Current procedures and practices on grid code compliance verification of renewable power generation

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Abstract

Generation assets applying for grid connection must comply with certain grid code requirements. Grid code compliance verification shall include revision of documentation covering technical data and models, checking of the requested capabilities, and validation of model performance. These procedures are singular regarding renewable power generation, due to their singular characteristics, specific topologies and short experience. This paper reviews current procedures and practices on grid code compliance verification, encompassing modelling and validation requirements, testing set-ups and certification procedures.

Keywords: Grid code,
compliance, generator testing, staged fault testing, model validation, generic model, verification, certification, wind power, renewable generation, commissioning.

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1. Introduction

Grid codes specify the electrical performance and other regulations that a renewable generation plant must comply with in order to obtain the required approval for its connection to a grid. Demonstrating grid code compliance and achieving a grid connection agreement are, therefore, essential milestones in the development of a renewable power plant project. The increase in renewable generation plants formed by a large number of individual generating units poses a challenge to system operators, in terms of connection process and plant modelling management. In order to cope with these issues, compliance procedures based on testing and simulation, and modelling and validation requirements for renewable generation plants have already been established in many countries around the world.

Grid code compliance verification has a double objective. On the one hand, plant owners are responsible for demonstrating compliance of the grid code to the relevant network operator. And, on the other hand, network operators have to assess the compliance in order to ensure that the new plant will not adversely affect the secure operation of the power system. To avoid misinterpretations of the requirements, a grid code should be complemented by a good verification plan. According to ENTSO-E [1], compliance testing is defined as the process of verification that power generating facilities comply with the specifications and requirements provided by this grid code. It can be carried out, for example, before starting operation of new installations. The verification should include the revision of documentation (including technical data and models), the verification of the requested capabilities of the facility by practical tests and simulation studies and, last, the validation of the model performance based on actual measurements. This compliance shall be maintained throughout the lifetime of the facility. Hence, power plants shall undergo periodical compliance monitoring processes, in order to verify that their technical capabilities are maintained and simulation models are still valid.

A grid code verification plan is as important as the regulation itself and it should not need to leave room for interpreta-

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tion regarding how each requirement shall be assessed. Unfortunately, not every grid code is complemented by a clear and detailed compliance verification plan. Grid code evolution has been extensively studied in the literature, mainly focused on technical requirements for large Wind Power Plants (WPP). Thorough analysis and comparison of grid codes were conducted most recently in [2–10]. However, grid code verification and generation unit and system certification procedures are still at an early stage, and information is sparse, scattered [4] or focused on specific countries [11]. Often it can also be found within grid code review documents [12]. A review of modelling and simulation requirements for variable generation in the grid codes would also be useful [13] and previous works can be found in [14, 15]. Therefore, this paper aims to carry out an updated review of the international regulations and current practices regarding the verification and certification of the electrical performance in renewable generation systems, including any technology. The countries analysed are Australia, Denmark, Ireland, New Zealand, Spain and UK. The selection covers a broad spectrum of countries with different power system structures and different degrees of renewable energy penetration, whose grid codes were also reviewed in [10]. Besides, German technical guidelines have also been included in this study, as their verification, validation and certification procedures for generating systems are pioneering in Europe.

This paper is organised as follows. Section 2 describes renewable power generation asset modelling and simulation requirements, reviewing generic model development initiatives. Simulation models must be accompanied by validation tests to show the validity of the models. Model validation practices and practical set-ups are indicated in Section 3. Finally, compliance verification procedures regarding technical requirements in grid codes are gathered in Section 4, with special emphasis on certification procedures in Spain and Germany.

2. Renewable power generation modelling and simulation

According to ENTSO-E [1], system operators may require generating unit models for both steady state and dynamic simulations (50 Hz component) and, where appropriate and justified, also for electromagnetic transient simulations. Model format must also be provided, and model structure and block diagrams shall be documented. Regarding dynamic simulations, models shall contain submodels of alternator and prime mover, speed and power control, voltage control, protection and converters.

Grid code requirements regarding data, modelling and simulation have been previously reviewed in [14, 15]. [14] gathers practices by several system operators regarding modelling requirements, ranging from Argentina, where non-confidential and non-black box models are required for all WPPs above 10 MW, and Croatia, where no generator model is required before connecting a generator. However, the enquiry was carried out in 2005, and since then, modelling requirements have evolved. Therefore, requirements regarding modelling and simulation in the countries under study are described and compared, including the application scope, model characteristics, and simulation requirements. Table 1 indicates the documents containing modelling and validation prescriptions required by system operators for renewable generation. Regulations are often complemented by guidelines with a more specific explanation. This is the case for most of the countries under study. Three approaches regarding generation assets are used in the regulation under review: technical regulation in Australia and New Zealand is technologically neutral; Ireland and Denmark have separate specifications for wind power; and last, in UK and Spain requirements not only apply to wind power but also to other intermittent energy technologies.

2.1. Challenges regarding renewable power generation modelling

In the traditional power systems, it was not necessary to include renewable power generation models in dynamic simulations, because penetration was still low. Thus, disconnection of renewable generating units during disturbances was a usual practice. Nowadays, situation has changed and many grid codes require manufacturers and generators to supply valid dynamic models.

Among the countries under study, in Australia all new generating plants must provide validated models, regardless of the technology. Requirements regarding modelling are technology-neutral, analogously to technical requirements imposed on to generation assets in the grid code [32]. In the Danish grid code, synchronous generators, as well as wind farms with a power output greater than 1.5 MW, must supply a valid dynamic model. The minimum capacity for WPPs with the obligation to supply modelling information is set to 5 MW in the Republic of Ireland, as well as in UK, where it applies to any power park module type, i.e. generating units powered by an intermittent power source. In Germany all generators are subject to dynamic model provision, unlike New Zealand where little information can be found with regard to asset modelling. In general, generation assets with a power output smaller than 30 MW are excluded from providing asset capability information.

Conventional power plants are constituted by either a single large unit or a few large units. In contrast, a variable generation installation such as a WPP can be made up of multiple small size generating units. Therefore, for large scale power system simulations it is often preferred to reduce the whole power plant to a single equivalent unit. Thus, aggregated simulation models are often accepted for large multi-generator power plants for practical reasons. The aggregation approach was evaluated in [33] and its validity was found adequate for wind farm transient studies, based on the National Renewable Energy Laboratory (NREL) equivalencing method [34], as long as wind speed is considered constant during the grid event. In some cases, when a WPP consists of different Wind Turbine Generator (WTG) types or distinct clusters, using two or more equivalent generators is also accepted [35].

In most of the countries under review, aggregated models are accepted. In any case, in Australia the model aggregation methodology must be clearly specified and in Denmark, it must be proved that aggregation does not significantly impact simulation results. The aggregate models of wind farms must include

Table 1: Renewable generation modelling and validation requirements in the countries under study

Country	Title	Technology
Australia	*National Electricity Rules* [16]	Any technology
	Generating System Model Guidelines [17]	
	Data and Model Requirements for generating systems of less than 30 MW [18]	
	Dynamic Model Acceptance Guideline [19]	
Denmark	*Technical regulation 3.2.5. for wind power plants with a power output greater than 11 kW* [20]	Wind power
Germany	*FGW Technical Guidelines for Power Generating Units Part 3, Determination of electrical characteristics of power generating units and systems connected to MV, HV and EHV grids* [21]	
	FGW Technical Guidelines for Power Generating Units Part 4, Demands on Modelling and Validating Simulation Models of the Electrical Characteristics of Power Generating Units and Systems [22]	Any technology
Republic of Ireland	*EirGrid grid code* [23]	Wind power
New Zealand	*Connecting and Dispatching New Generation in New Zealand. Overview* [24]	Any technology
	Asset Capability Information Overview. Guideline [25]	
Spain	*P.O. 9.0 Información intercambiada con el operador del sistema* [26]	Any technology
	Guía descriptiva del procedimiento de puesta en servicio [27]	Any technology
	Requisitos de los modelos de instalaciones eólicas, fotovoltáicas y todas aquellas que no utilicen generadores síncronos directamente conectados a la red [28]	Any non-synchronous generation
	Condiciones de validación y aceptación de los modelos [29]	Any non-synchronous generation
UK	*The Grid Code* [30]	Any technology
	Guidance Notes-Power Park Modules [31]	Any non-synchronous generation

in some cases the central park level controller (Australia), as well as the collector network (Ireland).

The scope of application normally includes both the generating unit and the complete generation system. In Australia, the complete power plant model includes any dynamic reactive power support and the power plant controller. The German regulation indicates the modelling requirements at generating unit level, whereas modelling fundamentals for power generation system are only described as a framework for future application. Installation models shall include generating units, transformers, cables, reactive power compensation systems and the external grid. In Ireland, the wind farm model shall include the WTG models, converter controls, reactive compensation and protection relays.

Main challenges reported in the literature regarding renewable power generation modelling are [32, 36]:

- Generators are usually based on power electronic devices. Thus, modelling can pose some issues, especially regarding control systems and algorithms which are often proprietary.
- Available models typically represent only large signal performance, but the impact of wind farms on small signal performance needs also to be assessed.
- Performance under unbalanced network conditions, caused by unbalanced faults or asymmetric line impedances and loads, can impact significantly power electronic control systems and is difficult to model using only positive sequence models [32, 36]. Hence, some grid codes require models that can represent both balanced and unbalanced situations.
- In some areas, such as Australia, it is becoming more common to connect renewable generation in weak points of the network. Concerns about simulation model accuracy under these circumstances is highlighted in some references [11, 37].
- The aggregation approach might not be adequate to represent a large wind farm by a single equivalent for all cases. This can be the case for large wind farms with multiple feeders, where the response of individual or groups of turbines might be different, or power plants where generators are operating at different speed. The equivalencing of collector, transformer and compensation devices might show the same issues.

2.2. *Root Mean Square (RMS) against ElectroMagnetic Transient (EMT) models*

Static and dynamic simulations are needed for operational, planning, interconnection and plant design purposes. System models are required at three general levels [22, 33]:

- Load flow and short-circuit models are used for basic design studies.
- Positive sequence or RMS models have traditionally been used for system integration studies and stability studies. Perfect balanced conditions are assumed and stability issues under study tend to be bounded within a small frequency band around the fundamental frequency of the system.
- Detailed three-phase EMT level models are necessary to study the effect of fast transients and electromagnetic interference, which require higher frequency components.

The bandwidth of dynamic models is directly related to the required simulation time-step and, thus, to the resulting simulation speed. EMT models result into smaller time-steps and longer simulation times. However, they are necessary, because phenomena such as Subsynchronous Resonance (SSR), Subsynchronous Torsional Interaction (SSTI) or the study of behaviour of variable generators in weak nodes of a power system require detailed models. For instance, in Australia, detailed EMT-type models must be provided when seeking assessment of the model for a Short-Circuit Ratio (SCR) lower than three. In addition, transient stability models should have a bandwidth of at least 0.05Hz to 10Hz. EirGrid regulation indicates that dynamic models must represent features likely to be relevant to angular and voltage stability. However, using EMT-type models for the whole system can be impracticable if the connecting network is large [11]. So, some simplifications need to be assumed. For instance, positive sequence EMT models are used for routine stability studies in Australia [11].

When the power system topology and simulated disturbances are balanced, positive sequence models are adequate. However, unbalanced conditions can affect power electronics and, therefore, are required to be studied. It can be performed by using three-phase RMS or EMT simulations. In addition, positive sequence models might not be adequate for representing sufficient details of the converter control system [11].

Generally, positive sequence RMS models must be handed in by manufacturers. This is the case for large power plants in strong areas of Australia, Germany, and UK. In Denmark, it must be possible to use the simulation models for RMS balanced and unbalanced studies. Besides, the Danish grid code indicates that models must be valid for a frequency range of 47-53 Hz and 0-1.4 p.u. of voltage.

Related to the model type, model minimum constants and simulation time steps are often specified. In Australia, transient stability models must allow numerically stable and accurate performance for time step-sizes down to 1 ms. Time constants of less than 5 ms should only be included if their inclusion is critical. Regarding model time constants, dynamics under 5 ms and 10 ms must be discarded in Spain and in UK respectively . In Ireland, simulation time steps must be higher than 5 ms, whereas in Germany the limit is set on 10 ms, even if it must be demonstrated that simulations with different increment sizes obtain equivalent results. Last, simulation models in Denmark must be capable of using numerical equation solvers with variable time steps.

System operators often specify the compulsory software simulation package. On the whole, the preferred option is PSS/E from Siemens. In UK, the model structure and complexity must be suitable to be integrated in Powerfactory from DigSILENT. However, model could be implemented in the software package chosen by the manufacturer. In Denmark and New Zealand, there is no indication about the software simulation package to be used. However, according to [36], the system operator in New Zealand performs steady-state, dynamic and transient networks analysis using DigSILENT Powerfactory.

2.3. Generic models against proprietary models

Regarding dynamic modelling requirements, system operators and manufacturers have conflicting perspectives [15]. System operators prefer to use standard models representing the plant performance with an adequate accuracy and are simple enough to be included in large network simulation runs. On the contrary, equipment manufacturers are concerned with achieving a high degree of accuracy and protecting their intellectual property. They are reluctant to disclose details of their products and, hence, models are often not standardised. Propietary models include user-written positive sequence models and three-phase detailed equipment models. However, in recent times manufacturer-specific models have become available in software tools such as DigSILENT [36].

In Australia, black box type representations are not accepted by the system operator and functional block diagrams, as well as model source code, is compulsory for generating systems over 30 MW, preferably in source code formats FORTRAN and FLECS. In Denmark, black box modelling is allowed for individual WTGs making up a wind farm with a power output greater than 25 MW. Simulation models must be supplied in the form of block diagrams using primarily transfer functions and accompanied by model descriptions. The source code must be sent and encrypted parts are not acceptable. In Germany, a grey box approach is adopted. Even if during generating unit certification black box models are accepted, they must be accompanied by simplified open models. In Spain, user models shall be provided as open code objects in FLECS or FORTRAN programming languages.

During recent years, the need of harmonised generic model standards for the different parts and applications of power systems has been enhanced [38]. Generic models are simplified and publicly available. These models have a simple but comprehensive structure and constitute a generic structure based on physical principles, which enable to emulate the design of different manufacturers simply by changing appropriate parameters [36]. Generic models must (1) allow a straightforward exchange of model data between interested parties, (2) be implementable and their performance comparable in different simulation programs, and (3) their parameters tunable to best represent the specific equipment, without having to reveal proprietary information [39]. In addition, a generic model should include external modules to be connected to the model, e.g. for protection functions, and be valid for both strong and weak systems. So, models should not behave erratically when the SCR is low. A limit SCR value of 2 is cited in literature [39].

According to [39], generic models should be described including connectivity diagrams (with links to external modules), block diagrams used to represent the main components or other pertinent information, e.g., non-standard limit implementation. The description of the models should be sufficient for program developers to implement the models in positive sequence, large-scale, transient stability programs. Besides, the computation of initial conditions must be described . Finally, model parameters, test systems and operating conditions used for model evaluation need also to be provided.

The development of generic models regarding variable generators has been focused on wind power. During recent years, generic models representing different types of wind turbines and their controls have been published and provided for power system studies [13, 33]. They allow simulating the typical behaviour of wind generator types and control concepts, and are well suited for general power system planning studies or feasibility studies. Wind speed variations have been commonly neglected in proposed generic WTG models, as it can be considered constant during the simulation period (up to 20 seconds in typical transient stability simulations [39]). Generic models not only have been proposed for wind farms, but also for solar photovoltaic generation [40], reactive power compensation equipment (SVC, STATCOM) [41] or High Voltage Direct Current (HVDC) [42, 43]. In the United States, many of the initiatives come from the Western Electricity Coordinating Council (WECC), whereas the National Renewable Energy Laboratory (NREL) has been engaged in an extensive model validation project aimed at testing the models against field measurements and refining the WECC generic models if needed. Models proposed by the WECC are included in PSS/E, PSLF and PowerWorld software packages. Internationally, IEC 61400-27-1 is an ongoing effort to standardise generic simulation models of individual wind turbines for transient stability simulation in large power systems. The main differences with regard to WECC models is that a common modular structure applies to all wind turbine types and the turbine and plant model are separated [44]. A future release of IEC 61400-27-2 will include the plant controller.

For generating systems of less than 30 MW, the Australian Energy Market Operator (AEMO) accepts the use of generic models for connection studies (e.g. standard IEEE models for synchronous generators or IEC/WECC generic wind farm models) provided that the model can reasonably represent the plant components of the generating system and the SCR is reasonably high [18]. In Ireland, user-written models must be supplied if there is no suitable library model. Similarly, in Spain a list with preferred models regarding conventional generation assets, as well as wind and photovoltaic power, reactive compensation systems such as Flexible AC Transmission Systems (FACTS) and protection relays, has been released. For synchronous generators, IEEE standard, CIM and PSS/E preferred models are indicated, whereas for renewable generation, generic models in PSS/E are stated. If none of these models allows to represent adequately the dynamic performance, user-written models are also accepted. In UK, the use of standard models is encouraged.

However, generic models might be inadequate for studies aiming to improve or assess equipment details [36]. Besides, the validity of generic models for system frequency disturbances is still pending [33, 39]. Generic models have been tested against vendor models, but should be compared to actual recorded disturbance monitoring.

3. Renewable power generation model validation

The purpose of model validation is to ensure the correct performance of control systems and validate the computer models used for stability analysis [45]. Consequently, model parameters must represent adequately the dynamic performance of the device being modelled for power system studies [33]. Along with the requirement for simulation models, there is an increasing demand in the grid codes to assure the proximity of models and physical behaviour [46]. Table 1 indicates the documents containing validation prescriptions required by system operators, which are strongly related to modelling requirements. Model validation is compulsory in all the countries.

There is considerable international experience regarding the validation of synchronous generator models [45, 47–50]. Validation methods are mainly based on staged tests, involving off-line tests such as enhanced short-circuit tests and partial load rejection tests [45], and frequency response testing covering Standstill Frequency Response (SSFR), Open Circuit Frequency Response (OCFR) and On Line Frequency Response (OLFR) described in [45, 51]. Both processes take significant time and are expensive, and might be harmful for the generating units [50]. An on-line disturbance monitoring based methodology is presented in [50], where validation is carried out by comparison with generator measurements recorded during system events. Then, parameters can be optimised through an automated iterative simulation approach. In addition, reactive power capability, excitation system and governor testing is also extensively described in literature [45].

There is less experience regarding validation with generation based on renewable energy sources, and it is mainly focused on wind and photovoltaic systems. Validation must ensure that models represent the characteristics of generating units with sufficient accuracy, especially during severe transient disturbances.

Figure 1 illustrates the main steps that are necessary to evaluate the correspondence of a model with reality, based on a model definition [33, 46]:

(1) Collect actual data from the devices under modelling, which can be recorded or measured during tests.
(2) Simulate the same set of tests or events during the data collection process on the model.
(3) Compare measured or recorded data to simulation results and decide if the validation is acceptable or the model parameters have to be adjusted.

Each of the steps will be further explained in next subsections.

3.1. Test data collection

In the early stages of the development of standard models, generic RMS models were validated against manufacturer detailed EMT models using a similar simulation tool [36]. It is an easy method, but it has some shortcomings regarding the model assumptions and the area of application. However, parallel validation of positive sequence RMS against EMT models could be necessary for generation assets connected to weak power grids [11].

Currently, validation is mostly carried out by testing. Tests can be carried out on-site or off-site, via factory, laboratory or bed tests [52]. On-site or field tests are more realistic and, as a consequence, they are generally preferred by system operators. In Australia model validation must be carried out with on-site tests whenever possible. In Spain, the validation report shall include results obtained under real tests, even if bench tests are accepted. In Ireland, both test types are accepted, because validation is based on the comparison of simulation results with actual observed behaviour of a prototype or production WTG under laboratory conditions and/or actual observed behaviour of the real WTG as installed and connected to a transmission or distribution network. In Germany, the use of bench tests is permitted only if the behaviour of the generating unit is equal to the free-field measurement or when free-field testing equipment is used, as men tioned in standard IEC61400-21.

However, real tests might have some impact on the nearby grid users, so significant cost and test-time reductions can be obtained via proper factory testing [53]. Repeatability of the tests is also much better and, thus, it is much easier to identify any equipment problem, if necessary.

Model validation is required for different transient conditions, depending on the country. Generally, dynamic models are validated by testing the generating unit performance under faults. Thus, Low Voltage Ride-Through (LVRT) capability of the generation asset under test is evaluated. In these cases, staged testing is a preferable option, with two factory implementation options [36, 54]:

- Staged generator testing: it can be carried out using the turbine generator and controls alone, without the blades, during manufacturing process or at a dedicated test facility.

- Staged full-scale testing: a full-scale turbine subjected to electrical disturbances at dedicated test facilities.

Factory test set-ups for short-circuit emulation are called *voltage dip generators*, which are able to emulate the actual network impedance during a fault. Four types of emulators have been proposed in the literature [53, 55–57]: generator based, shunt impedance based, transformer based, and full converter based emulators. Full converters have the advantage to be able to emulate any voltage waveform [53], not only voltage dips but also active and reactive power steps, or voltage and frequency changes, as presented in [58]. Some commercial testing solutions have been patented such as the Megha for LVRT tests or QuEST Lab, also able to carry out High Voltage Ride-Through

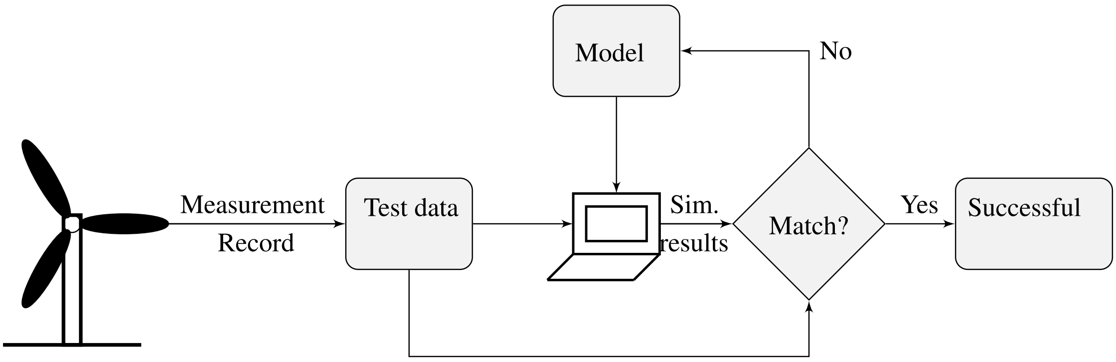

Figure 1: General validation process

(HVRT) or phase angle jump tests [59], which are aimed for on-site tests.

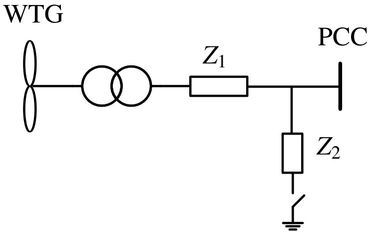

Figure 2: Low voltage ride-through test equipment principle based on voltage divider

The most common approach among the countries under review is based on the shunt impedance based voltage dip generator as a voltage divider, proposed in standard IEC61400-21 [60] (Figure 2). German and Danish validation tests are based on this standard. In the case of Germany, it can be used to validate both WTGs and photovoltaic generation units, for which the power at the DC side could be supplied by a suitable source. It has the advantage that it can be easily constructed and the setup is quite similar to a real fault situation, and thus, a realistic voltage dip is obtained [53]. The impedance Z_2 emulates the fault impedance. The voltage dip starts when the circuit breaker is closed, and ends when the breaker opens and clears the fault current. The impedance Z_1 is needed in order to limit the influence of the voltage dip in the supplying grid. In order to be able to set the remaining voltage level during the dip, according the grid code requirements, the impedance values have to be adjusted accordingly, or a shunt impedance bank can also be used [57]. In the German regulation, the impedances employed in the testing equipment must have an X/R ratio of at least 3. The SCR at the connection point must be at least 3. The Fault Ride-Through (FRT) tests must be performed for three-phase and two-phase faults at partial and full load. The test is aimed both for model validation and compliance verification for LVRT requirement. Nonetheless, other test benches other than a short-circuit simulator based on the voltage divider principle, are permitted: grid simulators or transformer-based testing equipment.

For weak connection points, on-site staged fault testing is usually more appropriate [11]. Several methods exist for the implementation of on-site staged fault testing, including the fuse-wire method, the dropped conductor method and the direct earthing method. A practical set-up and results of the latter method are presented in [11].

However, other non-fault disturbance tests are also required in Australia, Denmark, Republic of Ireland or UK. In Australia, general model acceptance tests are fault disturbance tests (three-phase-to-ground) and non-fault disturbance tests, such as step response test on machine active and reactive power, or grid voltage magnitude, rate of change of frequency and step response test on grid voltage angle. In Denmark, aside from voltage drop tests, model behaviour under voltage increase and frequency variations must be tested and results shall be obtained from test stations or measurement at commercial systems. In Germany, dynamic generating unit models are validated for LVRT requirement and at power station level, focuses on active and reactive power. Finally, the conditions validated in Ireland must be similar to those of interest, such as short-circuit levels, severe faults, voltage excursions, or large wind variations.

Test data can also be collected by opportunistic testing, also called on-line monitoring [36]. Thus, measurement equipment installed on-site records naturally power system disturbances used to validate the simulation models. However, transient model validation requires three-phase fault events, which rarely occur, and in any case, they seldom present the sufficient magnitude. Therefore, validation against single-phase short-circuits has been carried out in some cases [35, 36], as measurements were considered valid and it was reported to be a successful approach also for synchronous generators [50]. Otherwise, long-term monitoring approach can be used, and progressive model validation can be performed [11].

3.2. Model simulation

Model acceptance processes are often based on play-back techniques [33]. The simulation model is fed with recorded measurements from the low voltage terminals of the actual device. Accordingly, the same set of tests or events can be reproduced. In that case, the grid impedance and the dynamic behaviour of the grid is not included in the model. This choice is called open-loop model validation. Play-back techniques are more commonly used with positive sequence models [11]. However, open-loop validation could lead to error, if the correlation between wind speed and voltage is not taken into account [61] and if the non-linear characteristics of the step-up transformer are omitted [11].

An analogous technique is reported in [35], in use by WECC for some time. It is achieved with the aid of a modified classical generator model (GENCLS) capable of holding terminal voltage and frequency as specified in an input file with actual records. However, for some simulation software packages, it is not possible to usual an external file to establish a fictitious voltage. So, two alternatives are possible:

- Simulation of a similar event by adjusting disturbance conditions.
- Application of a specific voltage profile using a user-written model.

The latter option is adopted for wind farm simulation in Spain, in the case of grid code compliance verification. On the other hand, closed-loop model validation entails a farm level model being connected to the rest of the network [11]. The validation of an entire WPP is reported in [33], using recorded voltage and current at Point of Common Coupling (PCC) level. However, according to the experience of system operators in Australia, a number of high-speed data recorders at several locations are necessary, including the low and medium voltage terminals of critical nodes [11].

In Australia, the general model acceptance tests required are fault disturbance tests (three-phase-to-ground fault) and non-fault disturbance tests, such as step response test on machine active and reactive power, or grid voltage magnitude, rate of change of grid frequency, and step response test on grid voltage angle. The same case studies are required for wind farms and synchronous generators, although additional case studies are stated for each one: regarding LVRT for variable generation technologies, and regarding excitation systems, and governors for synchronous generators. Model acceptance tests are also indicated for dynamic reactive support plants and HVDC links. Model acceptance set-up for wind farms is shown in Figure 3. A similar set-up is proposed for synchronous generation, where the connection arrangement of the generating unit is slightly different. Models are expected to work for a range of the simulation parameters rather than for specific settings. Fault disturbance tests must consider factors such as fault duration, grid SCR, grid X/R ratio, pre-fault load levels, or fault X/R ratio. For each test, a combination of study cases are presented based on varying aforementioned factors.

3.3. Model validity acceptance rules

A perfect match between the measured and simulated response is not expected, but an adequate match that captures the relevant dynamics and properly represents the dynamic response of the plant [33]. Few grid codes indicate the minimum accuracy level. For instance, in Denmark, the accuracy of simulations models must be kept within ±10% for voltage, active power, active current, reactive power and reactive current. The actual accuracy shall be documented in the validation report. In Australia, accuracy requirements are detailed for both load flow and short-circuit models, and transient and oscillatory stability models. Regarding load flow models, the deviation of the plant model from the actual plant response for active power and reactive power must not exceed 10% of the total change in that quantity, and the model must not show characteristics that are not present in the actual plant response. These accuracy requirements apply also for transient stability models and further specifications are indicated for control system models, time domain responses including non-linear responses or performance and responses to switching or controlled sequence events.

Even if most notable approaches to model validation are based on measurements, validity decision based on expert engineering judgment is considered in some countries such as the United States [33].

If simulation and test results show a different behaviour from the generation asset, model parameter values shall be adjusted or derived upon the observance of test response or through internal measurements [32]. However, unlike the case of synchronous machines, for power electronic interfaced technologies it is not generally possible to derive most model parameters directly from time-domain analysis of on-site test results nor from frequency domain transfer function testing [11]. Indeed, parameter tuning based on curve fitting against on-site testing measurements has to take into account a wide range of operating conditions.

Type validation is admitted in most regulations. In Australia validation on a single generating unit would be sufficient, as the same performance is observed in other units of the same type. However, factory and/or type tests alone are not sufficient for model validation, so a long-monitoring program must also be established [32].

4. Verification of the compliance of technical requirements

Manufacturers and generators have to show compliance with the technical connection requirements included in the grid codes under force. There are two alternatives to carry out this compliance verification [1]: practical tests or simulation, provided that the generating unit model has been validated. Each approach has its own advantages and disadvantages, and the risk and costs of the both methods have to be assessed. Testing represents the real behaviour of the power system, but it has a high cost and can have side effects on the system if it is performed on-site. On the contrary, simulation does not involve any additional charge and it is harmless. However, validation of the model against field measurements is necessary. In general, compliance verification is performed through a combination of both techniques, including on-site testing, comparative simulation studies, long-term monitoring and provision of overseas test experiences [11]. However, on-site testing is the primary approach expected to be applied [11].

In addition, the relative size of the generating system has to be taken into consideration, as well as the type of generation technology and the location at which requirements are expected to be met. Regarding generation systems based on renewable

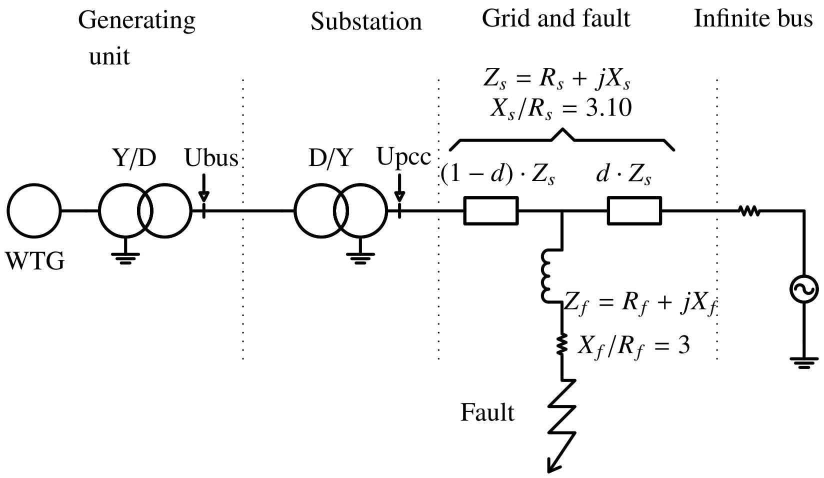

Figure 3: Test circuit for model acceptance testing

energy sources, power plants are made up of several small size generating units, but grid code requirements are expected to be met at the PCC. Therefore, depending on the technical rule under study, verification shall be carried out on two levels [62]: a single generating unit, and the entire plant level.

4.1. Review of compliance verification practices

Comparison of compliance verification practices in the countries under study is a demanding task, since procedures are related to heterogeneous grid code structures and requirements. Besides, the detail degree, structure and even terminology employed in the relevant documents is heterogeneous. Nonetheless, following are gathered the most remarkable international compliance testing practices and rules. This section introduces general requirements and practices regarding generating system performance verification in order to comply with grid codes under force. Reference documents for the countries under study are summarised in Table 2.

Australia. As stated in [63], during commissioning applicants must demonstrate that their generating system meets the performance standards. Wherever practicable, the performance must be demonstrated by test. However, these tests cannot demonstrate that the performance standards are met under all system conditions. Indeed, some requirements cannot be demonstrated by test. The actual plant performance must meet the expected behaviour within predefined and agreed tolerances. Commissioning tests are undertaken considering power system conditions at the time of commissioning. However, the comparison of actual results to modelled results provides reasonable evidence that the generator can remain in service for the full range of power system conditions.

The rules do not detail any specific commissioning test. Instead, as technologies, types and the specific installation may vary from site to site, tests are expected to be tailored to the requirements of the equipment. In order to assist the applicant, typical tests for synchronous and non-synchronous machines are outlined based on former practices. For some of the rules more than a testing and monitoring method is proposed, along the required testing frequency and the basis for compliance assessment.

Some of the performance standards can be fully demonstrated based on on-site tests: power quality, protection system, active power control, monitoring and control requirements and power station auxiliary supplies. On the other hand, reactive power cannot be fully demonstrated on-site for the full voltage range, as well as the response of the generation system to frequency, and voltage disturbances or contingencies which are unlikely to be demonstrated on field. Only the limits of the protection system related to these requirements may be proved. Regarding frequency control, the actual performance of the system under frequency variations is unlikely to be demonstrated on-site. With respect to voltage and reactive power control, the actual performance of the generating system during all oscillations considering all system conditions is unlikely to be demonstrated on-site. The performance of the system may be partially demonstrated through model validation. Some of the rules can be tested by modelling and simulation of the plant, such as fault level, partial load rejection, or responsiveness of governor system. The response to voltage disturbance, frequency control, impact on network capability and voltage and reactive power control can also be demonstrated through model validation.

Denmark. IIN Denmark, verification requirements depend on the generating unit technology and size, analogously to grid code requirements. Regarding WPPs, plant owners are responsible for ensuring that generating assets comply with technical regulation and to provide some documentation in accordance with the total rated power of the power plant at the point of connection [70]. Even small WPPs above 11 kW require type-approval and power quality verification according to standard IEC 61400-21 [60], apart from other documents. In addition, WPPs with a power output above 1.5 MW need to verify the capability of the power plant to remain connected during voltage drops, and dynamic simulation is an acceptable verification method [70]. [65] and [66] contain guidelines for implementing

Table 2: Grid code compliance verification in the countries under study

Country	Title	Technology
Australia	*Commissioning requirements for generating systems* [63] *Template for Generator Compliance Programs* [64]	Any technology
Denmark	*Technical regulation 3.2.5. for wind power plants with a power output greater than 11 kW* [20] *Appendix 5.1. Wind power plants with a power output range of 1.5 MW to 25 MW* [65] *Appendix 5.1. Wind power plants with a power output greater than 25 MW* [66]	Wind power
Germany	*FGW Technical Guidelines for Power Generating Units Part 3, Determination of electrical characteristics of power generating units and systems connected to MV, HV and EHV grids* [21]	Any technology
Republic of Ireland	*Grid Code Compliance Test Procedure* [67] *EirGrid grid code* [23]	Wind power
New Zealand	*Companion Guide for Testing of Assets* [68]	Any technology
Spain	*Procedure for verification, validation and certification of the requirements of the PO 12.3 on the response of wind farms and photovoltaic plants in the event of voltage dips* [69]	Wind and PV power
UK	*The Grid Code* [30] *Guidance Notes-Power Park Modules* [31]	Non-synchronous generation

commissioning tests for wind power plants respectively with a rated output over 1.5 MW and up to 25 MW, and over 25 MW. Regarding electrical conditions, tolerance to frequency and voltage deviations, and power quality are listed for verification, and many items can be verified by using simulation models. For instance, under normal operation, conditions wind farms must withstand phase-angle jumps without disconnecting and the compliance can be verified by using a simulation model. LVRT requirements regarding balanced and unbalanced short-circuits can also be assessed with simulation models. In any case, set-ups for testing or simulation are not indicated.

Germany. The grid connection regulations to be verified are listed below.

- Active and reactive power generation depending on the primary power supply
- Active power control for defined set points and frequency deviations
- Power quality
- Performance during faults (LVRT)
- Cut-in conditions
- Performance of protective devices

The aim of the LVRT test is to determine whether the generating unit is capable of detecting voltage dips and riding through them, as well as providing current during the voltage dip. The voltage dip detection methodology must be described. Testing, measurement and verification of the unit performance can be carried out in accordance with standard IEC61400-21 for any of the requirements. Test benches can be used for:

- Active and reactive power provision based on predefined set-points
- Transition behaviour of active and reactive power provision based on predefined set-points
- Reduction of output power with overfrequency
- PQ diagram
- Performance during faults

In some cases, if the safety of the unit is not guaranteed, tests cannot be carried out with the unit running. In order to verify the voltage regulation requirement, the test can be carried out on a test bench by means of a suitable grid or via adjustment of the rated voltage in the control system. Flicker determination can be carried out on-site, by using a test bench on the actual grid or an AC network simulator.

Regarding the compliance at system level, only measurement of harmonic current is described in the reference document.

New Zealand. Generation assets must pass through testing at the commissioning stage. There is no compliance requirement in the connection rules, but an explanatory guide for asset testing has been released by the System Operator (Transpower) covering routine tests and commissioning tests. Routine tests are designed to ensure that the generators are able to meet the technical requirements, as well as to verify operational ranges and limits of the generating plant, and steady-state performance, including over-under frequency performance. Initial tests apply to all generators above 1 MW, but test types differ depending on generation technologies. Detailed test programs for synchronous generators and wind generators are indicated. Regarding FRT, the test entails applying a fault to the grid and monitoring the wind farm response. The test must confirm that the co-ordinated control systems operate correctly and also allow the validation of the model. In addition, this test must confirm that the wind farm stays connected during under frequency excursions.

Republic of Ireland. The reference document encompasses major technical requirements for wind farms:

- Active power management
- Transmission system voltage requirements
- Signals, communication and control

In each section, a series of tests are defined, in order to be performed at wind farm level. For each test the following items are described: purpose, instrumentation, procedure and pass-criteria. All tests can be carried out on-site without additional equipment, with exception of the frequency response compliance test of wind farms. Since the grid frequency cannot be changed at will, this test requires to be simulated by means of injection of a frequency signal into the wind farm controller to simulate appropriate changes of frequency.

Spain. Only verification regarding LVRT requirement included in the Operation Procedure 12.3 is documented. The verification procedure is explained in Subsection 4.2, within the certification procedure.

United Kingdom. Compliance processes for both synchronous generators and power park modules are included in the grid code document. Tests for the final operational notification must include:

- Reactive capability tests, that shall be performed by modifying the voltage set-point of the voltage control scheme
- Voltage control system tests, that can also be used to validate the excitation system or voltage system model. The voltage control system shall be perturbed with a series of step injections to the voltage reference, and where possible, multiple up-stream transformer taps.
- Governor or frequency control system tests, that can also be used to validate the governor or frequency control system model. Frequency modulation is possible by using a frequency injection signal.
- FRT tests for power plants above 100 MW

For each compliance test, the description, purpose, required results and assessment criteria are given. However, measurement and acceptance requirements are not indicated. If a power park contains two or more identical generating units, compliance testing may be reduced if the first unit completes the full testing.

Regarding FRT, manufacturers can demonstrate compliance using tests carried out with the facilities available. However, manufacturers are expected to replicate each fault type (3-phase, phase-phase, two-phase to earth and single-phase to earth) with varying magnitudes. The tests should illustrate any changes in characteristics or internal operating modes that depend upon fault severity, such as active and reactive power fault contribution and power recovery characteristic. The tests should be performed on a single power park unit using a test circuit based on the voltage divider.

Data and performance characteristics with respect to certain grid code requirements may be registered by manufacturer for specific non-synchronous generating units. It is called *Manufacturer's data and performance report*, which covers FRT capability and the generating unit mathematical model. Simulation studies must be submitted to the system operator to demonstrate compliance with the connection conditions. The reactive power capability of the generator must be demonstrated by a load flow simulation study. On the other hand, voltage control, reactive power stability and FRT capability of power park modules shall be proved dynamic simulation series.

4.2. Certification procedures

Showing compliance with grid codes is especially challenging regarding renewable power generation systems, and is best done by compliance certification [71]. According to the international standard ISO/IEC 17000:2004, certification is a third-party attestation related to products, processes, systems or persons, whereas attestation includes the issue of a statement, based on a decision following the review, that fulfilment of specified requirements (e.g. guidelines, codes and standards) has been demonstrated. The review itself covers the verification of the suitability, adequacy and effectiveness [72].

Certification is generally achieved in two steps. Firstly, a type of generating unit will obtain a **Type Certificate** based on one or more country specific grid codes according to the relevant certification procedure. A recognised certification system for WTGs is IEC 61400-22 [73], that includes the evaluation of design, type-testing and manufacturing, as well as an optional type characteristic measurements module (power quality and noise). Procedures for assessing compliance regarding power quality requirements are gathered in IEC 61400-21 [60], including voltage quality (emissions of flicker and harmonics), voltage drop response, power control (control of active and reactive power), grid protection and reconnection time. The type certification process ends with the issuance of a certificate, maintained and verified over time.

In a second step, a site specific **Project Certificate** will be issued for each power plantbased on site specific data and the type certificate. In Europe, the most complete and documented certification procedures regarding grid code verification are the *Procedure for Verification, Validation and Certification of the Requirements of the OP 12.3 on the Response of Wind Farms in the Event of Voltage Dips (PVVC)* in Spain [69], and the German *Technical Guidelines for Power Generating Units. Part 8. Certification of the electrical characteristics of power generating units and systems in the medium, high- and highest voltage grids* [74], which describe the procedures to certify power generation systems according their corresponding grid codes. A theoretical and practical comparison between both certification systems can be found in [4].

4.2.1. Germany: FGW-TG8 procedure

The FGW-TG8 document [74] describes the procedure for the preparation and issue of a unit and system certification in accordance with the German grid connection regulations. The scope of the guideline is limited to the electrical characteristics impacting load flow, grid stability and voltage quality in an electrical grid. The document is complemented by documents [21] and [22].

As summarised by [75], applicants must provide the type testing according to FGW-TG3 [21], proved by the test report that includes measurement data, a comprehensive computer based model of the power generating unit and an open model of the power generating unit. The computer model may be encapsulated as a black box model and compatible with type tests in FGW-TG3 in order to facilitate verification of the model simulation based on measuring results. Regarding the detail of the open model, it must be clarified in advance between the certification authority and the manufacturer. In some cases it may be sufficient to present block diagrams. It is necessary to comprehensively describe fault detection for verification of performance in a fault situation. Model validation is performed based on the comprehensive computed-based unit model, by comparing simulation results to the measured data given in the test report, as well as on the basis of simulation results for test specifications for a variety of defined set points and/or grid conditions. Model validation is completed by inspecting the aforementioned open model.

The document also includes the procedure for generating system certification. To certify power generating systems the applicant must provide:

- Details on all the units connected in the system, including unit certificates, product certificates and/or test reports.
- Details on the electrical components of the system, where applicable component certificates must be provided. This includes all operational resources in the system internal grid up to the grid connection point. Single line diagrams must be provided.
- Details on the grid connection point, grid operator and connection regulation. The characteristic data of the public grid (short-circuit power and impedance phase angle) are provided by the grid operator.

To certify old systems, the applicant must provide verification of type testing according to FGW-TG3. Furthermore, the document must contain the specification of the original power generating unit and the specifications on the retrofitted power generating unit. Model validation is not included in this procedure [4].

4.2.2. Spain: PVVC procedure

The PVVC includes the verification, validation and certification of wind farms, photovoltaic conversion systems and FACTS. In the regulation under force, only wind farms are requested for LVRT, and accordingly, grid code verification is focused on wind power. However, steps are being taken for enlarging this requirement to every non-synchronous generation. For wind farms, two possible processes to verify the conformity with the response requirements established in OP 12.3 for FRT: the *General Verification Process* and the *Particular Verification Process*. The General Verification Process consists of verifying that the generating unit does not disconnect and that the requirements stated on the OP 12.3 are met. Three actions must be completed: testing, model validation and, finally, wind farm simulation. Regarding test procedure, field tests are preferred, even though laboratory tests could be accepted for FACTS. WTG simulation model validity must be accredited by a model validation report confirmed by measurements in the field tests. Next, the simulation models of all dynamic elements of the wind farm have to be integrated inside a wind farm simulation model. Using this model, a wind farm simulation can be carried out evaluating its response. A WTG with an accredited test report will constitute a unit type. A generator of the same manufacturer and with the same characteristics can avoid to have to repeat field tests. Wind farms with a verified wind farms report will be considered a wind farm type (i.e. project type). Figure 4 shows the three steps of the general verification process.

As an alternative to the general procedure, the particular verification process obtains the direct wind farm verification by testing the dynamic elements of the wind farm and without having to carry out computer simulations. Hence, model validation and wind farm simulation are not needed.

The particular verification process is faster and cheaper than the general verification process [4]. Hence, wind turbine manufacturers and wind farm operators may prefer this process if the WTG (or the system made up by WTG and FACTS) can be tested and can ride through the voltage dip test defined in the particular verification process. However, the general verification process is necessary in those wind farms whose wind turbines can not ride through the voltage dip defined in the particular process and a compensating system is installed at the wind farm substation to fulfill the OP 12.3 requirement [4].

Test procedure. As testing equipment, the use of a voltage dip generator using an inductive divider is recommended. Other types of dip generators are accepted, but resulting residual voltages must be similar to those defined in the document. Four test categories are defined from the combination of partial and full load operating point, and three phase and two phase voltage

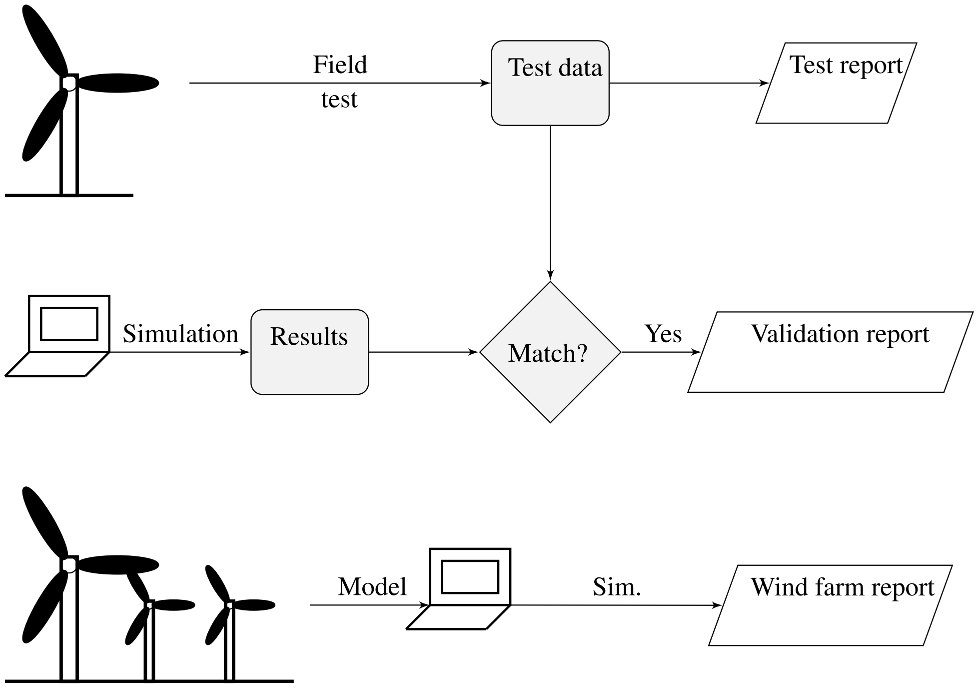

Figure 4: General Verification Process

dips: three-phase short-circuits at partial and full load, and two-phase isolated short-circuits at partial and full load. The definition and conditions in which the test will be carried out depend on the objective of the test: for model validation (general verification process) or observance of FRT (particular verification process). In both cases, if the wind turbine is connected to a weak point in the system, the voltage dip will be obtained with no load, i.e. the generator disconnected from the dip generator.

Model validation procedure. The generating unit model validation consists of three steps:

- Instantaneous voltage and current values are recorded for all the test categories. The duration of comparison window is a second, with 100 ms before the voltage dip.
- The manufacturers models must reproduce each of the tests carried out in the field. For that purpose, the test bench will be modelled as a voltage source set to the time series of the measured values, in the case of a WTG. For FACTS, the test bench can be modelled as a voltage source and a current, so that they give exactly the same voltage and current as during the test. This is the aforementioned playback technique. The integration step must be equal to or less than the time interval for the sampling frequency of the measurements.
- The results of the simulation model and the field tests must match. The model will be considered validated when the difference between simulation and test for active and reactive power does not exceed 10% in the 85% of the cases.

Wind farm simulation procedure. In order to carry out a wind farm simulation, the model of the wind farm will be based on validated WTG models. Existing reactive compensation devices, cables, step-up transformer and internal lines will be also modelled. WTG aggregation is accepted. In addition, the interconnection substations has also to be represented by a MV/HV transformer and the evacuation line until the PCC. The rest of the power system (the external grid) must be modelled so that the fault clearance at the PCC reproduces the usual voltage profile in Spain: a sudden increase upon the clearing of the fault and a slower recovery afterwards. This profile will be considered fixed and independent of the location of the wind farm. The single line scheme is shown in Figure 5, based on the reference document. The Union for the Coordination of the Transmission of Electricity (UCTE) equivalent includes a synchronous generator that reflects the UCTE system. To take into account the dynamics of the closest grid, a synchronous generator is included, as well as a load, modelled as constant current and constant impedance asset. Data of the synchronous generators and their excitation systems are indicated. The fault reactance is adjusted so as to have a voltage magnitude of 0.2 p.u. and 0.6 p.u. during respectively a three-phase and a two-phase short-circuit. Parameter values can be found in the reference document. Voltage profile is shown in Figure 6. All sequence impedances have been considered equal, as there is no specific indication in the document.

For each of the four test categories, it must be shown that:

- The wind farm remains connected during the voltage dip. Therefore, the simulation model must include the protection relays. If the wind farm model is not based on unit aggregation, the loss of generated active power must not

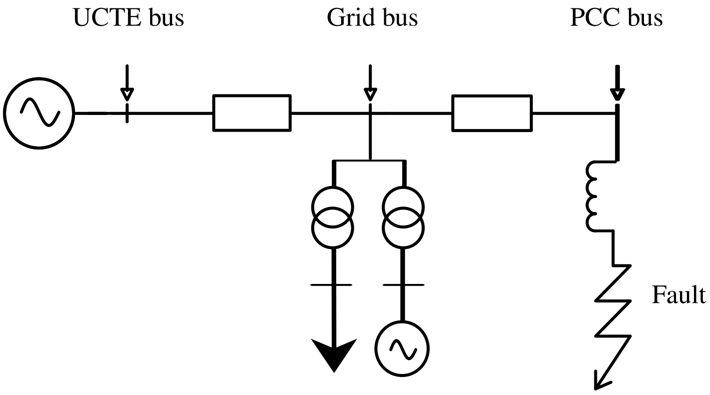

Figure 5: PVVC: model of the equivalent electrical grid

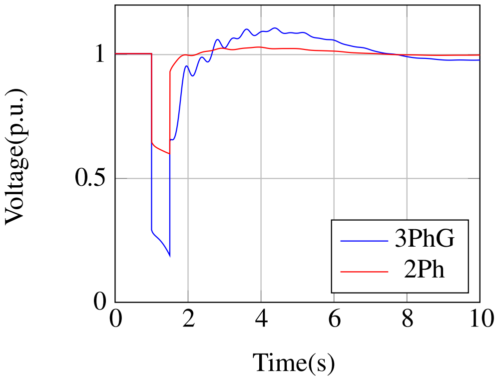

Figure 6: Voltage at the PCC bus during faults

exceed 5% of the pre-fault value.

- Voltage and current levels at WTG terminals must be compared to test values and admitted error tolerances are defined (2% for residual voltage level).
- Exchanges of active and reactive power must be as described in the technical requirement. Measurement techniques and power calculating methodologies for testing and simulation are indicated in the reference document.

For existing wind farms, simplified WTG models can be used, as usually no data to model the installations exists. If the wind turbines have an accredited test report, general library models can be included in the wind farm simulation. The models will consist of a current/voltage source and protections, either so as to meet the limits of the report. If the requirements to use library models are not fulfilled, validated models of WTGs or FACTS must be provided by the manufacturers and the validation must be carried out according to the PVVC.

Verification of requirements for photovoltaic plants. Annex II of the reference document indicates the verification of the requirements in P.O. 12.3 for photovoltaic plants. The testing process is based on feeding the AC side of the photovoltaic conversion system by a system that simulates voltage dips. The conversion system will be tested by a continuous source at its DC part, either consisting of a set of photovoltaic modules or a DC power supply. Regarding the voltage dip generator, it can be:

- An inductive generator similar to the set-up proposed for WTGs and FACTS.
- A power electronics device or other device able to simulate a variable AC voltage with the profile as defined in the technical requirement.

Regarding test validation criteria, active power must be within indicated ranges, the system disconnection must be less than one in three consecutive tests, injected current during the dip must meet specified requirements and the residual stress level and time during the load test must be as indicated. The voltage dip profile depends on whether the system is connected to a strong or weak PCC.

5. Conclusions

The increase in renewable generation plants formed by a large number of individual generating units poses a challenge to system operators, in terms of connection process and plant modelling management. In order to cope with these issues, compliance procedures based including on-site testing and comparative simulation studies have already been established. This paper has reviewed and analysed regulations and usual practices of system operators in Australia, Denmark, Germany, New Zealand, Republic of Ireland, Spain and United Kingdom.

It can be concluded from the this study that grid code verification, model validation and certification procedures are still under development in many countries, which on the contrary have rather stable, harmonised and complete grid codes. Each regulation provision should be complemented by compliance tests including description, purpose, testing set-up, required results, and assessment criteria. Thus, compliance verification should not leave room for interpretation. However, even if compliance processes are well documented in some countries like UK, mostly there is usually little information and documents are not clear nor definite.

Recently, RES certification have been launched in some countries, such as Germany and Spain. The German regulation encompasses generating unit and system certification. The process includes type testing verification, as well as the provision of simulation models of the assets under certification. On the other hand, Spanish procedure is based on requirement OP 12.3. Thus, wind farm certification is based on the verification of LVRT requirement based on simulation models of the whole wind farm, which are made up by previously validated wind turbine models.

However, simulation procedures are scarcely documented and basically focused on FRT requirement, since fault disturbances are also used for model validation. On the other hand, modelling requirements are more widely standardised, although mostly not adequate for weaker parts of the power grids and EMT studies. The development and use of adequate generic non-synchronous generator models would certainly smooth the way to straight-forward certification procedures.

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