IEC TC 88 WIND POWER GENERATION STANDARDS IN RELATION TO GRID CONNECTION REQUIREMENTS

Björn Andresen
Electrical Energy Technology
Aarhus University
Aarhus, DK
bjra@ase.au.dk

Frank Martin, Thomas Dreyer,
Konstantinos Ntovolos
Siemens Gamesa
Brande, DK
frank.martin@siemensgamesa.com

Flemming Brinch Nielsen
System Opertion Development
Energinet.dk
Fredericia, DK
fbn@energinet.dk

Poul E. Sørensen
Department of Wind Energy
Technical University of Denmark
Roskilde, DK
posq@dtu.dk

Łukasz H. Kocewiak
El-System Design & Grid Integration
Ørsted Offshore Wind
Gentofte, DK
lukko@orsted.dk

***Abstract* — TC 88 - Wind energy generation systems has existed for 30 years, and grid connection-related standards have existed for 20 years. These standards played a major role in the growth of the wind industry, going from small single wind turbines to large power plants, ensuring reliable and high quality products in an international market. The journey of the grid connection standards is still in its early stages, and there is an urgent need to continue the development and harmonization of the standard-related activities to support a fast, reliable and stable development of the future energy system. The paper presents the journey of the development of grid connection-related standards as well as their current status, usage and relation to other grid connection requirements. The paper will present different perspectives from the main stakeholders as well as predicted future needs.**

Keywords— standard, standardization, grid code, grid code compliance, measurements, model validation, compliance testing, wind power plant, wind turbines, components,

I. INTRODUCTION

This paper will give an overview and status of the latest standard developments from the technical committee TC 88 - Wind power generation systems, in relation to grid connection requirements, focusing on measurements, tests, verification and simulation of components, wind turbines (WTs) and wind power plants (WPPs). The paper presents the actual status of the standards 61400-21 series for the measurement, test and assessment of WTs and WPPs, as well as the latest development of the 61400-27 series in relation to the generic simulation models and model validation procedures for the WTs and WPPs. The overview, usage and challenges of these and other related standards will be presented from different perspectives (standard organizations, manufactures, developer and system operators), who will present their experiences with these standards and best practices, as well as future needs for standardization in relation to testing, simulations, certifications, assessment procedures etc.

II. STANDARDS IN RELATION TO GRID CONNECTION

A. *Role of IEC Standards*

The IEC (International Electrotechnical Commission) is an international standards organization that prepares and publishes the international standards for all electrical, electronic and related technologies (www.iec.ch).

A standard is an agreement document based on consensus. Standards are voluntary unless they are required for certification. They define repeatable rules, guidelines or characteristics for products and activities.

The IEC standards are prepared by technical committees (TCs) and subcommittees (SCs) within a wide range of topics; from power generation, transmission and distribution to wind energy, solar energy and many others.

B. *TC 88 - Wind energy generation systems*

IEC TC 88 is responsible for international standardization in the field of wind energy. This includes WTs, on-shore and off-shore WPPs, as well as the interaction between WTs, WPPs and the electrical systems to which energy is supplied.

TC 88 was established 30 years ago, in 1989. Today, it consists of more than 42 different standards, which are either published or under development. Among other things, these standards cover WT design, mechanical and electrical systems, support structures, measurements, control, inclusive communication systems, as well as grid code compliance measurements, simulation and validation. In relation to grid connection requirements, TC 88 has developed the following standards series:

- IEC 61400-21 series - Measurement and assessment of electrical characteristics
- IEC 61400-27 series - Electrical simulation models

The above-mentioned series consist of several parts, which will be described in the sections below.

In addition, TC 88 has developed the following series for the control and communications systems in WPPs:

- IEC 61400-25 series - Communications for monitoring and control of wind power plants

C. Grid connection standards from other IEC TCs, organizations and authorities

The above-mentioned standards from TC 88 can be used as basis for the validation, compliance test and certification of electrical capabilities of WT components, systems and WPPs in relation to national and international grid code requirements.

Besides the IEC activities, there are several ongoing national and international activities (Cigré, IEEE, NERC) in relation to grid code compliance and assessment procedures. Some examples include:

- IEEE 1547: Standard for Interconnection and Interoperability of Distributed Energy Resources (https://standards.ieee.org/)
- IEEE P2800: Standard for Interconnection and Interoperability of Inverter-Based Resources (https://standards.ieee.org/)
- CIGRE WG B4.64: Connection of wind farms to weak AC networks (https://www.cigre.org/)
- CIGRE WG C4.49: Multi-frequency stability of converter-based modern power systems (https://www.cigre.org/)
- EN 50549-1 and -2: Requirements for generating plants to be connected in parallel with distribution networks (https://www.cenelec.eu/)

In combination with these, the TC 88 standards can be used as basis for system performance analyses.

III. IEC 61400-21 SERIES – MEASUREMENT AND ASSESSMENT OF ELECTRICAL CHARACTERISTICS

IEC 61400-21 has been developed over the last 20 years. What began as a standard focused on the test and measurement of power quality aspects has developed into a complete standard series, with focus on the testing, measurement and assessment procedures of electrical capabilities of wind generation systems, including testing and measurement of power quality aspects, over- and under-voltage fault ride through capabilities, control performance of WTs and WPPs, as well as testing procedures of electrical components, subsystems and complete nacelles on test bench systems. Furthermore, the expert team of IEC 61400-21 has developed guidelines for harmonic models of WTs, which can be used as the basis for harmonic analyses, resonance studies etc. of WTs and WPPs.

The IEC 61400-21 series - Measurement and assessment of electrical characteristics consist of the following standards and standard proposals, which have been published or are under development:

- IEC 61400-21-1– Measurement and assessment of electrical characteristics **-** Wind turbine [1]
- IEC 61400-21-2 – Measurement and assessment of electrical characteristics - Wind power plants
- IEC 61400-21-3 – Measurement and assessment of electrical characteristics - Harmonic models [2]
- IEC 61400-21-4 - Measurement and assessment of electrical characteristics - Wind turbine components and subsystems

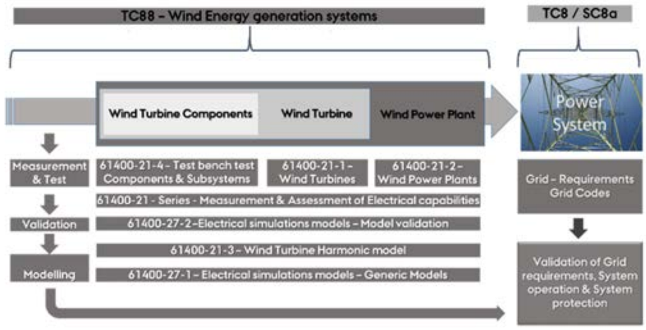

Figure 1*:* **Overview of TC 88 – Standards related to grid connection**

Figure 1 gives an overview of the different TC 88 standards, their interface with the other standards from the TCs in the IEC, and the grid connection requirements. The detailed scope, purpose, application range and working stages are explained in more detail in the next sections.

A. IEC 61400-21-1 - Wind turbine

The first edition of IEC 61400-21 was released in 2001 and focused mainly on power quality issues (flicker, voltage variations, cut-in and cut-out etc.) in relation to the connection of the negative consumer WTs to the public grid.

To cover the rapid grid code development, the second edition was published in 2008 with an increased scope of measurement and testing of grid connection requirements such as fault ride through testing, reactive and active power control performance, as well as increased harmonic measurements.

Together with the further development of new grid codes, new control functions and the need for simulation model validation, work on the third edition began in 2013 [3] and was finalized in 2019. Among other things, the third edition includes the following new and updated parts:

- The FRT tests, which include both under-voltage ride through (UVRT) as well as over-voltage ride through (OVRT) tests. The FRT tests are based on measurements of the capabilities of the WT and can therefore be used as basis for the validation of different grid codes, as shown in Figure 2:

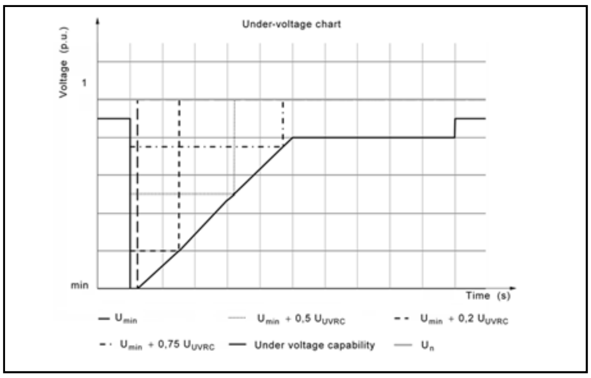

Figure 2: FRT undervoltage capability test chart

- The control performance measurements have been updated and include frequency control tests, inertia response and voltage control features.
- Updated and new methods for harmonic assessment, as well as measurements to be used as basis for the IEC 61400-21-3 - Harmonic model.

Parts of the assessments procedures related to WPPs have been updated and moved to Annex E. They will be replaced by IEC 61400-21-2 - Wind power plant.

Furthermore, all power quality measurements are now based on power bin instead of wind speed bins, which makes it possible to adapt the measurements procedures and assessment methods to other renewable energy (RE) generation systems.

The third and final edition/version has been unanimously approved by all national committees, and the final first edition was released in May 2019. As the title has changed from "Measurement and assessment of power quality" to "Measurement and assessment of electrical characteristics", the edition/version number has changed to edition 1.

B. IEC 61400-21-2- Wind power plants

IEC 61400-21-1 is based on the measurement and testing of the individual WT. Annex G includes some guidelines for extrapolating and estimating the power quality measurements from a single WT to a WPP. However, as WPPs have reached a size where they can have a strong influence on the grid, it was necessary to define standardized methods for performing measurements and tests at the WPP level.

Thus, IEC 61400-21-2 includes the following aspects:

- Definition and specification of the quantities to be determined for characterizing the electrical characteristics of grid-connected WPPs.
- Measurement procedures for quantifying the electrical characteristics in relation to power quality, steady state operation, dynamic response and control performance.
- Procedures for assessing compliance with electrical connection requirements.
- Procedures for measurement and fault recording for the verification of WPP models.

In addition, IEC 61400-21-2 describes methods for validating the functions and the performance of the wind power plant controller in relation to the requested grid control features.

The measurement and described methods refer to the point of connection of the WPP and allow the TSO/DSOs to analyze the fulfilment of their grid connection requirements in respect to the above-mentioned characteristic.

The committee draft of IEC 61400-21-2 will be published by the end of 2019 and the intention is a very generic description of the methods for the purpose of being able to adapt the standard to other renewable energy (RE) generation systems.

C. IEC 61400-21-3 - Harmonic models

Harmonic measurements are heavily affected by background noise at the actual test site, which has a strong influence on the harmonic contribution from the WTs. In Annex D, IEC 61400-21-1 describes guidelines for the evaluation of background harmonics.

Furthermore, the working group behind the IEC 61400-21 series published a new technical report (TR) describing how harmonic WT models can be developed and used as the basis for harmonic analysis and resonance studies of wind power generation. The development and validation of the harmonic models are based on the measurements described in the other parts of the 61400-21 standard series.

The harmonic models can be built as e.g. a Thévenin/Norton equivalent circuit, as shown in Figure 3. The harmonic models are a linearized model representation defined as a frequency dependency impedance, where the converter control is part of the impedance.

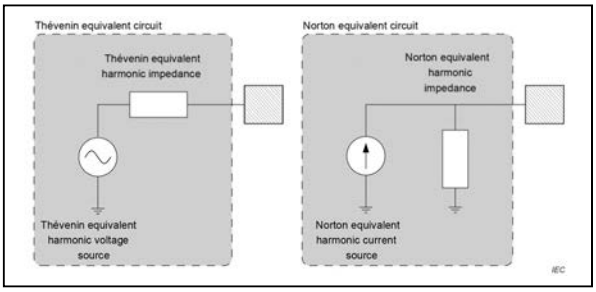

Figure 3: Generic harmonic model structure represented as Norton/Thévenin equivalent circuit.

The harmonic models represent the influence of the grid impedance and background noise on the harmonic emissions from the WT. Therefore, it is possible to normalize the emissions independently of the grid.
Afterwards, the harmonic models can be applied in conventional harmonic assessment studies as basis for harmonic analysis, resonance studies etc. of WTs and WPPs, as shown in Figure 4.

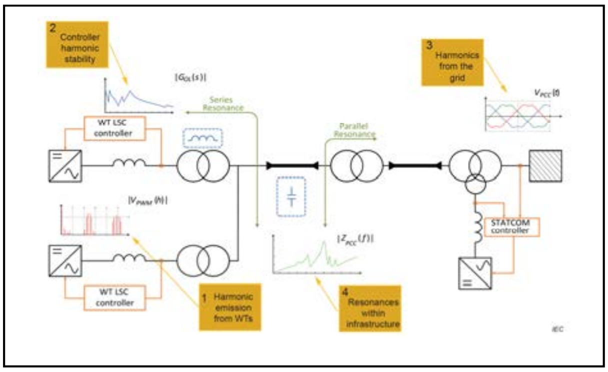

Figure 4: Example of harmonic studies and potential challenges in harmonic performance.

The first edition of this Technical report (TR) was released in 2019.

D. *IEC 61400-21-4 - Wind turbine components and subsystems*

Over the past years, several test bench systems have been developed around the world, which has resulted in many experiences with manufacture tests and research projects. An example of this is grid emulator options, which allow the verification of the drive drain systems and nacelles grid code compliance. Figure 5 shows an example of a complete nacelle test, where the electrical capabilities of the system can be tested under different operating and grid conditions via a grid emulator.

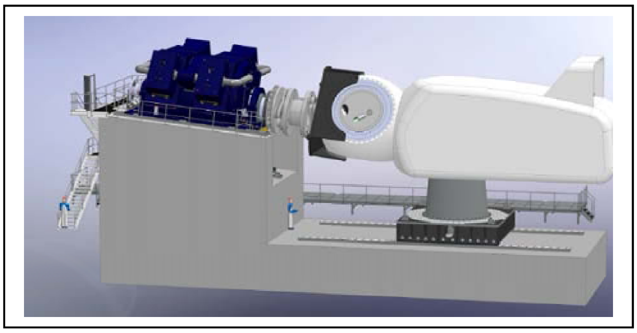

Figure 5: Test system for complete nacelle test from LORC – DK.

In addition, as WTs (especially for offshore) have reached a MW size where tests are becoming technically demanding and very expensive, test sites are becoming more limited in their capabilities. In October 2018, TC 88 authorized work to begin on a new technical specification TS 61400-21-4, which aims to define measurement and test procedures on test bench level in order to move WT field test setups to a controllable test bench setup.

The proposed technical specification TS IEC 61400-21-4 will define a uniform methodology that standardizes measurement, testing and assessment procedures of electrical characteristics of WT components and subsystems as basis for the verification of the electrical capabilities of WTs and WT families.

TS 61400-21-4 will include the following aspects:

- Definition of test systems as well as system requirements for the test bench in order to perform these measurements.
- Test and measurements procedures of electrical characteristics of components and subsystems in relation to grid code compliance requirements.
- Procedures for the transferability of the component and subsystem test results measured at the test bench to WT product families.

In addition, the results of the measurements, validation and assessments will be used as input for the verification of e.g. the electrical simulation models as described in IEC 61400-27-2.

E. *Relation to grid connection standards and other IEC Standards*

For many years, the IEC 61400-21 series have been used as basis for type certification of electrical capabilities as well as a reference in several grid codes [4] and national technical regulations e.g. [5].

The existing and new parts in the – 21 series will form the basis for the evaluation of compliance grid code assessment as described in, e.g. EN-50549-10 and IEC TS 63102, as well as compliance in national and international grid codes. In addition, due to their generic descriptions, the described measurement and test procedures can be applied to other RE systems such as PV generation systems, battery storage systems, CHP systems etc.

IV. IEC 61400-27- Series – Electrical simulation models

The development of the IEC 61400-27 series was initiated in 2009. The scope of this standard series is to specify generic electrical models and model validation procedures for WTs and WPPs. The first edition of IEC 61400-27-1 [6] was published in 2015, including specification of generic models and validation procedures for WTs.

The original plan was to publish IEC 614000-27-2 with generic models and validation procedures for WPPs. However, while drafting the first version of the standard for WPPs, this division of scope between part 27-1 for WTs and part 27-2 for WPPs appeared to be irrational. Instead, the working group proposed to restructure the scope of the two parts in the next edition so that IEC 61400-27-1 Edition 2.0 [7] specifies generic models of WTs as well as WPPs, whereas IEC 61400-27-2 Edition 1.0 [8] specifies model validation procedures, including both WTs and WPPs.

IEC and the national committees have approved the proposed structure, but since the two parts will replace the existing IEC 61400-27-1 Edition 1, they have to be published at the same time. This publication is expected in the beginning of 2020.

A. *IEC 61400-27-1 Edition 2.0*

There are two major reasons for specifying generic models in an IEC standard. The first reason is that generic models reduce the work the wind power industry will need to do to implement and maintain manufacturer-specific models in several different power system simulation software tools, which are used by TSOs. The second reason is that generic models support the sharing of models between TSOs who use different simulation software tools. Exchange of dynamic models is often essential for the credibility of stability studies because the TSO systems are interconnected. Therefore, stability in one TSO area often depends on dynamics in neighbouring TSO areas. These two reasons are illustrated in Figure 6.

The standard generic models can be implemented by the software vendors. Although the parameters of the generic models are not generic and therefore not specified in the standard, it is still much simpler to exchange the model parameters between the TSOs than to exchange complete dynamic models implemented in different simulation tools.

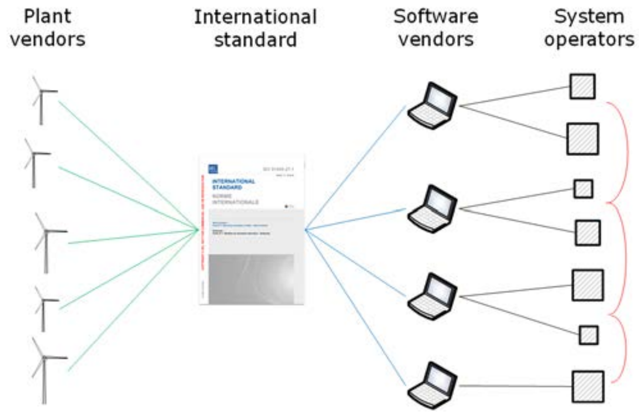

Figure 6. Generic models intend to reduce model implementation work and support exchange of models between neighboring system operators.

The exchange of data between TSOs is supported by the 61970-3xx series for common information model (CIM). Exchange of basic static data for system states are specified in 61970-301 [9] while exchange of dynamic data is specified in 61970-302 [10], referring to dynamic models specified in other standards, including IEC and IEEE. Regarding wind power models, 61970-302 refers to the models specified in IEC 61400-27-1 Edition 1.0. The next edition of 61970-302 is already at Committee Draft (CD) state, and this edition will include updates from IEC 61400-27-1 Edition 2.0.

Traditional short-term power system stability studies are based on fundamental frequency positive sequence models. The scope of the IEC 61400-27-1 models is therefore limited to fundamental frequency positive sequence models. With this limitation of the scope, it has been possible to specify models accepted by all the manufacturers who have been involved in the specification. Thus, the generic models are proven to represent Siemens Gamesa, Senvion, Vestas, GE and Enercon WTs, and no other manufacturers have expressed inability to use the models.

The IEC 61400-27-1 models are specified in a modular structure [11]. This structure supports the use of one module in different models. For instance, this is the case for the reactive power control module, which is used in models for type 3 and type 4 WTs, and also in the model for STATCOM's specified in IEC 61400-27-1 Edition 2.0. In addition, the modular structure makes it possible to use the same module several times in a model. For instance, this is the case for the electrical measurement module, which is used in control system and protection systems. Here, the modules can have the same specifications, but the parameters can be different, just as in real life.

B. IEC 61400-27-2 Edition 1.0

The main reason for specifying standard procedures for model validation in IEC 61400-27-2 is to reduce the need for documentation of various national procedures and to improve the transparency in the applied model validation procedures. With this scope, IEC 61400-27-2 specifies measures for model accuracy, including detailed specification of the procedures for deriving those measures. TSOs or other national authorities are still responsible for specification of acceptable limits for model accuracy, but they should specify the limits using the measures for accuracy specified in IEC 61400-27-2.

The model validation procedures specified in IEC 61400-27-2 are developed for validation of fundamental frequency models. This includes validation of positive sequence models, such as the generic models specified in IEC 61400-27-1, as well as validation of models that includes the negative sequence. Technically, the signal processing procedures specified in IEC 61400-27-2 can also be applied to validate EMT models, but the procedure is not intended to quantify the accuracy of modelling electromagnetic transients.

The validation procedures specified in IEC 61400-27-2 are based on tests specified in the IEC 61400-21 series. This means that the validation of WT models is based on tests specified in the recently published IEC 61400-21-1, while the validation of WPP models is based on the latest draft version of the IEC 61400-21-2 standard. The validation procedures only include the tests of relevance to the validation of dynamic models, i.e. fault ride through tests and the dynamics of the responses to changes in controller references.

IEC 61400-27-2 specifies two types of validation procedures: the full simulation procedure and the play-back procedure. The full simulation procedure is illustrated in Figure 7. According to this procedure, the dynamic simulations are done independently of the measured variables. The advantage of this method is that it can verify the stability of the WT or WPP controllers interacting with the grid. The drawback is that it requires models for the grid and for test equipment such as voltage dividers.

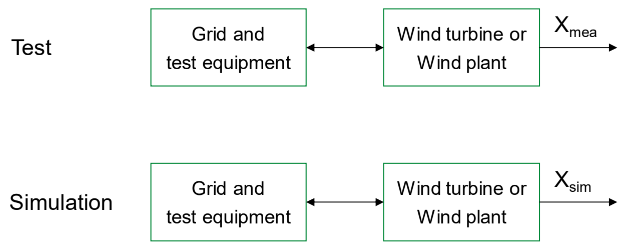

Figure 7. Full simulation procedure for model validation.

The play-back procedure is illustrated in Figure 8. According to this procedure, one or more measured variables (typically the voltage) is played back in the simulation. The advantage of this method is that the accuracy of the grid and the test equipment model do not influence the validation, which is intended to assess the accuracy of the WT or WPP model. However, if the voltage is played back, then the measured and simulated voltages cannot be compared.

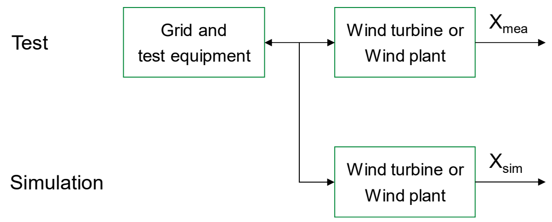

Figure 8. Play-back procedure for model validation.

The German technical guideline FGW for validation of simulation models [12] has accepted the validation procedure specified in IEC 61400-27-1 Edition 1.0, and since the main change in IEC 61400-27-2 will be to add validation of WPP models, the German technical guideline is expected to be updated to refer that instead after it is issued.

C. *Validation of IEC 61400-27-1 models*

In addition to the internal validation of the IEC models performed by the members of the IEC 61400-27 series working group representing the manufacturers, a number of academic papers have published about the validation of the IEC 61400-27-1 models against measurements. Most of the validation work has focused on the WT models, but validation has also been performed on wind farm models.

The type 1A WT model was validated against measurement of a fault ride through event in Zhao et. al. [13]. The type 4B WT model was validated against measurement of a fault ride through event in Sørensen et. al. [14]. Finally, type 3A, type 3B and type 4A WT models have been validated against measurements in [15].

The procedure for validation of wind farm models is not yet published in a standard. The wind farm model in the informative annex of IEC 61400-27-1 Edition 1.0 was validated against measurement of a change in power factor setpoint of a WPP in Göksu et. al. [16].

D. *Future needs for IEC 61400-27*

While the present standards in the IEC 61400-27 series are based on well-established best practices, the continued development towards higher shares of RE generation based on power electronics and the connection of WPPs to HVDC systems calls for further development of modelling and model validation standards.

Inclusion of options for modelling negative sequence was already discussed in the working group because more and more TSOs require models that include the negative sequence in order to simulate cases with asymmetrical faults. As the negative sequence modelling is strongly integrated with the positive sequence modelling, it will be most convenient to include it in e.g. Edition 3.0 of IEC 61400-27-1.

The use of and requirement to provide EMT models for grid connection is also growing, driven by the high share of power electronics, which is particularly pronounced in HVDC-connected WPPs. While it is not realistic to standardize generic EMT models, which represent the vast majority of manufacturers, it is more realistic to standardize requirements for EMT model interfaces and to model validation procedures. The generic model interface is already described in an informative annex of IEC 61400-27-2. This could be the starting point for a technical specification or a standard about requirements for and validation of EMT models.

IEC 61400-21-3 defines three classes for validation of harmonic models. But in the future, there will be a need to specify a detailed and transparent procedure for validation of harmonic models based on tests specified in IEC 61400-21-1, IEC 61400-21-4 or other test standards, e.g. for PV. IEC 61400-21-3 also provides recommendations of minimum requirement for harmonic models. Further standardization of the harmonic models could be done in collaboration with other technical committees such as TC 22 for power electronics or TC 82 for PV conversion.

Finally, system operators are requesting several new control functionalities from power converter-based generators. This includes "virtual inertia", grid-forming operation and black start capability. Typically, the functional requirements for those controls are not standardized and often not specified in detail by the TSOs. There is a need to standardize functional specifications as well as generic modelling and model validation of those controls.

V. Application of IEC TC 88 standards - Manufacturer experience and perspective

For grid connection of wind power plants (WPP), extensive assessment studies and grid code compliance tests must be performed in order to obtain grid code compliance and allowance from system operators to connect the WPP to the electrical power system. Furthermore, an extensive amount of documentation, measurements reports and validation reports are required by WPP developers, WPP operators and system operators. On the other side, system operators has the responsibility to maintain the electrical power system security and supply.

Besides all of the relevant standards utilized during the development of a wind turbine (e.g. equipment, design, safety, components), the standards under TC 88, (especially the IEC 61400-21- and -27 series) are of high relevance to WT manufacturer as they specify relevant aspects of grid code compliance measurements and generic model development and its validation. The standards are applied at different stages during the WT development process. For instance, simulation models usually need to be delivered early, and grid code compliance measurements and tests are performed at the end of the development during the prototype testing of a WT or WT type.

Examples of uses of standards during WT development, grid code compliance testing of the prototype WT and during WPP grid code compliance testing:

- Determination of the relevant grid code requirements and relevant national and international standards a new WT type will fulfil as well as the related deliveries.
- Determination of the required tests for a new WT type. Usually IEC 61400-21-1 is the foundation for this process. Furthermore, test plans are developed based on IEC 61400-21-1, national grid code requirements and internal demands.

- Execution of relevant grid code compliance tests and utilization of measurement data for assessment of the WT performance, model validation and reporting.
- Development and provision of simulation models and determination of model parameters for the generic model in accordance with IEC 61400-27-1. Furthermore, IEC 61400-21-3 is utilized for the development and validation of the harmonic model.
- Validation of RMS simulation models against field measurements in accordance with IEC 61400-27 or other validation requirements.
- Reporting of the measurement results internally or by accredited measurement institutes. Measurement reports are usually used by WPP developers, certification bodies and grid operators for assessment.
- Specification of WPP control-related measurements and tests as grid code compliance tests by various system operators, e.g. in [17] and [18]. Furthermore, the German FGW TR 3 [5] specifies component tests of the WPP controller in order to verify the WPP control functionalities. It is anticipated that IEC 61400-21-2 will support and standardize the different tests defined by national standards and grid codes.

This leads to a challenge for WT manufacturer, because the time to market for new WT developments becomes shorter, while the grid code requirements become more stringent. Simulation models need to be provided at very early stages of WPP projects, but extensive validation by means of field measurements does not happen until prototype testing of the WT type. Activities related to the testing for validation and verification of components and subsystems during the development process are becoming increasingly relevant. Therefore, the work on IEC 61400-21-4 is of high importance as measurements on component or subsystem level are already carried out ((e.g. tests of WT nacelle at DyNaLab [19], tests of converters or other component by component manufacturer) without having the usability of such tests for grid code compliance fully defined in the standards and without acceptance from grid operators. Measurements results may come from components and the subsystem first, rather than the WT. How this impacts simulation model development, validation and transferability is a topic that needs to be defined in the standards.

From a manufacturer's point of view, future work should focus on the following aspects:

- Continue the work on IEC 61400-21-4 and align activities with IEC 61400-27 in order to allow application in e.g. RMS simulation model validation.
- As a result of the national implementation of the European Commission Regulation [20], grid code compliance certification is being increasingly discussed in various forums. Development of the IEC RE WG10 is of high importance to an aligned and generic approach towards grid code compliance certification. This development will be carried out in very close collaboration with TC 88.
- Several new control features are being discussed and will be specified in the future (e.g. black start, island operation, much weaker connection points). Especially the IEC 61400-21 and the IEC 61400-27 should focus on such features for the next revisions to follow the fast-changing electrical power system proactively.
- Development from grid code requirements to a more standardized grid code compliance approach. In order to further increase renewable penetration levels and follow the changes and challenges of the power system, it is essential that the whole power system industry works together on the development of grid connection-related standards.

Within the recent year's standardization, especially within the grid connection / grid code compliance area got more and more complex and the standardization landscape dramatically increased in complexity. Beside IEC TC88 also other TC's working on related aspects as e.g. TC8. Furthermore, other standardization bodies as e.g. CENELEC and IEEE define aspects around grid connection requirements and grid code compliance testing. The whole area of certification is under IECRE and the topic of grid code compliance certification is developed by WG10 with the main purpose of:

- Specify guidance for acceptance criteria for grid code compliance certification in collaboration with ENTSO-E and system operators of the European member states.
- Prepare OD's for harmonized certification covering testing, simulation model validation and assessment.
- Utilize and established references to other IEC standards and TC's related to grid code compliance.

The main challenging is to manoeuvre in the standardization landscape and it is also not possible to follow each activity. Furthermore, alignment of these standardization activities is of high relevance in order to avoid misleading definitions at several places and to avoid over-standardization – a kind of overview system at e.g. IEC level which covers standardization and related activities.

VI. USE OF STANDARDS IN WIND POWER PLANT DEVELOPMENT AND OPERATION

Installed wind power capacity has been increasing rapidly for at least the last decade. Furthermore, the 100% renewable-based power system is becoming a realistic objective in the near future. To achieve it, there is a need to continue the productive dialogue among wind power industry stakeholders and to maintain a standard technology platform in order to ensure a consistent development strategy in the wind energy sector.

The IEC technical committee TC 88 is responsible for international standardization in the field of wind energy generation systems. This includes WTs, on-shore and offshore WPPs, as well as the interaction between WTs, WPPs and the electrical system. One of the most important objectives on the road towards a future with 100% renewable-based power systems is the integration of wind power into the grid. Therefore, a series of IEC standard within 61400-21 and 61400-27 have been proposed in order to harmonize the integration of WTs and WPPs into the power system.

The standards have been broadly used by WT suppliers, WPP developers and operators, as well as distribution and transmission system operators. For developers, it important to develop and utilize a common platform of standards, as it is the key factor in the maintenance of both high quality and high reliability in power delivered by wind.

A. IEC 61400-21

IEC 61400-21-1 ensures that WT electrical performance is maintained and benchmarked across the entire supply chain. A standard method of evaluating the electrical characteristics of WTs is important for WPP electrical infrastructure design. Furthermore, the standard supports the grid-connection process, since standard documentation can be exchanged easily. The standard has a long track record and exhaustively covers WT testing procedures for obtaining electrical characteristics. Therefore, it is commonly used by wind power industry stakeholders and does not require any other supplementary standards.

IEC 61400-21-2 provides a standard method of evaluating the electrical characteristics of WPPs. This standard is expected to elaborate on how to perform WPP testing. Currently, each market has its own standards and/or procedures, which may be used to prove grid code compliance or perform additional tests during WPP operation. Furthermore, the IEC 61400-21-2 standard can be considered a solid foundation for new markets, where local recommendations and guidelines regarding WPP testing have not yet been developed. This will allow a shared understanding among all relevant stakeholders and de-risk first projects. However, on well-established wind power markets, like the one in the UK, a set of relevant documents already exists. “Guidance Notes for Power Park Modules” and “The Grid Code” [21] provided by National Grid clearly describe the testing and compliance process. One of the challenges recognized by the working group is related to harmonization across all markets in order for the standard can serve the entire wind power industry.

IEC 61400-21-3 - Harmonic wind turbine models can be used as the basis for harmonic analysis, resonance studies etc. of WTs and WPPs [17], [18]. This standard covers the missing part of WT harmonic modelling for system-level studies in order to ensure electromagnetic compatibility within the WPP electrical infrastructure and external grid, as well as validation WPP grid code compliance. CIGRE TB 766: JWG C4/B4.38 “Network Modelling for Harmonic Studies” currently covers this part as well and also shows how to apply the WT harmonic model in harmonic propagation studies. However, both documents are fully aligned and supplement each other in a harmonized manner.

The concept of WT subsystem testing has been used extensively by the manufacturers. However, the concept of a standardized approach that can be utilized by WPP developers to obtain information about WTs, especially new products, is quite new. The standard IEC 61400-21-4 - Testing of WT components and sub-systems is expected to fill the gap and ensure that relevant WT data will be provided even before the full-scale site testing. The relevant WT models for e.g. load flow, fault and harmonic studies can be developed and validated earlier, addressing the tendency in time-to-market reduction time.

B. IEC 61400-27

The standard is focused on verification of the electrical simulation models for WTs and power plants in future. A standard method of modelling WTs for dynamic studies allows us to understand the entire system behaviour and to easily address improvements or modifications in order to achieve the performance desired. At this stage, WT positive-sequence models are standardized. However, the need for negative sequence representation is increasing as more system operators would like to integrate this functionality. Furthermore, it is common practice to perform detailed studies based on EMTP-type modelling, which is not yet standardized at this stage.

The application of the newly developed IEC 61400-27-1 is very broad and successfully brings understanding among wind power industry shareholders such as WPP developers, WPP operators, transmission and distribution system operators, WT manufacturers and certifying bodies. From a WPP developer’s perspective, the main advantages of having a standardized WT model are:

- Model data can be easily shared as a simple list of parameters without any need to focus on a specific simulation environment. The model structure is already described in the standard.
- The model structure and implementation can be implemented in various power system analysis tools. This makes the implementation fully transparent and not associated with any commercial software.
- The integration of models from several vendors is easier on a large-scale system as the models can be implemented in a way that ensures the same timescales and no encryption, which is useful for further debugging.
- The TSOs can share their system models between each other without violating any confidentiality agreements. The standard ensures that the models shared between the parties are not encrypted.
- The parameter adjustment and dialogue can be performed using open standard protocols/structures. This appears to be very useful in ensuring the performance and stability of the entire system.
- The same model will have the same interface, structure and timestep. Thus, the integration and execution time will be optimized in comparison to multiple user-defined models.

VII. TSO’s Experience and Perspective

National grid connection requirements have historically used a variety of standards as reference within the different functional requirements. The standards are a vital part in the energy generation and electricity system area, and has served every stakeholder, i.e. generator manufacturer, generation facility owner, RSO, TSO, the electricity market etc. They have harmonized and standardized the functional requirements. However, supplementary national or grid-specific requirements have typically been a part of the complete connection requirements.

This is also the case for Energinet, the Danish TSO. All national technical regulations make relevant references to international standards. In TR 3.2.5 (WPPs above 11 kW), for instance, references to IEC 61400-21, -22 and -25 standards are included.

From a European perspective and as a part of the national implementation of [20], a new level of harmonized connection requirement is obviously achievable and must influence international standardization in an extremely positive direction by reaching a new level of harmonized functional requirements, provided that the standards stay within the scope and comply with legislative basis.

During the Danish national implementation of [20] and the update of simulation model requirements, references to IEC 61400-21 and IEC 61400-27-2 were used as basis for the Power Park Module (PMM) validation requirement and process.

As the energy system is undergoing a tremendous transformation, which includes both generation and consumption, compliance testing takes on a more significant role. The increasing penetration of RE generation demands adequate and transparent compliance testing of PMMs, not only during final validation for archival of Final Operation Notification (FON), but also during the scheduled periodic follow-up compliance test. The standardized test needs to match the modularity and scalability of the PPMs, which impacts functionality and nominal power and, for this reason, the connection requirements as well. There is a well-founded expectation between stakeholders within connection requirement activities that standardization and harmonization of compliance testing will improve the quality and process of onsite compliance test.

The development of new standards never stops and should never stop. However, it is extremely important for standardization organizations to ensure usable scopes and to prevent unnecessary overlap of scopes. This applies to both standards and TC scopes. Unclear scopes of standards and TCs create blurry understandings of the applicability, which in turn creates unnecessary uncertainty and misunderstandings. This impacts everything from product design to connection requirement.

In addition to this, maintenance of already published standards is as important as developing new ones. Maintenance is crucial, especially when references are used in national technical regulations. The maintenance will prevent the development of parallel national requirements, which do not always serve harmonization of requirements.

When looking to the future and its expected energy system transformation, which will offer, among other things, mixed facilities, wind, PV and energy storage, the need for common functionality and compliance test becomes obvious. Knowing the maturity level between wind, PV and energy storage systems is different for obvious reasons when it comes to large-scale compliance testing the need for harmonization and standardization is considered vital. Sharing knowledge and experience at this stage will be beneficial for everyone.

VIII. Future needs

Today, wind power is the cheapest energy producer in over 120 countries, and its price level can beat most other generating sources. To ensure fast development of wind energy with new products and systems without losing the quality, there is a strong need to redefine and develop the standardized test, measurement and validation procedures towards more component and subsystems validations based on test bench systems and simulation models in relation to the grid connection requirements.

As shown above, there are many ongoing standard activities in the area of WTs, WPPs and other RE systems in relation to grid codes and grid code compliance testing. It has also been shown that there is a strong need for harmonization in these standard-related activities in order to strengthen the usage of IEC standards and avoid misunderstandings of the different standards, regulations and guidelines.

Since all future RE systems (wind, PV, batteries, CHP, hybrid-systems) will be connected to the same grid, and since all systems have to support the system in order to guarantee a stable system operation independent of their energy source, there is a strong need for harmonization across technologies, standardization organisations, authorities, end-users, TSOs, manufactures etc.

In addition to the need for combined control systems of the different sources (hybrid-systems), several other areas in which the existing standards need to be updated to cover the existing grid codes requests have been identified. This includes negative sequence simulations models, EMT models for detailed systems studies, as well as stability and harmonic assessment studies.

In the long term, there will be a further need to standardize the ongoing research activities in relation to e.g. grid-forming systems, new types of HDVC connection and new system control features (black start, power system stabilizer etc.) necessary to support stable system operation.

IX. Conclusion

Standards are important and help simplify and streamline the grid code compliance process in the complete value chain, from the design and type test of wind turbines to compliance tests of wind power plants, as well as system studies and interfaces. The standards helps to reduce costs and increase the quality of the products and systems, as well as the integration of renewable energy systems in the overall power system.

As standards are based on best practice and proven technology, they are always behind the actual technological development, which happens very fast in relation to new connections rules and systems, control features etc. Therefore, the standards have to be continuously updated, aligned and harmonized with other standard organisations, authorities and renewable energy technologies in order to support the necessary transformations of the electrical power supply system into a fossil-free system.

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