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Review of Procedures for Verification of Grid Code Compliance of Renewable Generation

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Abstract. Renewable generation has undergone an enormous increase in the last decade all over the world, in terms of energy, installed power and number of plants. In order to cope with a huge number of connection applications, system operators are detailing specific procedures for verifying the compliance of the plant performance to the grid code requirements.
This paper reviews the procedures used by system operators of different countries with the objective of introducing actual practices and highlighting the similarities and differences among countries. In general, for plants that include multiple similar units, the compliance procedure includes a mixture of commissioning tests and simulations results, with the later used for plant model validation purposes. Also, for some specific requirements only simulation results are accepted for the entire plant, when a single unit has been validated against measurements for the same requirement.

Key words

Grid Code, Verification, Validation, Renewable Generation

1. Introduction

Grid codes specify the electrical performance and other regulations that a renewable generation plant must comply with in order to achieve 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.

Due to the huge increase in renewable energy generation in the last decade, system operators have adapted their grid codes to manage an increase level of variable generation and, as a consequence, they are requiring plant promoters to show evidence of grid code compliance of their projects to streamline the connection process.

Grid code compliance requirements are different from one country to another and, in general, they are more demanding in those countries with a high penetration of renewable energy. The requirements have evolved from the Low Voltage Fault Ride Through (LVFRT) requirement for wind turbines to more elaborate ones that apply to renewable power plants in general [1].

This paper reviews the procedures for verification and validation of Renewable Generation for Grid Code Compliance in different countries around the world. The countries analysed are: Australia, Denmark, Great Britain (UK), Ireland, New Zealand and Spain. The selection covers a broad spectrum of countries with different power system structures and different degrees of renewable energy penetration.

The paper is organized in 5 chapters including this introduction. Chapter 2 reviews grid code compliance verification procedures. Chapter 3 reviews compliance procedures based on testing and Chapter 4 procedures based on simulation. Finally, Chapter 5 contains the conclusions.

2. Grid Code Compliance Verification

Grid code compliance verification has a double objective. On the one hand, plant owners are responsible for demonstrating compliance to 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 does 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, regarding how each requirement must be validated.

According to ENTSO-E [2], there are two alternatives to carry out a verification plan: compliance testing and compliance simulation. Each approach has its own advantages and disadvantages, shown in Table I, but they should take into consideration the following factors [3]:

1) The technology of the plant, including whether its performance is likely to drift or degrade over a particular timeframe.
2) Experience with the particular generation technology, including manufacturer's advice.
3) The connection point arrangement.
4) An assessment of the risk and costs of different testing methods, including consideration of the relative size of the plant.

Table I. - Advantages and disadvantages of grid code verification methods

Method	Advantages	Disadvantages
Testing	Representative of real behaviour	High costs, effects on grid
Simulation	Low costs, no effects on grid	Needs validation

Besides, depending on the grid code requirement under study and the type of generation technology, the verification shall be carried out on two levels [1]: a single generating unit, and the entire plant.

For multi-unit generating systems comprising tens of identical units, on-site testing of each and every unit can be impractical. For these, proof of type test may be acceptable. This will serve to demonstrate that various generating units installed on-site are identical. In the case of simulation verification, aggregated simulation models can be accepted for large multi-generator power plants.

3. Grid Code Compliance Testing

A. General remarks

Testing of power generating plants is carried out for two main reasons [4]:

1) Performance compliance: to test compliance to contractual requirements and grid codes. These criteria point out specific levels to be met. Therefore, tests may be designed with binary pass/fail objectives.
2) Model validation: many system operators require dynamic models to be used in stability analysis for operation and planning purposes. Tests may be performed to tune and verify simulation models to closely match the performance of actual equipment.

Tests can be performed on-site or off-site, via factory, laboratory or test bench [5]. Significant cost and test-time reductions can be obtained via proper factory testing. Also, repeatability of the tests is much better and, thus, it is much easier to pinpoint reasons to any equipment problems, whether they are encountered.

Regarding renewable power generation, mainly LVFRT testing is addressed in all countries. LVFRT capability can be tested using voltage dip generators. Four types of dip generators, shown in Figure 1, have been proposed in the literature [6]: generator based, shunt impedance based, transformer based and full converter based.

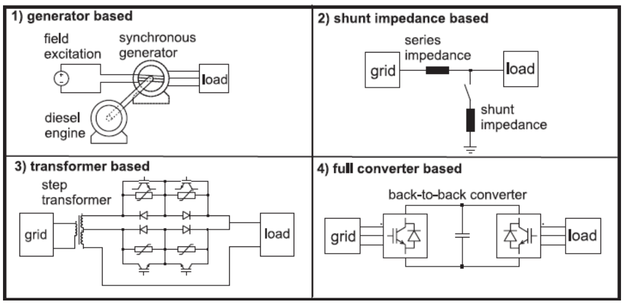

Fig. 1. Voltage dip generator types [6]

Some commercial testing solutions have been patented such as QuEST Lab or Megha [7], but the most common approach used is based on the voltage divider proposed in standard IEC 61400-21[8], and shown in Figure 2.

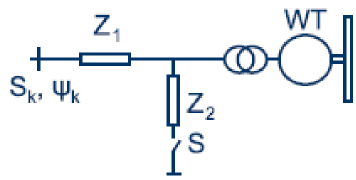

Fig. 2. Low voltage ride-through test equipment principle in IEC61400-21

The impedance Z_2 emulates the fault impedance. The dip starts when the circuit breaker S is closed, and ends when the breaker opens and clears the fault current. The impedances usually are inductors, because they have lower losses than resistors. Moreover, inductive fault impedance is more demanding in terms of reactive support to be provided by the generator. The impedance Z_1 is needed to limit the influence of the voltage dip in the supplying grid. In order to be able to select the remaining voltage level during the dip (according to the grid code requirements), the impedance values have to be adjusted accordingly. In most grid codes, FRT conditions are specified at the Point of Common Coupling (PCC). Testing procedures usually prescribe the same retained voltage levels as required at PCC also at the generator terminals. Indeed, this would indicate that the generator is fully compliant.

Besides the FRT tests, there are further tests to check the active and reactive power capability of renewable generators. Especially, the ramping of active power is a major test, as variable renewable generators often face requirements not to exceed a defined active power gradient at start-up after a disconnection. Regarding the reactive power capability test, the procedure is similar to the typical tests for conventional power plants.

B. International experiences

In Australia, on-site tests are required to confirm the performance of the generating system and to assist in the validation of the model [9]. Both off-line and on-line tests are proposed in [10]. These tests, shown in Table II for non synchronous generators, are expected to be tailored to the requirements of the installed equipment and settings. For model validation tests, these are defined in [11] for large and small disturbances.

Table II. – List of compliance test in Australia

Requirement	On-line test	Off-line test
Reactive power capability	Operation at reactive power limits	n.a.
Power quality	Monitoring	Monitoring
Response to frequency disturbances	On load protection test	Secondary injection
Response to voltage disturbances	On load protection test Model validation	Secondary injection Model validation
Response after contingency	On load protection test	Secondary injection
Network impact	Model validation	Model validation
Protection from system disturb.	On load protection test	Secondary injection
Frequency control	Step response test Model validation	Step response test Model validation
Voltage control	Step response test	Model validation
Active power control	Step response test Dispatch command test	Model validation
Reactive power control	Step response test	Model validation

In Denmark, regarding wind power plants, grid code compliance can be verified only by simulation [12]. Hence, only validation purpose tests are defined, for individual types of wind turbine generator systems and for the entire wind power plant. In the first case, voltage drop and grid protection test are based on the standard IEC 61400-21, while the remaining tests (voltage increases and frequency variations) should be validated by means of test results obtained from test stations or measurements performed at commercial wind turbine generator systems. Similarly, for the entire wind power plant, the simulation model must be validated for all control types against measurements.

Besides the compliance processes included in the grid code, in Great Britain, document [13] gives guidance notes for non-synchronous (power park unit) generators to demonstrate compliance with the grid code. In general, simulation studies are required where it is impractical to demonstrate capability through testing as the effects on other system users would be unacceptable. Table III summarises main tests carried out for power parks.

Concerning response to frequency disturbance testing, several scenarios (high and low system frequency and various primary resource variations) are covered for each of four different operating points: full and no load power output for frequency sensitive mode operation and full and no load power output for limited frequency sensitive mode.

Table III. – List of compliance test in United Kingdom

Requirement	Test
Reactive capability	Measure reactive power supplied/consumed for different active power output and grid voltage
Voltage control	Measure voltage response to step changes in the voltage reference and to tap changes of an upstream grid transformer
Frequency control	Response test to injection of frequency deviation signals into the frequency controller
Response to frequency disturbances	Test control systems reaction to changes in system frequency with fluctuations in the intermittent power source
Fault ride-through	Control short-circuits applied to a test network

Regarding FRT, manufacturers may 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 the test circuit shown in Figure 3.

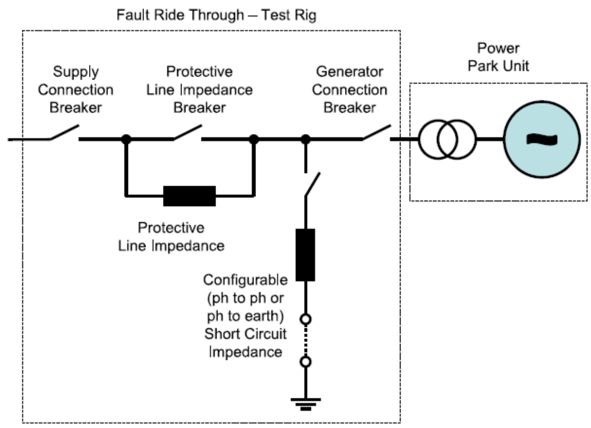

Fig. 3. Low voltage ride-through test circuit used in UK

In the Republic of Ireland, grid code tests are compulsory before operational date. In the case of wind farms, a grid code compliance test procedure has been issued [14], but studies are being carried out to establish more complete certification procedures. The document is divided in three sections: active power management (Section A), transmission system voltage requirements (Section B), and signals, communication and control (Section C). In each section, a series of tests are defined, listed in Table IV. Every test is to be performed at wind farm level. For each test the following items are described: purpose, instrumentation, procedure and pass-criteria.

Table IV. – List of compliance test in Ireland

Number	Test
Section A: Active power management	
1	Active power control
2	Frequency response
3	Ramp rates and start-up test
Section B: Transmission system voltage requirements	
4	Automatic voltage regulation
5	Reactive power capability
6	Voltage emissions and harmonic test
Section C: Signals communications and control	
7	Signals, communications and control
8	Capacity test
9	Disturbance test
10	Black-start shutdown test

All tests can be carried out without additional equipment with exception of the Test 2, which tests the frequency response of the wind farm. As the grid frequency cannot be changed at will, this test will require to be simulated by means of injection of a frequency signal into the wind farm controller to simulate appropriate changes of frequency.

In New Zealand, the types of tests differ across different generation technologies. Synchronous generators must pass a detailed test program explained in [15] while wind generators are subject, at the commissioning stage, to the test program shown in Table V [16].

Table V. – List of compliance test in New Zealand

Requirement	Test objective
Asset Capability Statement and grid compliance testing	Confirmation of system performance for the components of the wind farm Voltage performance of the wind farm
Power quality	Monitoring according to Rule 2.3 of Section II of Part C of the EGR [16]
Fault ride-through test	Apply a fault to the grid and monitor the wind farm response
Security requirements and ancillary services	Confirmation of requirement for ancillary services to cover the wind farm during commissioning

Regarding fault ride-through, 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 function correctly and also allow the validation of the model. Also, this test must confirm that the wind farm stays connected during under frequency excursions.

Finally, in Spain, document PVVC [17] specifies the conditions and validity criteria for field tests as well as defines the equipment needed to carry out the test for wind farms and photovoltaic generation plants. Unfortunately, only voltage dip response is assessed. Spanish PVVC proposes testing equipment for FRT which is similar to the IEC61400-21 standard. Testing is only proposed as part of the simulation validation procedure. Four test categories are defined from the combination of partial and full load operating point and three phase and two phase voltage dips.

4. Grid Code Compliance Simulation

A. General remarks

Most grid codes require generation unit manufacturers to provide technical data (from generating unit and associated control system) to the system operator. Regarding control equipment, they often are described in block diagram form showing transfer functions of individual elements. Their behaviour is expected to have been verified by simulation studies and validated against test measurements, as accurate models are fundamental for efficient planning and operation of the power system.

Depending on the requirements, different types of simulation studies and calculations may be required. Figure 4 summarises main grid code requirement with corresponding simulation study type [18].

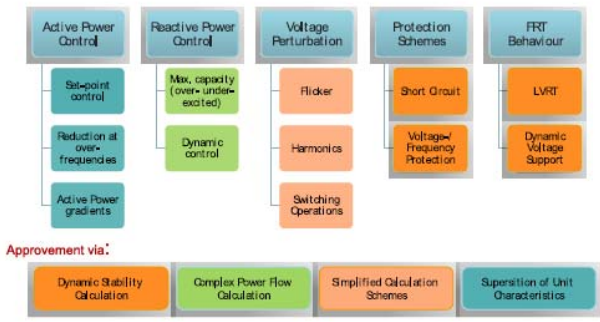

Fig. 4. Grid code requirements and corresponding simulation practices [18]

Regarding dynamic modelling requirements, network operators and manufacturers have conflicting perspectives [19]. Network operators prefer to use standard models that represent with sufficient accuracy the plant performance 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 protect their intellectual property. Therefore, they prefer user-written models.

Actually, only standard models for wind turbines exist and so, for other type of renewable generators, plant owners have to supply manufacturer user-written models to the system operator. However, this situation will improve in the future, as working groups of different organizations are developing standard dynamic models for new generation equipment, such as the Western Electricity Coordinating Council [20], IEEE [21] or IEC [22].

Another concern regarding modelling and simulation is the software platform. The requirements vary among the countries analysed but two platforms are prevailing: PSSE from Siemens and PowerFactory from Digsilent, as shown in Table VI.

Table VI. - Dynamic model requirements for renewable energy plants

Country	Block diagram	Specific Software	Source Code	Time Step	Aggregation
Australia	Yes	PSS®E V.32	Yes	1 ms	Yes
Great Britain	No	PowerFactory	Yes	10 ms	No
Denmark	Yes	No	Yes	Variable time step	No
Ireland	Yes	PSS®E	Yes	5 ms	Yes
Spain	Yes	PSS®E	Yes	5 ms	Yes

B. International experiences

Regulation in Australia requires that dynamic models must be provided for variable generation technologies. An aggregated equivalent model shall be available including central park level controller. In addition, dynamic reactive support plant equipment must be provided, including main and auxiliary control systems with a generic large generating system representing the source power system.

For generating systems of less than 30 MW, AEMO accepts the use of generic models for connection studies provided that the model can reasonably represent the plant components of the generating system. For larger plants, the generator must supply a positive sequence RMS-type dynamic model developed in PSSE V.32. The use of black-box type representation is not accepted and the source code must be provided.

On-site tests are required to confirm the performance of the generating system and to assist in the validation of the model. Validation on a single generating unit would be sufficient, as the same performance is observed on other units of the same type. Confirmation of model performance consists of factory test results or comparisons of simulations for step response tests against the on-site step response test results.

In Denmark, simulation models for wind farms are required to analyse the dynamic properties of the transmission grid and the distribution network, including stability. Dynamic simulation is acceptable as a method for verifying the requirements for wind farms with a power output higher than 1.5 MW. In this case, the system operator requires a simulation model of each individual wind turbine generator system in the wind power plant. In addition, an overall model of the wind turbine generator systems and the power infrastructure is acceptable, provided it can be proved that aggregation does not significantly impact the simulation results.

Simulation models must be supplied in the form of block diagrams using primarily transfer functions in the Laplace domain. It must be possible to use the simulation models for RMS balance and unbalance studies. The source code must be sent and encrypted parts are not acceptable. No requirement for a specific software platform is established.

The model response for LVRT and grid protection requirements must be done based in IEC 61400-21. For other requirements, the model should be validated against test results. Simulation models of the entire wind power plant must also be validated, including all control types.

In Great Britain, in addition to the manufacturer's technical data, a mathematical model of each type of power park unit must be provided, including voltage and frequency controllers, capable of representing its transient and dynamic behaviour under both small and large disturbance conditions. The model shall include non-linear effects and represent all equipment relevant to the dynamic performance of the power park unit. Besides, the model must be suitable for the study of balanced, RMS, positive phase sequence time-domain behaviour. The model structure and complexity must be suitable for National Grid to integrate into their power system analysis software (currently Powerfactory from DigSilent).

Additionally, the submitted power park unit model and the supplementary control signal module models shall have been validated. The validation shall be based on comparing the submitted model simulation results against measured test results. Validation evidence shall also be submitted and this shall include the simulation and measured test results. Type validation is accepted.

In Ireland, EirGrid regulations include simulation model requirements for wind power generation in the grid code. Each wind farm shall provide a dynamic model, or an unambiguous reference to an appropriate dynamic model previously provided to the Transmission System Operator. The model shall be in PSSE format, and must represent the features and phenomena likely to be relevant to angular and voltage stability. For computational reasons, it is essential that the models of individual Wind Turbine Generators (WTGs) can be aggregated into a smaller number of models, each representing a number of WTGs at the same site. A representation of the collector network may be included in the aggregate model of the wind farm.

All models provided for use in dynamic simulations must be validated. 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 the case of New Zealand, models of wind farms are required to prove that there are no adverse impacts on other connected parties, or on the National Grid itself and that FRT and voltage support requirements can be met. For a typical wind installation, the asset capability information required includes turbine, generator, model aggregation, dynamic voltage control devices, overall voltage control coordination model, and governor control if applicable. Although no specific requirement has been found regarding model validation, it is supposed that the plant model will be validated against the measurements taken during the plant commissioning tests.

Finally, the certification process in Spain for P.O.12.3 includes WTG and wind farm simulation. The simulation models of all dynamic elements of the wind farm (WTGs and/or FACTS) are integrated inside a wind farm simulation model, once their validation reports have been obtained. Generally, the model of a wind farm will include any WTG, FACTS and existing reactive compensation devices, cables, step-up transformers (LV/MV) and internal lines. The models must be supplied in Fortran or Flecs and prepared to be integrated into PSSE V32 software platform. In case no standard model is available, the plant owner must supply the source code of the model following the specifications contained in [23].

Only simulation details for LVRT requirement compliance are specified, but it includes a completely parameterised model of an equivalent electrical grid able to emulate the maximum dip to be ridden through by a wind farm. The results of the simulation must be validated against the measurements recorded in the field tests.

5. Conclusion

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 simulations have already been established in many countries around the world.

Regarding commissioning tests, procedures are very similar, with slight differences in the number and detail of the tests, as shown in the review carried out in this paper. As for modelling requirements, model types, along with their specification and validation share many aspects in the regulation under study in this paper. However, the software platform required by system operators often differs.

New generation technologies based on renewable energies and control devices are being standardised and included in simulation software packages, as conventional assets. Therefore, the modelling requirements will predictably evolve to simpler procedures. On the other hand, grid code harmonisation processes have recently been launched, both regarding structural and technical aspects. Therefore, grid code compliance procedures are called to follow the same trend.

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