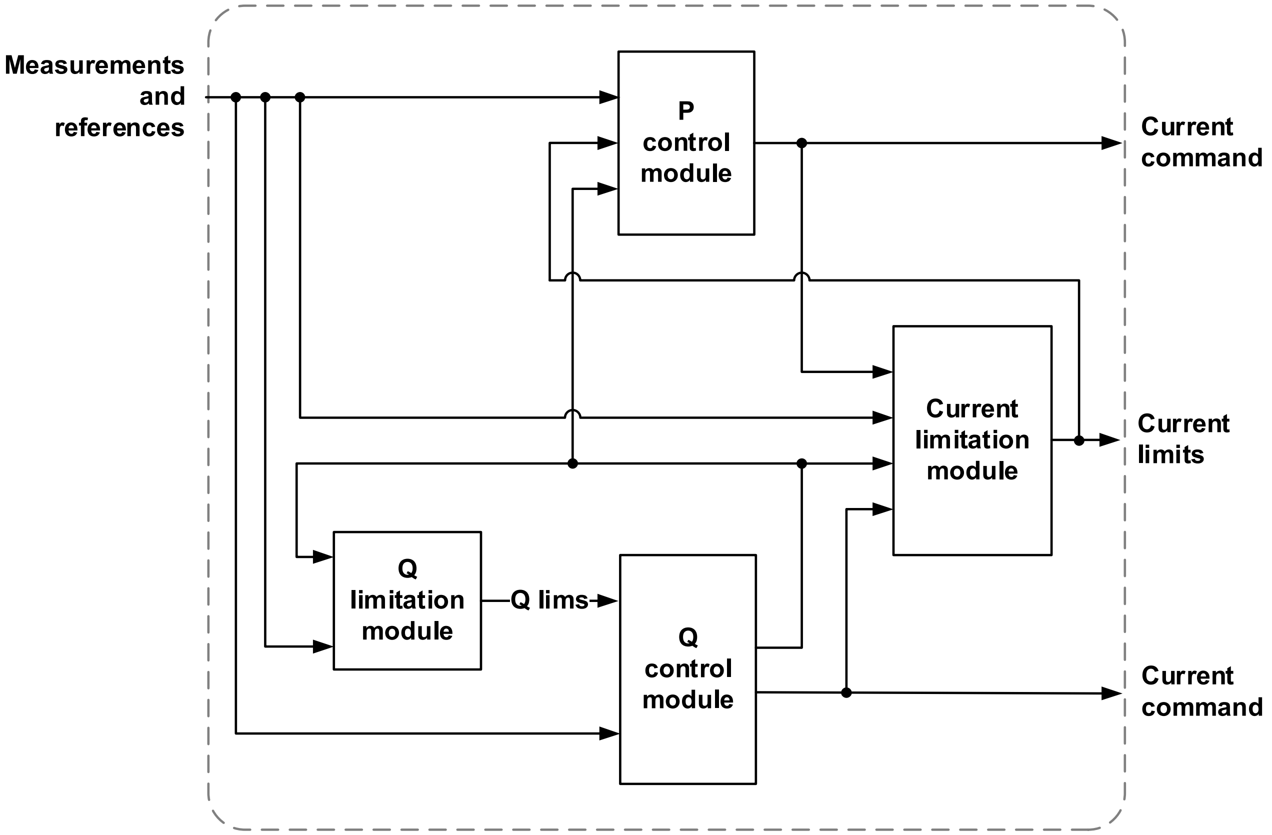
Type 4A modular structure

- Two type 4 models:
  - 4A: Full DC chopper capacity
  - 4B: Limited DC chopper capacity
- Type 4: Full converter generator system
  - Aerodynamic system and associated pitch control not modelled
- Subtype 4A:
  - no mechanical oscillations
- WT reference values:
  - P_{WTref}:
    - Active power
  - x_{WTref}:
    - Reactive power
    - Voltage (delta)



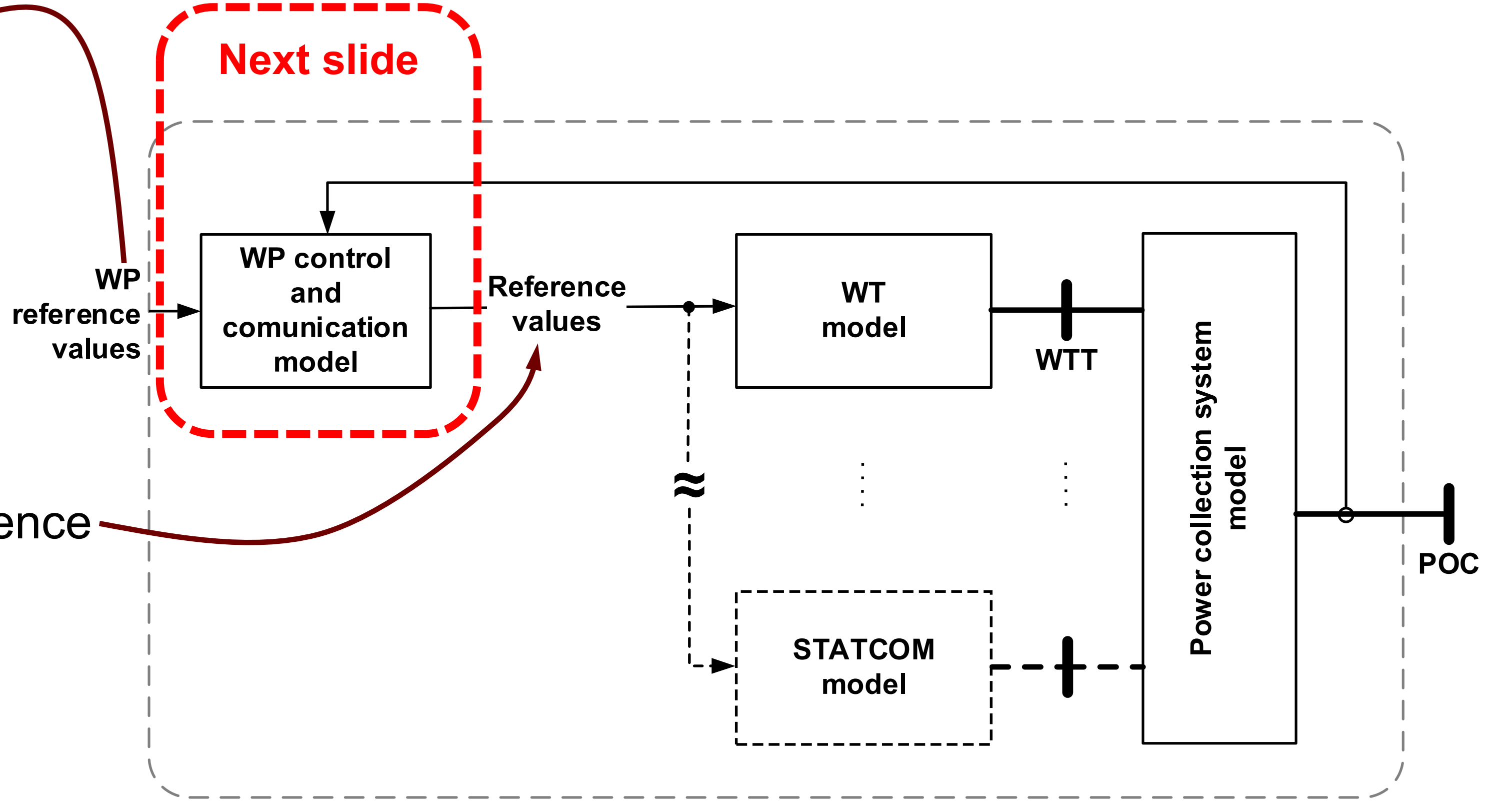
Type 4A generator control modular sub-structure

- P-control: specific for type 4A
- Q-control: same as for type 3 and type 4 (A and B)
- Current limitation:
  - Maximum current depending on P/Q-priority
  - Includes voltage limitation
- Q limitation:
  - Lookup table (e.g. from grid code)



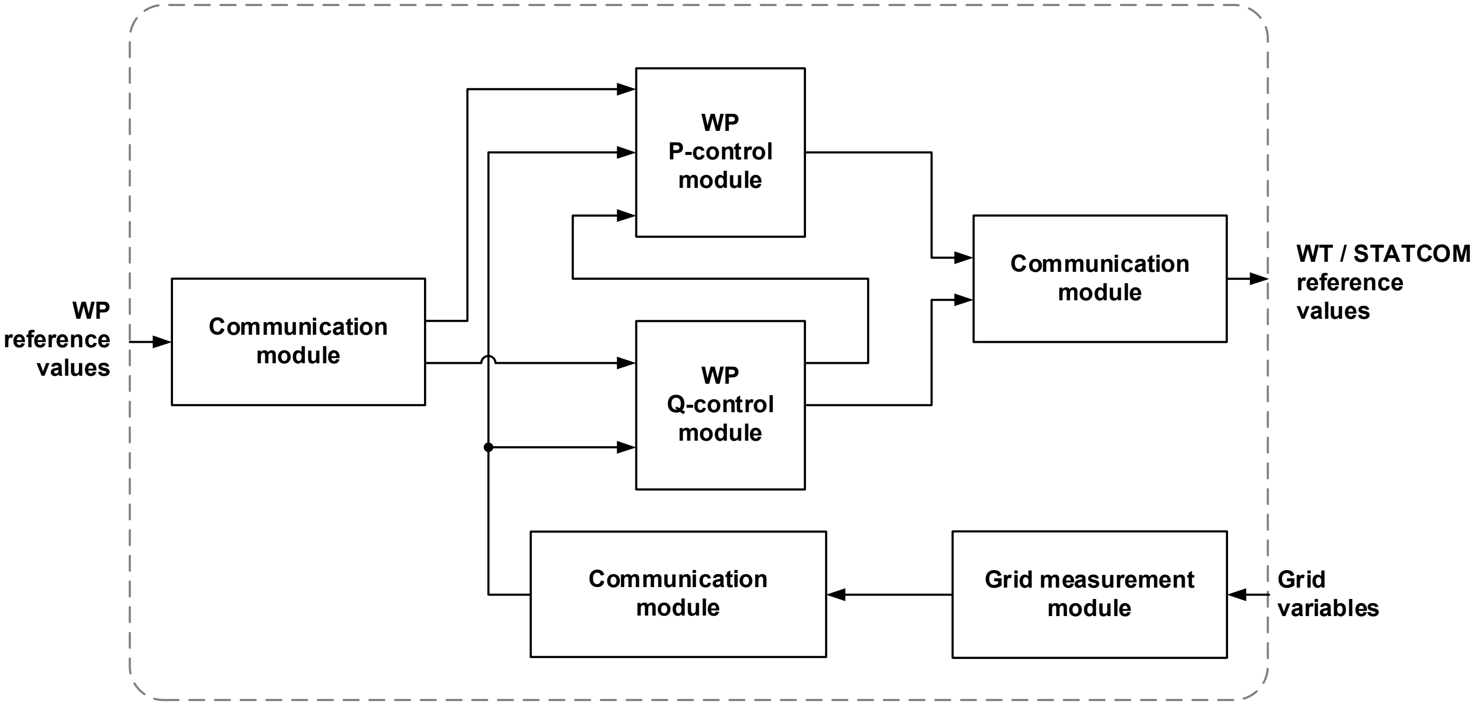
Interfaces between turbine, plant control and grid models

- Plant reference values:
  - P_{WPref}:
    - Active power
  - x_{WPref}:
    - Reactive power
    - Power factor
    - Voltage
- WT and STATCOM reference values:
  - P_{PDref}:
    - Active power
  - x_{PDref}:
    - Reactive power
    - (Delta) voltage



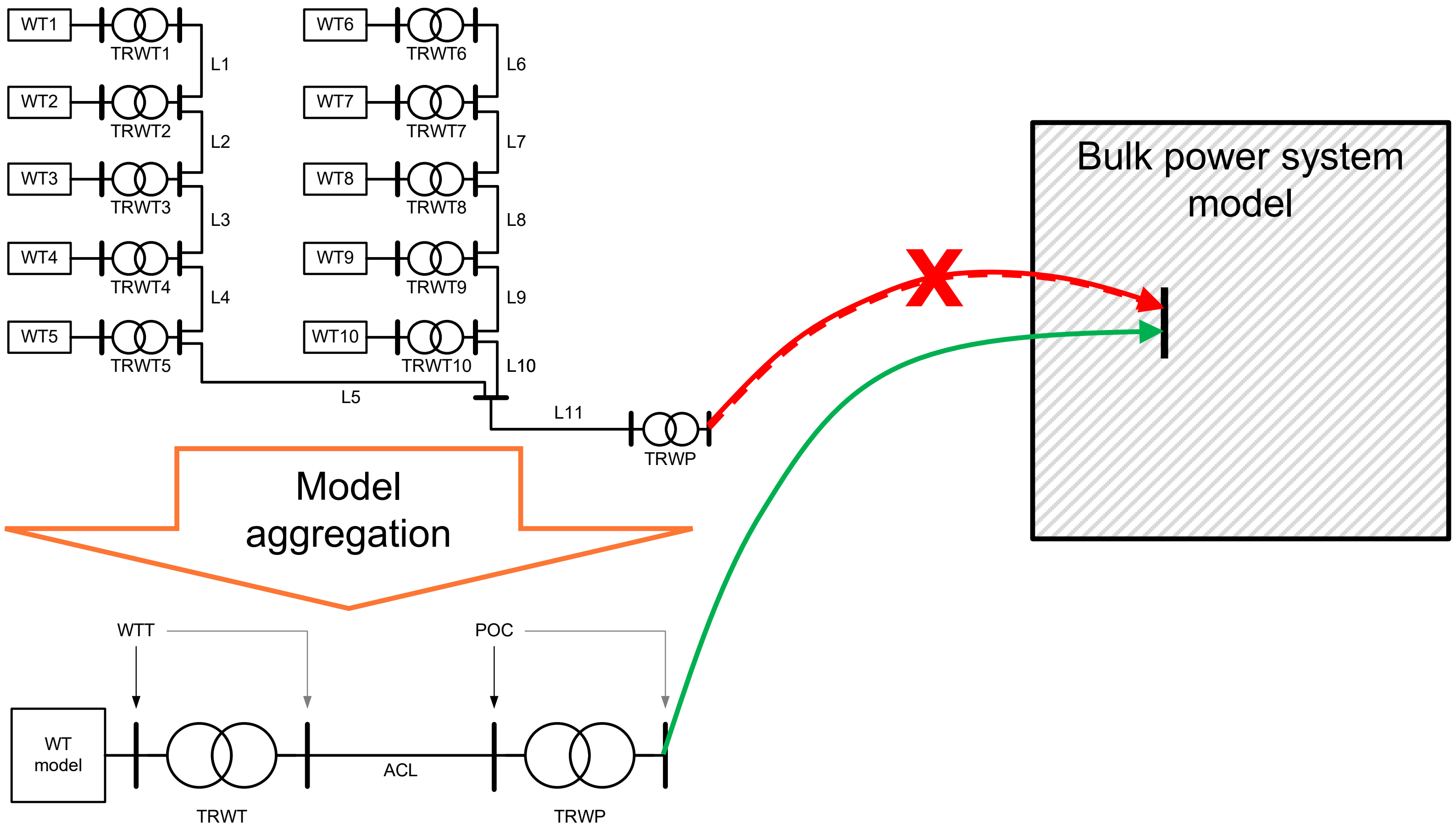
WP control and communication model - substructure

- 3 communication modules:
  - Same dynamic specification
  - Different parameters



IEC 61400-27

Power collection system models - aggregation

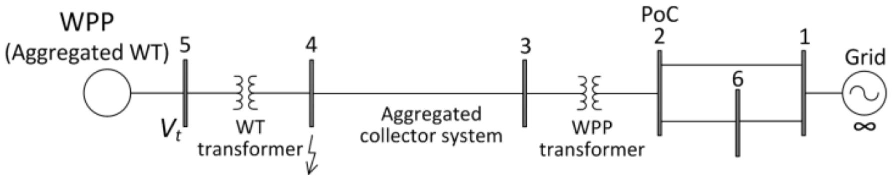


Link to WECC / IEEE models

- The Western Electric Coordinating Council (***WECC***) Renewable Energy Modeling Task Force, in North America, ***and*** the ***IEEE Working Group*** on Dynamic Performance of Wind Power Generation have jointly developed a set of generic wind turbine models, which are ***implemented in Siemens PTI PSS®E and GE PSLF®***.
- A ***2nd generation of the WECC models*** (2014) has been developed ***jointly*** with the development of IEC 61400-27-1 Ed1 (2015-02).
- As these models have been developed jointly, they are ***very similar, but*** at this stage, there are also ***some differences*** the IEC models and the 2nd generation WECC models.
- The main reason for the present differences between WECC and IEC models is that the ***WECC models*** mainly aim at credible simulation of the post-fault behavior of the wind plant behavior with a ***minimum model complexity***, while the ***IEC models*** include more details to meet more ***demanding European requirements for model accuracy*** during faults.
- IEC models aimed to be ***compatible*** with WECC models, but ***not 100%*** successful

Comparison og IEC and WECC models

- Comparisons between IEC 61400-27-1 Ed 1.0 and WECC 2nd generation is performed in
  - *Göksu, Ömer; Sørensen, Poul Ejnar; Morales, Ana; Weigel, Stefan; Fortmann, Jens; Pourbeik, Pouyan.* Compatibility of IEC 61400-27-1 Ed 1 and WECC 2nd Generation Wind Turbine Models. 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, 2016
- Simulation tools
  - IEC models in Power Factory (DIgSILENT)
  - WECC models in PSS/E
- Simulation case: WECC test system



- Reasons for deviations:
  - No stator current limits in WECC models
  - Minor differencies in generator system models
  - Differencies in active damping models

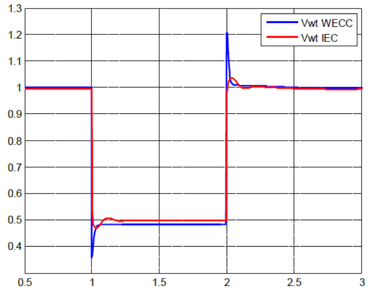


Figure 6. WT voltage for type 3 [pu] vs time [s]

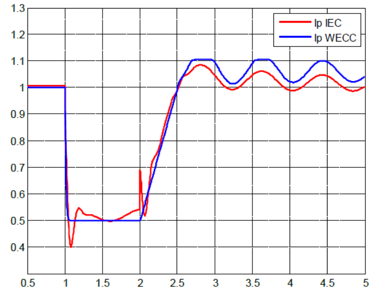


Figure 7. WT Active Current Actual Values for type 3 [pu] vs time [s]

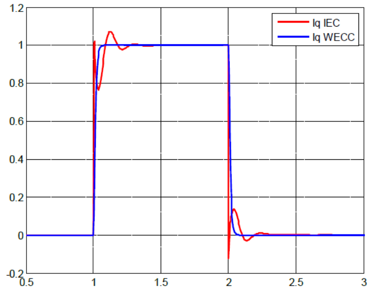
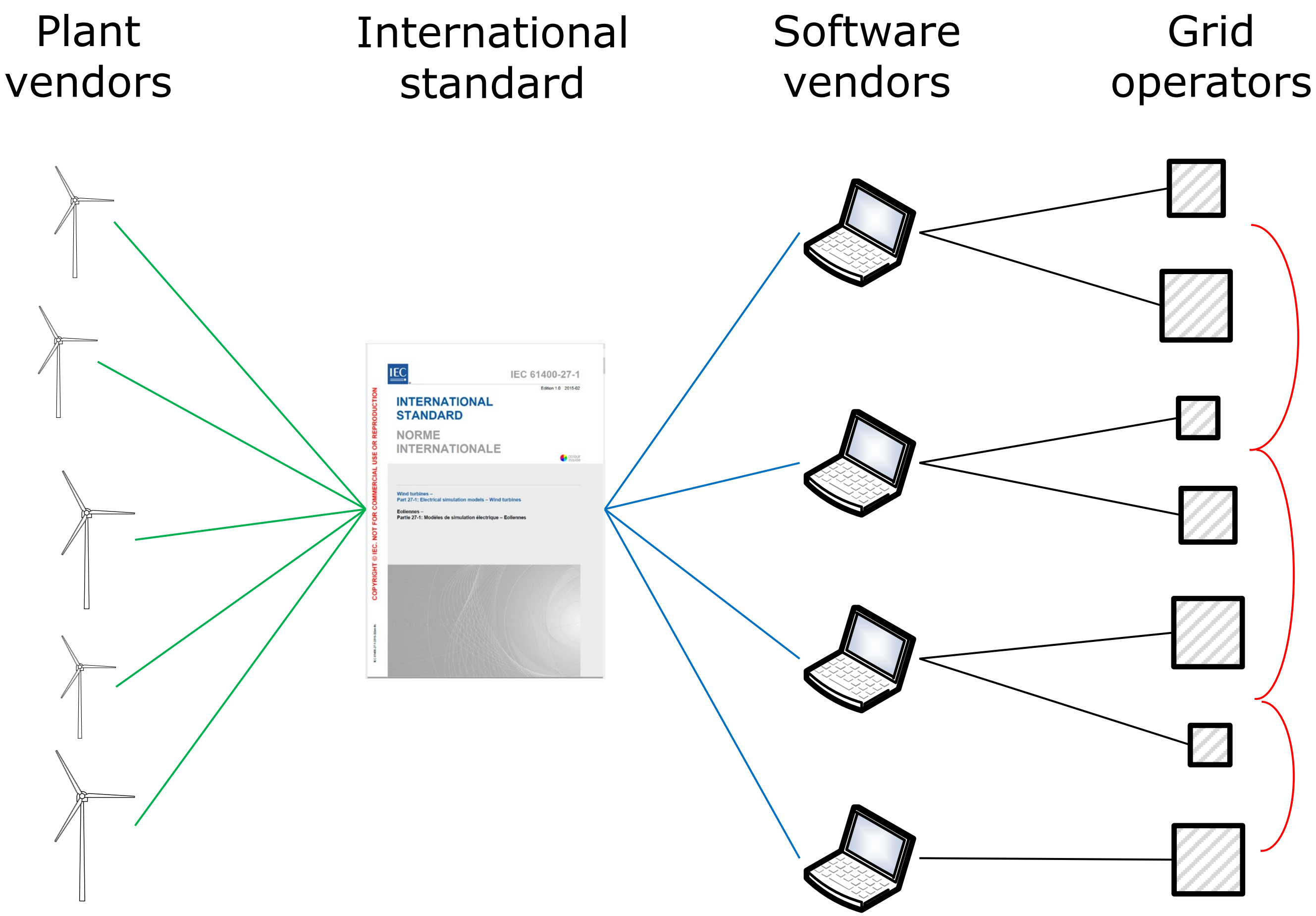


Figure 8. WT Reactive Current Actual Values for type 3 [pu] vs time [s]

IEC Common Information Model (CIM)

- IEC Technical Committee ***TC57*** deals with the scope Power systems management and associated ***information exchange***.
- As part of this scope, TC57 defines ***Common Information Model (CIM)*** standards for exchange of power systems data.



IEC CIM standards and link to IEC 61400-27

- TC57 standards for Common Information Model (CIM) are published in IEC 61400-3xx series:
  - IEC 61970-301:2016 Common information model (CIM) base
    - for exchange of the *static data* of elements of the power systems.
  - IEC 61970-302:2018 Common information model (CIM) *dynamics*.
    - This CIM dynamics standard is based on available standardized models by IEC or IEEE.
    - Uses the models specified in IEC 61400-27-1 to represent the wind power dynamics.

- The ***ENTSO-E Common Grid Model Exchange Standard (CGMES)*** is a superset of IEC CIM standards (including IEC 61970-30x)
  - CGMES Dynamics group compares software vendor implementations in PowerFactory, Eurostag, NETOMAC, Neplan.

Validation of fundamental frequency (“RMS”) models

Scope of IEC 61400-27 model validation – general

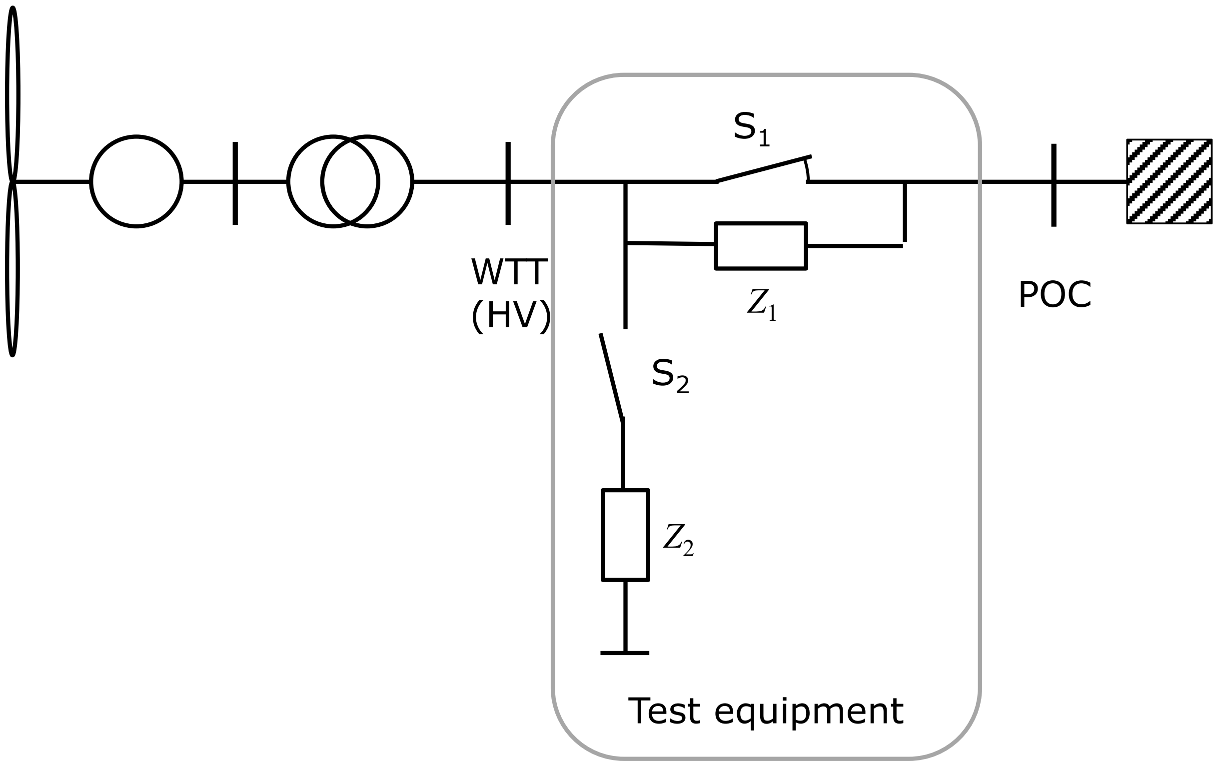
- The validation procedures are applicable to the generic models specified in IEC 61400-27-1 and to other fundamental frequency wind power plant models and wind turbine models.
  - Positive sequence
  - Negative sequence
- Uses tests from the IEC 61400-21 series
  - Part 21-1 Wind turbines published 2019
  - Part 21-2 Wind power plants – *under development*

Scope of IEC 61400-27 model validation – limitations

- The validation procedure does not specify any requirements to model accuracy. It only specifies measures to quantify the accuracy of the model
- The validation procedure does not specify test and measurement procedures, as it is intended to be based on tests specified in IEC 61400-21.
- The validation procedure does not include validation of steady state capabilities e.g. of reactive power, but focuses on validation of the dynamic performance of the models.
- The validation procedure does not cover long term stability analysis.
- The validation procedure does not cover investigation of the fluctuations originating from wind speed variability in time and space.
- The validation procedure does not cover phenomena such as harmonics, flicker or any other EMC emissions included in the IEC 61000 series.
- The validation procedure does not cover eigenvalue calculations for small signal stability analysis.
- This validation procedure does not address the specifics of short-circuit calculations.

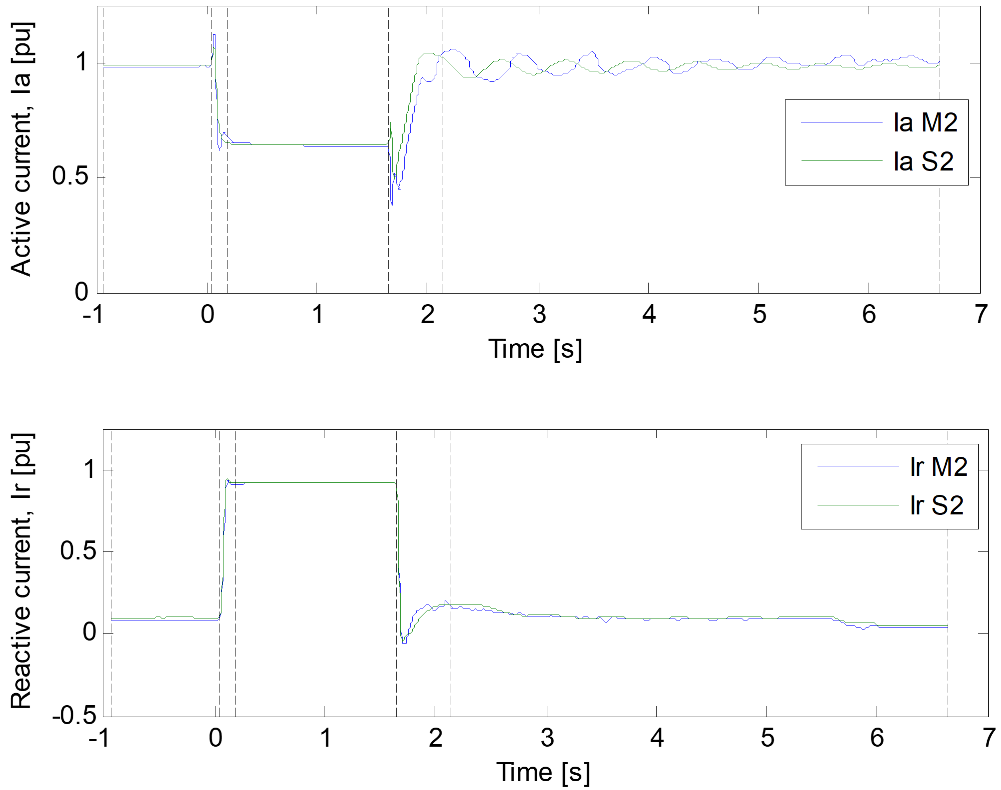
Model validation – wind turbine LVRT test

- Standard procedure for test of wind turbine response to voltage dips (low voltage ride through) is specified in IEC 61400-21



Model validation – wind turbine level

- Expected accuracy is higher in quasi steady state windows than in transient windows



Sørensen, Poul Ejnar ; Andresen, Björn ; Bech, John ; Fortmann, Jens ; Pourbeik, Pouyan. Progress in IEC 61400-27. In Proceedings of the 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 2012, Lisbon (PT), 13-15 Nov.

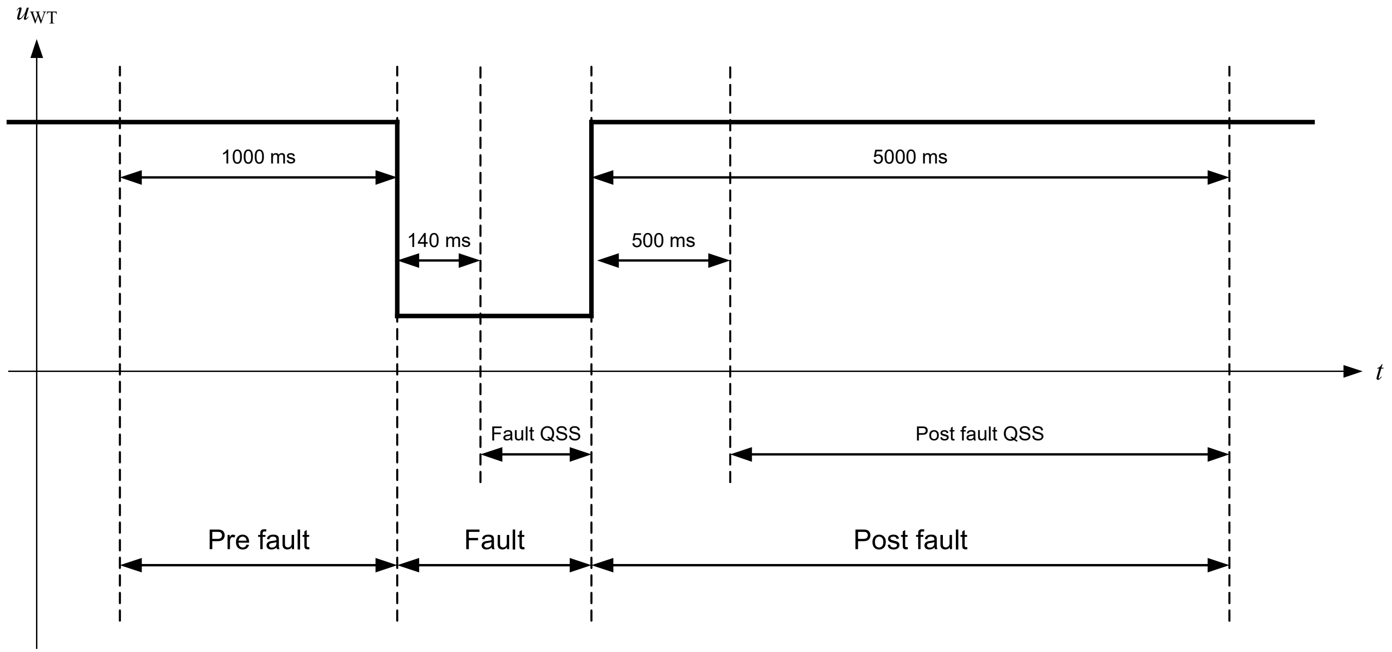
Error statistics calculation

- Definition of windows

- Error calculations
  - Max error (x_{MXE})
  - Mean error (x_{ME})
  - Mean absolute error (x_{MAE})

- Selection of windows:

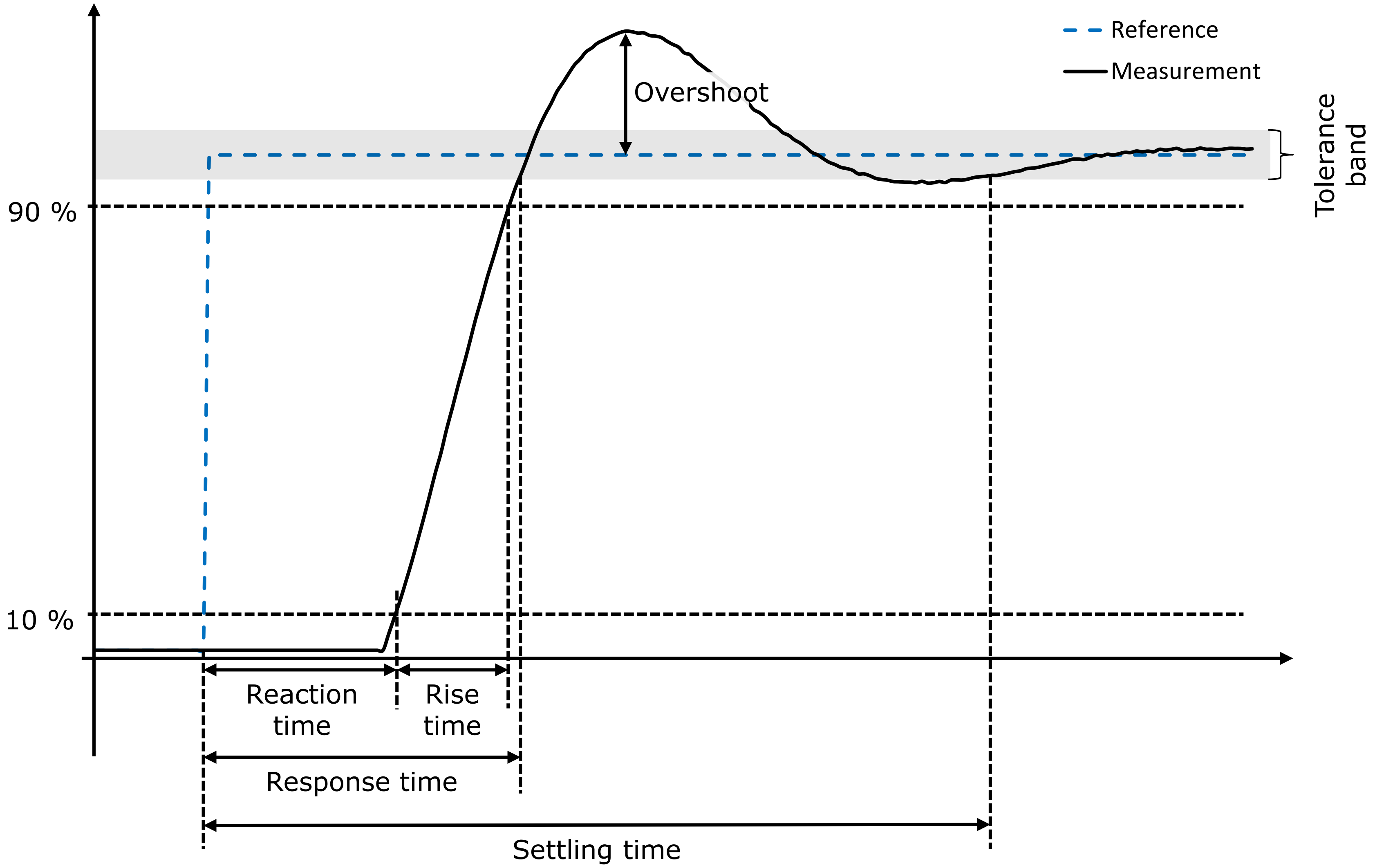
Window	x_{MXE}	x_{ME}	x_{MAE}
Pre fault	Full	Full	Full
Fault	QSS	Full	QSS
Post fault	QSS	Full	Full



Response to reference value changes

- Response results:
  - Response time
  - Reaction time
  - Rise time
  - Overshoot
  - Settling time

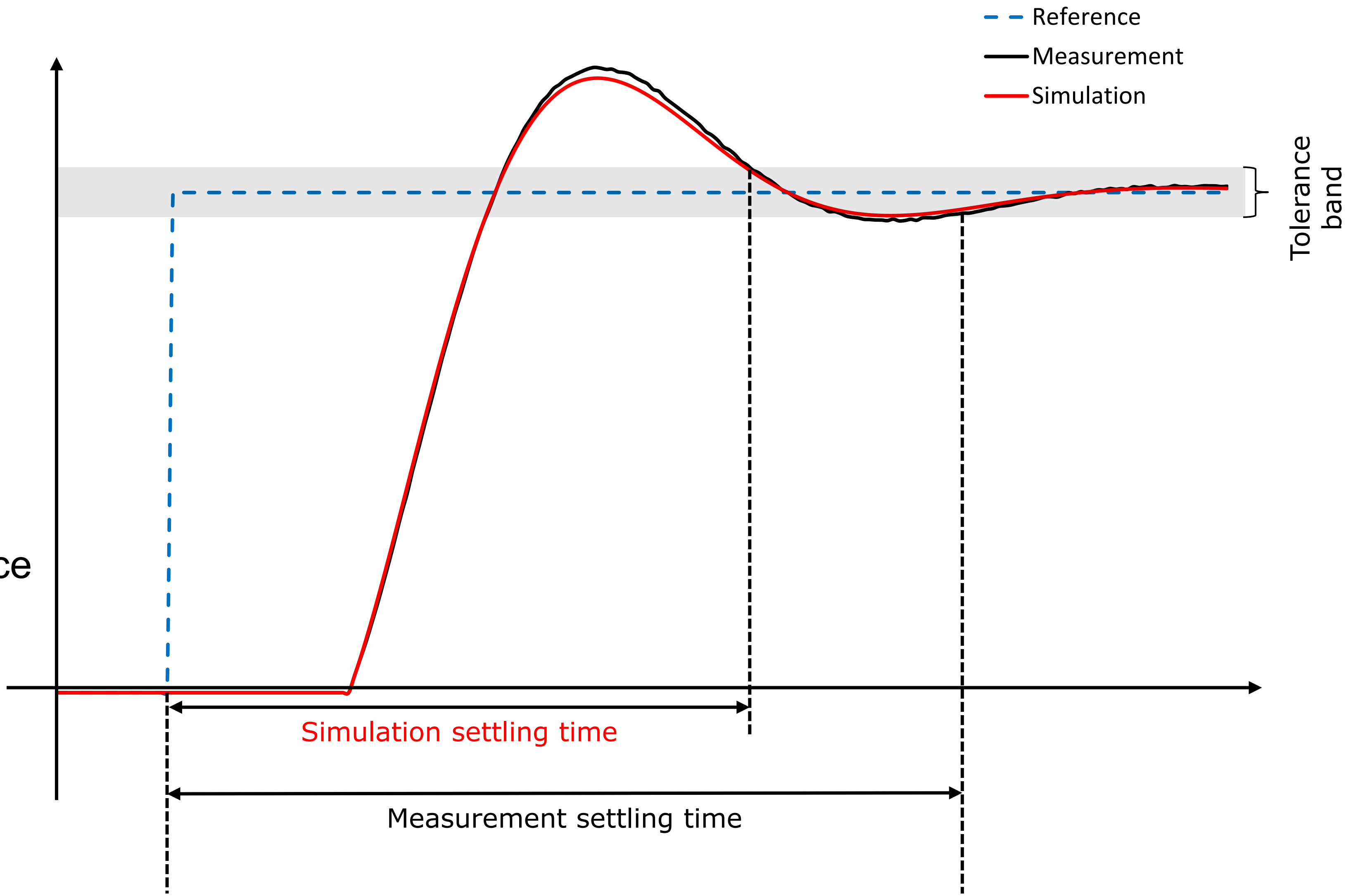
- Model validation:
  - Compare measured response results to simulated



Settling time validation

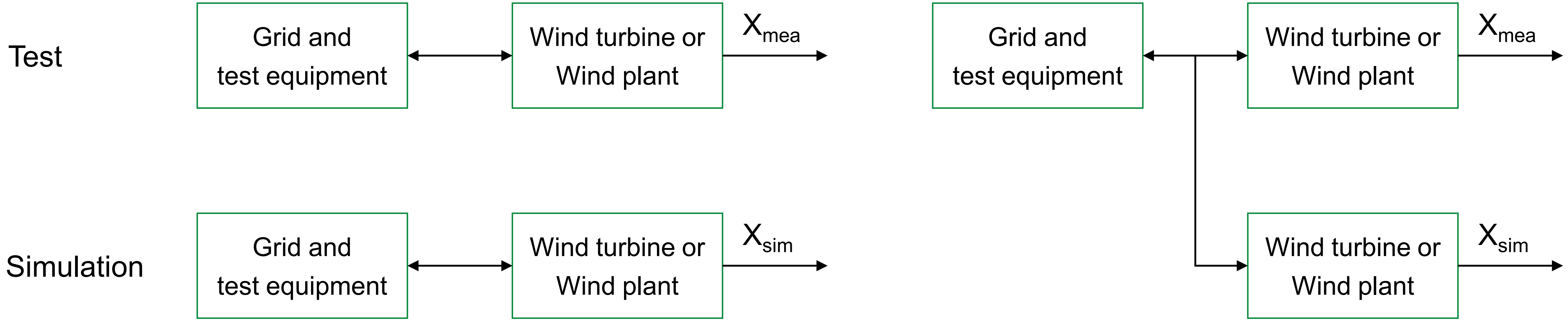
- Unfortunate tolerance band:
  - Small deviations of simulation from measurement can result in large differencies in settling times

- In such cases tolerance band can be adjusted



Playback vs. full system validation

- **Full system validation**
  - Includes grid model and model for test equipment in simulation
  - Adds uncertainty to WT / WP model validation
- **Playback validation**
  - Uses measured terminal variable (e.g. voltage) as input to simulation
  - Removes interactions between WT / WP and grid



Model validation – plant level

- TSO measurements on 56 MW wind power plant in France
  - PMU measurements in Point of Connection (PoC) (V, P, Q)
- Case: power factor step change

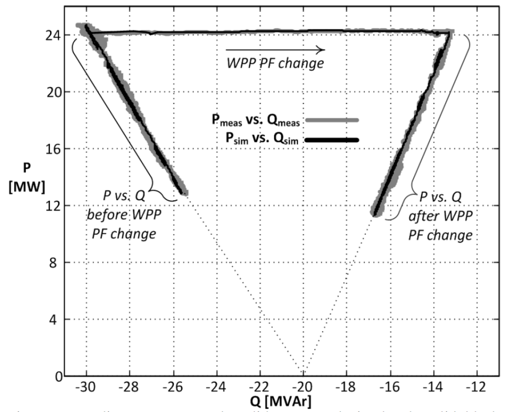


Fig. 5. PQ diagram; measured (solid gray) and simulated (solid black), 22.5 minutes periods before and after the WPP power factor (PF) change.

Göksu, Ömer; Altin, Müfit; Fortmann, Jens; Sørensen, Poul. Field Validation of IEC 61400-27-1 Wind Generation Type 3 Model with Plant Power Factor Controller. IEEE Transactions on Energy Conversion, Vol. 31, No. 3, 2016, p. 1170 - 1178.

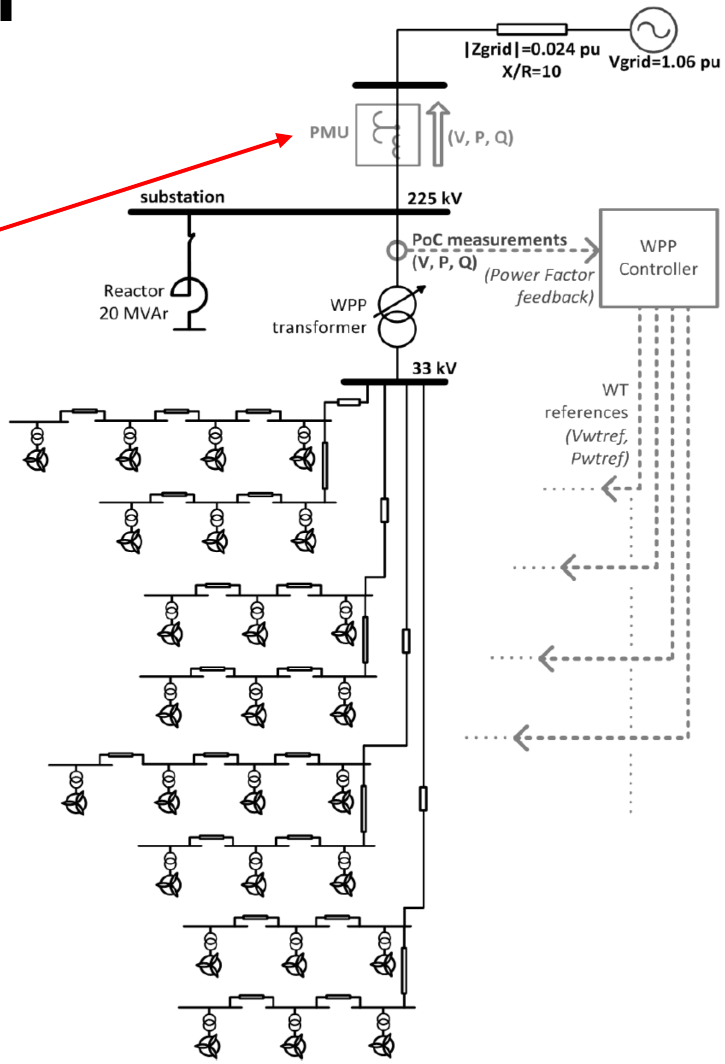
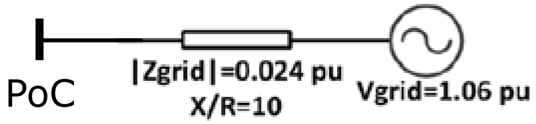


Fig. 2. The WPP layout, grid, and PMU location [Sbase=100 MVA].

Model validation – plant level

- Measured and simulated response to power factor step change

- Small error in simulated Q:
  - Mainly caused by *external voltage fluctuations* not in the ”full grid” model



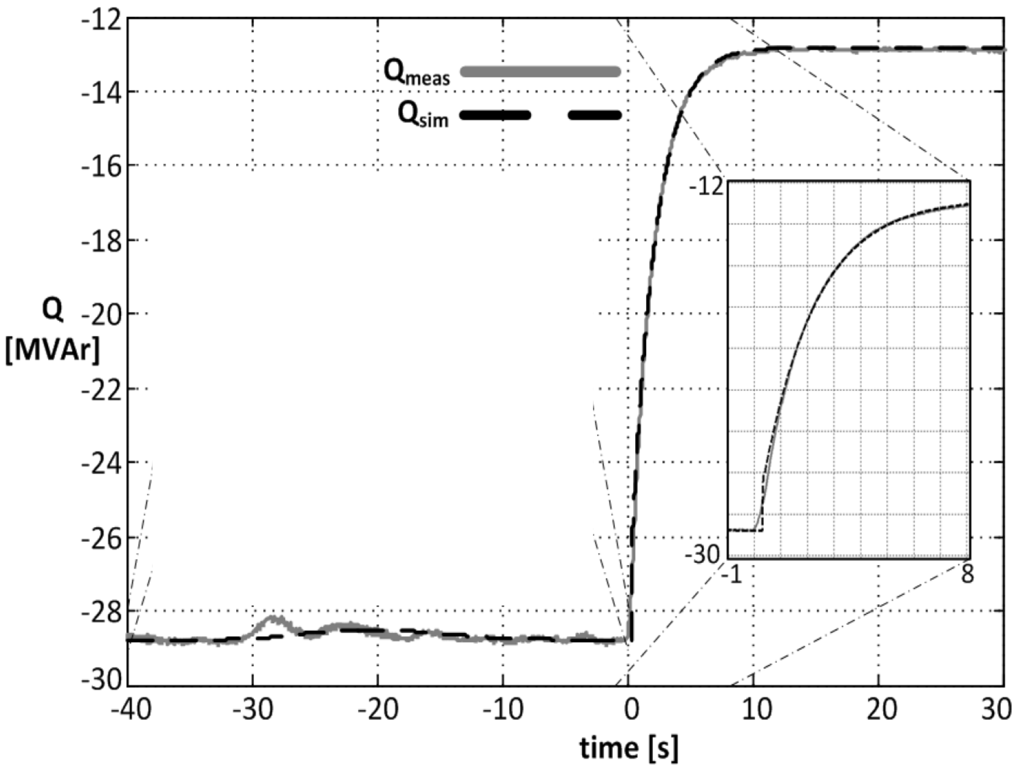
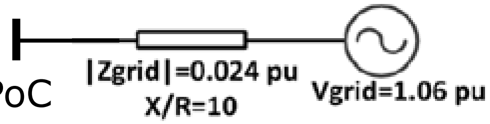


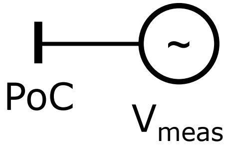
Fig. 7. Measured (solid gray) and simulated (dashed black) reactive power during WPP power factor change.

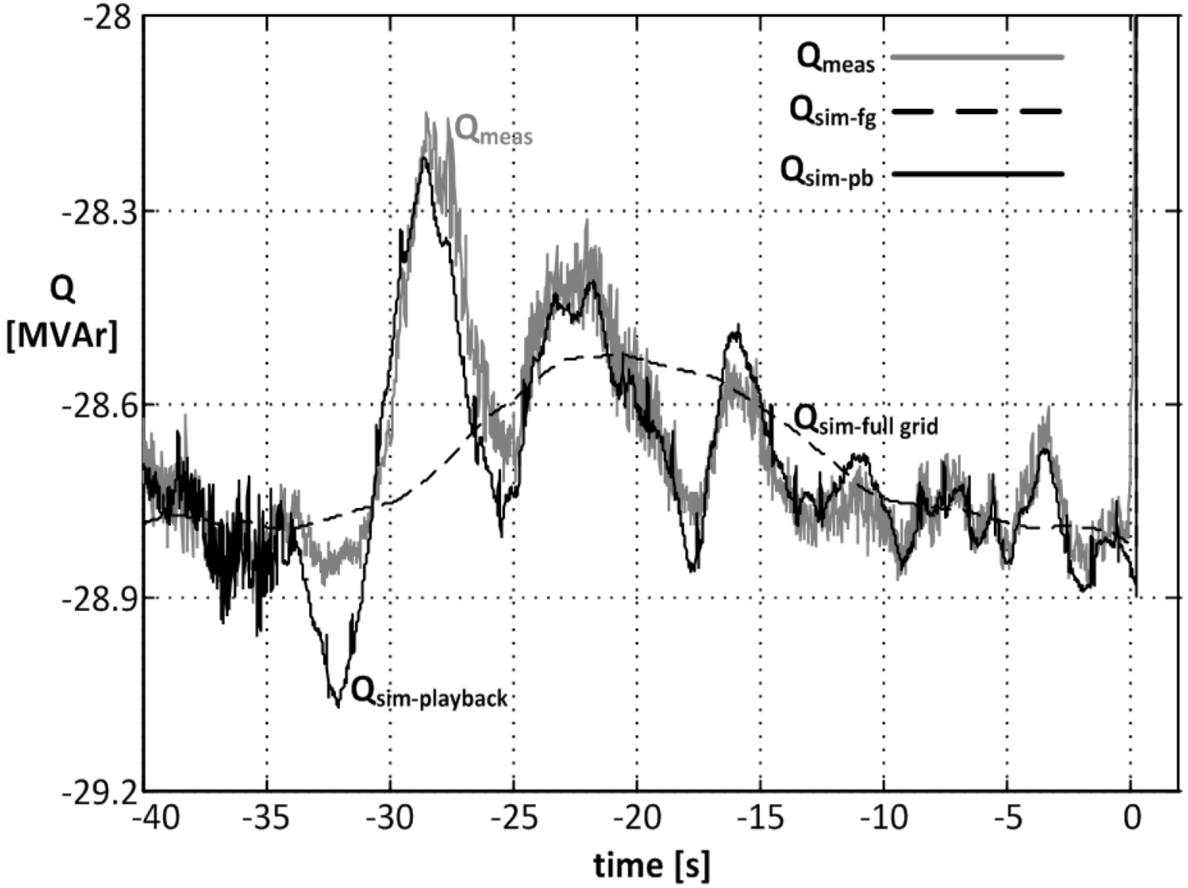
Play-back in validation

- Long term simulation: already played back power
- ”Full grid” model:



- ”Play-back” approach: :
  - ”Play-back” measured voltage to PoC





Summary and outlook

Summary and outlook

- Published IEC standards:
  - Generic fundamental frequency positive sequence models
  - Model validation procedures – for positive and negative sequencies
  - Common Information Model – static and dynamic

- Outlook
  - Generic negative sequence models
  - Validation of multifrequency models
  - Validation of EMT models

DTU