Testing procedure and Compliance of Power Generating units and Plants Per Indian Grid Code

Ajmal Kunjumon
Grid Code Compliance
DNV GL – Renewables Certification
Bengaluru, India
Ajmal.Kunjumon@dnvgl.com

Torge Wehrend
Grid Code Compliance
DNV GL – Renewables Certification
Hamburg, Germany
Torge.Wehrend@dnvgl.com

Tobias Gehlhaar
Grid Code Compliance
DNV GL – Renewables Certification
Hamburg, Germany
Tobias.Gehlhaar@dnvgl.com

***Abstract*—A grid code is a technical specification which defines the requirements to be met by stations, or plants connected to a public electric network. It is intended to ensure safe, secure, economic and proper functioning of the electric power system. The Indian Electricity Grid Code (IEGC) lays down the rules, guidelines and standards to be followed by the various agencies and participants in their different tasks around the electric system. Those tasks can be to plan, to develop, to maintain and to operate the power system or the power plant, in the most efficient, reliable, economic and secure manner, while facilitating healthy competition in the generation and supply of electricity. This paper summarizes the testing and certification procedure for the Indian grid code requirements.**

Keywords—grid code, power generation, LVRT, test, CEA, grid connection, unit, plant, station

I. INTRODUCTION

The penetration of renewable energy in the Indian grid is expected to be high. Loss of generation during faults will put in the risk of security and reliability of the electric power grid India plans to integrate more than 175 GW of TSO scale renewable energy generation by 2022[1]. It needs to fulfil these requirements to improve the secure operation of Indian electric power grid and enable continuous supply of power. The Licensee (one who approves the grid connection) shall ensure that the grid requirements shall be fulfilled by the requester (one who applies for grid connection). Failing to comply with any of the requirements leads to the disconnection from the electric power grid . The Central Electricity Authority of India (CEA) has issued guidelines in this respect. These connectivity guidelines are applicable to generating stations like wind, solar photo voltaic or hybrid systems including energy storage [7,8].

Grid code requirements can be roughly divided into two categories: static requirements relating to the steady state behaviour of unit (Power Generating Unit), and dynamic requirements relating to the temporary behaviour of units. Even though there have also been changes to the static requirements, most of the changes concern dynamic requirements, namely Fault Ride-Through (FRT), transient overvoltage and grid supporting events. Generally speaking, many of the recent changes can be associated with Over-Voltage Ride-Through (OVRT or HVRT) requirements in the 120…130% range in force in Germany. These requirements are typically defined at the point where a wind or solar station is connected to the grid (point of interconnection) but can sometimes also be defined at the point where a single unit (wind turbine or PV Inverter) is connected to internal grid of the station.

This paper describes the measuring procedure and certification scheme for power generating units and generating stations contributing to achieving the proper proof of evidence to show that they comply with the Indian grid code requirements. The test and measuring procedure generally follow the International Electrotechnical Commission (IEC) & other international standards. It is understood that the testing procedure mentioned in this paper helps in the alignment among the involved testing institutes, will smoothen the work of the certification bodies on a basis of fairness and transparency and will support the manufacturers in grid code compliance design process.

Regarding the structure of the paper: in Section II, grid code requirements are presented. Section III includes testing and measuring procedures for electrical characteristics like FRT, Control behaviour & Power quality. In Section IV, a brief discussion on the assessment for the certification of grid code compliance is included, while the conclusions of the present work are summarized in Section V.

II. GRID CODE REQUIREMENTS

The grid code requirements are basically classified into: 1) Control behaviour 2) FRT behaviour 3) Power quality.

1. Control Behaviour

Reactive Power Capability: "*The Power generating unit shall be capable of supplying dynamically varying reactive power so as to maintain power factor within the limit of 0.95 lag to 0.95 lead" at the POI.* A typical reactive power capability curve is shown below in figure 1.

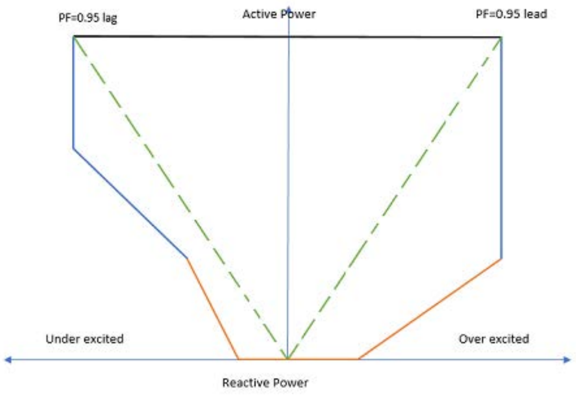

Figure 1: Reactive power capability curve

Frequency withstanding capability: Usually the system frequency is in the normal tolerance band in the range of e.g. ± 30 mHz (depending on the system stiffness). However, due to electrical load changes in the system (consumers) and corresponding power balance (generators) the frequency is varying dynamically. This can also happen due to disconnections related to faults in the system.

According to Indian grid code, power generating stations shall be capable of remaining connected to the network and operate within the frequency range of 47.5 Hz to 52 Hz. In addition, they should be able to deliver rated power in the frequency range of 49.5 to 50.5 Hz, subject to availability of the primary energy source (i.e. wind speed or solar radiation). This performance shall be also achieved with a voltage variation of up to ± 5 %.

Active Power Set Point Control: In an electric power grid, for the safety reason during line contingencies, it is necessary to reduce generation in order to keep the lines within allowed design limits. Therefore, the electric TSO respectively the load dispatch centers must be able to issue commands to generation units for reducing the power in order to avoid line disconnections by the protection systems.

According to Indian grid code, the generating stations with installed capacity of more than 10 MW connected at voltage levels of 33 kV and above shall be equipped with a facility to control active power injection in accordance with a set point, capable of being revised based on directions given by the State Load Dispatch Centre or Regional Load Dispatch Centre via remote control.

Frequency Droop Control: Droop control is a control strategy commonly applied to generators for primary frequency control (and occasionally voltage control) to allow parallel generator operation (e.g. load sharing).

According to Indian grid code, the generating stations with installed capacity of more than 10 MW connected at voltage levels of 33 kV and above shall have governors or frequency controllers typically within the units. These controllers implementing frequency sensitive power control shall be able to act with different droop values which can be set in the controller depending on the directions for the station to be given by the electric TSO. Units need to show the ability to operate at a droop of 3 to 6% and a dead band not exceeding ±0.03 Hz: Provided that for frequency deviations in excess of 0.3 Hz, the Generating Station shall have the facility to provide an immediate (within 1 second) real power primary frequency response of at least 10% of the maximum active power capacity available at the moment of occurrence.

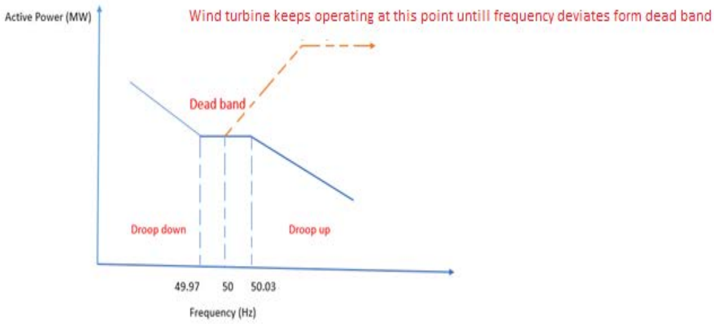

Figure 2: Frequency droop Control curve

Droop-up means the reaction with rising frequency (reducing power) and droop-down means the reaction during falling frequency (increasing power if available).

Droop control is used when connected to the electric power grid. Droop control is implemented as a function in the turbine controller to help the TSO in controlling system frequency on the grid. If too high output is generated compared to the load in the electric power grid the result is a high frequency. At high frequency all producing units have to decrease their output in correspondence to the frequency on the grid.
Droop used to be expressed as a percentage of speed change which will cause a 100% change in output (in synchronous rotating electrical machines). The droop will be a adjusted according to the directions of the TSO, normally set between 3 and 6%.

Ramp Rate Control: A ramp event is defined as the power change event at every time interval. If the power change is positive, it is defined as a ramp-up event. If the power change is negative, it is defined as a ramp-down event. The power change rate of a power ramp event is called a ramp rate, which is defined as the power difference from minute to minute, so its unit is a percentage of the currently available power in % per minute.

According to Indian grid code, the generating stations with installed capacity of more than 10 MW connected at voltage levels of 33 kV and above shall be equipped with the facility for controlling the rate of change of power output at a rate not more than ± 10% per minute.

2. Fault Ride-Through behaviour (FRT)

Fault Ride-Through (FRT) is the ability of a generating unit or station (e.g. a wind power generating station or a solar generating station with PV inverters) to remain connected to the grid when there is a short dip or swell in voltage due to a short-circuit somewhere in the grid. Additionally, specific characteristics are required regarding the transient behaviour during the fault. The phenomenon of a voltage dip is referred to as Low-Voltage Ride-Through (LVRT, nowadays IEC calls it UVRT: Under-Voltage Ride-Through). The short swell in voltage is referred to as Over-Voltage Ride-Through (OVRT, formally called HVRT).

UVRT fulfilment is required by CEA for the wind and solar generating stations when the voltage in the grid is temporarily dipping due to a fault. The required UVRT behaviour is defined in grid codes issued by the TSO in order to maintain system stability, thereby reducing the risk of black-out. The grid codes were originally developed considering the synchronous generator generally used in conventional power plants, whereas Wind Turbines (WT) and PV inverters (i.e. units of solar generating stations) have different characteristics compared to thermal power plants, leading to the requirements described below.

As per Indian grid code, the generating station connected to the grid, shall remain connected when voltage at the interconnection point on any or all phases dips up to the level depicted below in figure 3.

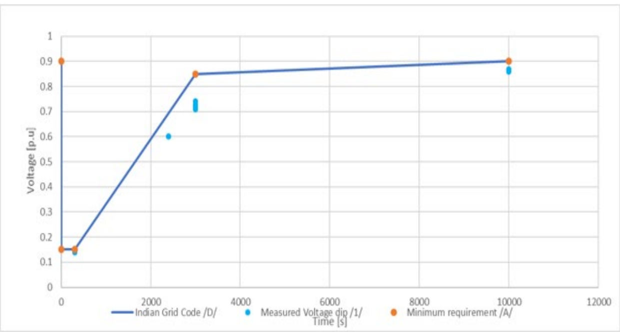

Figure 3: UVRT curve according to Indian grid code requirements with typical example proof of evidence by test

Provided that during the voltage dip, the supply of reactive power has first priority, while the supply of active power has second priority and the active power preferably be maintained during voltage dips, provided, a reduction in active power within the plant's design specifications is acceptable and active power be restored to at least 90% of the pre-fault level within 1 sec of restoration of voltage.

Depending on the severity of the fault, fault location, protection settings and the system condition, it can cause a short voltage swell, a voltage dip, or a complete loss of voltage and supply (interruptions). The duration and magnitude of the fault is dictated by protection technologies and their settings; whereas the slope of the voltage recovery likely depends on the strength of the interconnection and reactive power support. The quantity of reactive power to be injected depends on the percentage of grid voltage reduction during the dip, the unit's rated current, and the reactive power given to the grid during the dip appearance.

The OVRT capability handles the over voltages during faults. During the OVRT tests an overvoltage is applied to each of the three phases of the unit (wind turbine or the PV inverter).

According to the Indian grid code, the generating station connected to the grid, shall remain connected when voltage at the interconnection point, on any or all phases (symmetrical or asymmetrical overvoltage conditions) rises above the specified values given below for specified durations as shown in Table 1.

over voltage V at POI (pu)	minimum time to remain connected
V > 1.30	0 seconds (instantaneous trip)
1.30 ⩾ V > 1.20	0.2 seconds
1.20 ⩾ V > 1.10	2 seconds
1.10 ≥ V	continuous

Table 1: OVRT/HVRT requirements in India.

OVRT curve according to Indian grid code requirements is shown below in figure 4.

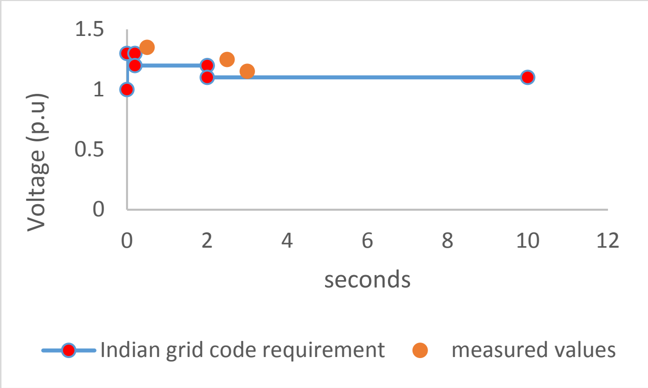

Figure 4: OVRT curve according to Indian grid code requirements and examples of proof of evidence with typical tests.

Short Circuit ratio: Short Circuit Ratio (SCR) relates to the system strength of an area in an electric power grid. The short-circuit strength is determined by calculating the short-circuit ratio at the point of interconnection (POI). The identified area with a low SCR requires more studies and thorough investigation because this is an indication of low system strength and conditions that can aggravate system disturbances and possibly impact protection system.

According to the Indian grid code requirements, the generating stations shall have a short circuit ratio not less than 5 at the interconnection point where the generating station is proposed to be connected.

3. Power quality

The TSO needs to ensure that impact stays below planning levels in the overall electric power system. This is also important for wind and solar stations connected to the grid. Typical power quality disturbances are current and voltage harmonics, DC current injection, flicker etc. According to the Indian grid code, harmonic current injections from a generating station shall not exceed the limits specified by the Institute of Electrical and Electronics Engineers (IEEE) Standard 519. The Generating station shall not inject DC current greater than 0.5 % of the full rated output at the interconnection point. The generating station shall not introduce flicker beyond the limits specified in IEC 61000. Measurement of harmonic content, DC injection and flicker shall be done at least once in a year in presence of the parties concerned and the indicative date for the same shall be mentioned in the connection agreement.

Testing, Evaluation, Validation and Certification: The standards used for testing the above grid code requirements includes FGW TR-3 [4], IEEE 519 etc. For certification procedure DNVGL-SE-0124, may be used in combination with the CEA rules [7 and 8]. DNV GL grid code compliance certificate ensures proof of evidence that Indian grid code requirements are fulfilled.

III. TESTING PROCEDURE

Testing, measuring recording and post processing of the measured values plays a pivotal role in obtaining a grid code compliance certificate. Testing and measurement are performed according to DNVGL-ST-0125 [3], FGW TR-3 [4] etc. These standards are also applicable to PV inverters, PV plants and hybrid systems. Following paragraphs, details the testing procedures for the Indian grid code requirements.

1. FRT behaviour

The most common test equipment (Figure 5) to generate voltage dips is the voltage divider-based solution shown in Figure 5, in general consisting of two switches (circuit breakers) and two impedances Z1 (serial impedance) and Z2 (short-circuit impedance). The serial impedance Z1 is interposed into the test circuit to prevent the unacceptable disturbances during the test in the grid. The Voltage at the unit shall stay within the operating range prior to the voltage drop when the unit runs at rated power. The impedances shall have a ratio of $X/R > 3$ (i.e. for Z1 as well as for Z2 this requirement shall be valid). The voltage dip can be achieved by using an impedance Z2 as voltage divider by short circuiting two and three phases at the unit side of the impedance Z2. The drop-in voltage drop shall be as fast as possible. During each test, the instantaneous values corresponding to voltage and current at MP2 shall be recorded with a sampling rate of at least 5 kHz.

Voltage dip testing: Before starting the voltage drop, S1 is opened (so the serial impedance limits the impact of the dip on the grid). Afterwards S2 is closed starting the dip with the drop and after the specified duration S2 is opened again ending the dip. Finally, the serial impedance is bypassed again by closing S1. Prior to performing the testing according to the test plan, determination of remaining voltage levels U_{rem} at the testing site shall be performed by “no load tests”. This shall be done by performing a first set of tests with disconnected generating unit (S4 open) in order to verify the locally adjusted settings of the voltage divider. After all relevant remaining voltage levels U_{rem} fulfil the specification of the test plan the real voltage dip testing can start with the connected unit being in operation. The setting of Z2 shall be adjusted properly in order to reach U_{rem} as specified in the test plan and as determined in the no load tests as described above.
The UVRT test procedure for Indian grid code requirements shall be in accordance with the curve as

shown in Figure 3. The test shall be done for 3-phase and 2-phase and for partial (between 0.1 P_n and 0.3 P_n) and full load (above 0.9 P_n) where P_n is the nominal power of the tested unit. Four different voltage levels are tested accordingly as a) small voltage dip test b) medium voltage dip test c) large voltage dip test d) long duration dip test.

Criteria for successful testing*:* For each certification process the different test values and success criteria shall be defined depending on the respective grid codes before the tests are performed. This is usually done when drafting the test plan. The assessment is based on measurement reports showing symmetrical component values of voltage and current as measured, post-processed and issued by an accredited testing laboratory. This is a prerequisite to be accepted for assessment within certification:

If the unit is regularly online 10 seconds after the test is over (standard production mode). This shall be stated as one criterion whether the test is passed or not.

If the unit did not disconnect during 2 consecutive tests (2 durations (t1 and t2) or (t2 and t2)) within one category. If disconnection took place the tests of this category are only regarded as passed, if the subsequent tests of the same category (for instance 3-phase, full load) did not lead to disconnection of the unit from the grid. In case of a failed test and unexpected behaviour of the unit, the test shall be aborted.

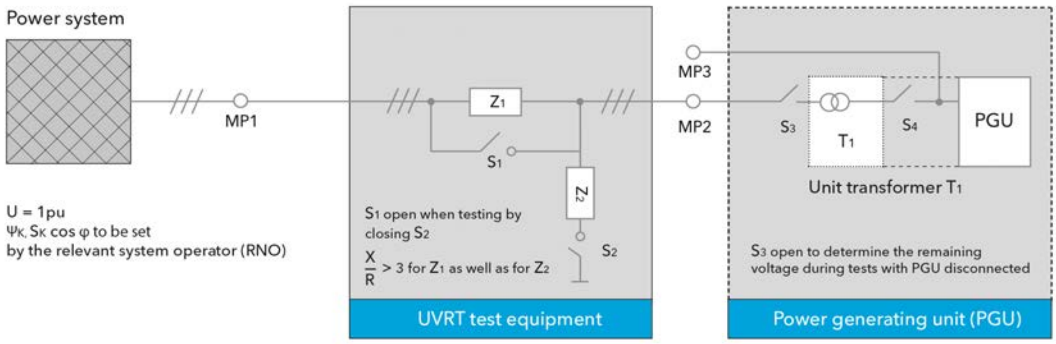

Figure 5: Fault-test set up for UVRT and measurement points MP

The OVRT test (figure 6) procedure for Indian grid code requirements shall be in accordance with the curve as shown in Figure 4. The test shall be done for 3-phase and 2- phase and for partial (between 0.1 P_n and 0.3 P_n) and full load (above 0.9 P_n) where P_n is the nominal power of the tested unit.

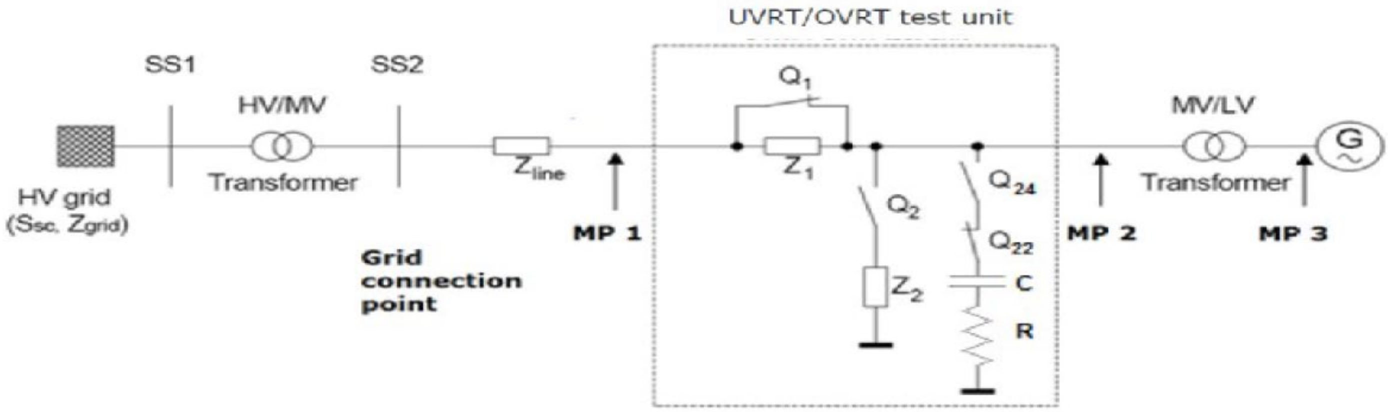

Figure 6: Fault-test set up for OVRT and measurement points MP

2. Control behaviour

Reactive Power Capability: The aim of this measurement is to determine the under- and overexcited reactive power capability of the unit to be used at POI as a function of the active power output ranging from a power factor of 0.95 lag to 0.95 lead for the station. The measurements shall be performed at a prototype unit in a field test or at a test bench. The following measurement method is applied:
The unit is running in the operating mode in which it can provide the maximum over excited or under excited reactive power across the entire power output range.
The maximum overexcited and underexcited reactive power must be determined for each 10% active power bin. 1-minute mean values must be recorded for each of the two measurement points of a power bin.
Active and reactive power as positive phase sequence values are continuously recorded as 1-minute mean values. The 1-minute mean values are grouped into the 10% active power bins.

Frequency withstanding capability: As the system frequency is not constant, the units as well as the plants need to be capable of being operated continuously or for certain durations within a specified frequency range specified by the grid codes. As corresponding tests are often not feasible (except long-term measurements installed on-site or special test facilities in European laboratories) this assessment is usually based on manufacturer declarations proving the requested ability. In both cases the reference points are the terminals of each single unit. The intention of this assessment is to assure, that units and other equipment are designed appropriately to withstand the maximum expected frequency deviation.

Active Power Set Point Control: The ability of the unit to operate in active power control mode shall be measured for various reference values given to the control interface. The aim of this test is to determine the response of the unit to different reference commands regarding the static error, the rise time and the settling time of active power, for both steady-state conditions and under dynamic response conditions.
For determining the static error, the following test procedure is recommended: a reference value shall request active power reduction from 1.00 p.u. to 0.20 p.u. in steps of 0.20 p.u. with at least a 2-minute operation at each reference value in accordance with [3 and 4]. The test for dynamic response shall be carried out by a step with a minimum step size of 0.4 p.u. of the nominal active power in accordance with [3 and 4].

Frequency droop control: During periods where the grid frequency is increased a reduction in the active power is required. While numerous units and stations are reducing the power fed into the grid, they commonly support the grid frequency decrease needed.

Testing possibilities: Changing parameters in the unit control system: The test can be carried out by adjusting the frequency rating value in the control software on the unit. This can be achieved for example, by changing the rated frequency from 50 Hz to 48.80 Hz in the control system to simulate a 1.2 Hz increase in grid frequency.
Grid Simulator: The function can be tested via a grid simulator on the control system or a test bench. This test can only be carried out with the unit stopped. When the unit is stopped, output of the control system can be recorded, and compliance can be shown in a suitable form. The test can be carried out with unit running if the safety of the unit is guaranteed by using a separate grid protection unit.
Detailed testing procedure is referred to in FGW TR-3 [4].

Ramp rate control: The aim of this measurement is to show the capability of the unit to follow given active power gradients, with positive and negative ramp rate limitations, during the following operational states:
start-up, normal stop and start up after grid disconnection; normal operation (with positive and negative ramp rate).
The wind speed or solar radiation shall be high enough for active power production above 0.7 p.u. for the entire test. At the beginning of the test, the unit shall be operated in normal operation mode. The active power of the unit can be set to an adequate start value above 0.5 p.u. of the nominal active power. Then the following two tests with different ramp rates shall be performed.
Test 1 (slow ramp rate), e.g. +/- 10 % P_n /minute.
Test 2 (fast ramp rate), e.g. +/- 2 % P_n /s.
The test shall be carried out with at least P = 0.2 p.u. of the nominal active power between each reference value (power steps).

3. Power Quality

Harmonic measurements: The CEA guidelines for the harmonic measurement refers to the standard IEEE 519 [11]. The instruments used for assessing harmonic levels shall comply with specifications of IEC 6100-4-7 [12] & IEC 61000-4-30 [13].

Flicker measurements: The CEA guidelines for the flicker measurement refers to the standard IEC 61000 series of standards which in turn refers to IEC 61000-3-7 [14] (Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems).

IV. ASSESSMENT PER GRID CODE

The measurement report from an accredited measurement institute shall be submitted to a certification body accredited according to ISO 17065 for grid connection of power generating units and generating plants. The certification body shall assess the measurement report, evaluate its compliance with the CEA grid code and issue a statement of compliance for each requirement and issue a type certificate for GCC if all the requirements at unit level are met. Most of the CEA requirements are to be fulfilled at the station level. The certification body validates the simulation model against measurement results as obtained from type tests at unit level (e.g. Matlab Simulink, PSS/E, PowerFactory etc.) to ensure that the requirements tested and measured at unit level are fulfilled at the station level by simulations. Only simulations made with validated simulation models are acceptable. After simulations are performed the certification body shall issue a project certificate for GCC, if the requirements at station/plant level are met.

1. FRT assessment

According to Indian grid code requirements, the FRT behaviour is to be fulfilled to be compliant at the station level (POI, point of interconnection). Testing is conducted at the unit level and simulation should be performed for confirming the requirements at POI (station level). The success criteria for the UVRT requirement for India are: a) that reactive current shall be injected during the fault, b) active power is maintained, and c) active power is recovered postfault to 90% of the prefault value within one second after restoration of voltage. In some cases, the active current can be reduced to increase the reactive current for supporting the voltage recovery.
For the OVRT behaviour, the generation station shall stay connected to the grid during a voltage rise per Table 1. There is no additional success criteria for the OVRT behaviour to fulfil for India. In line with the UVRT and OVRT assessment, the protection systems shall be taken into account as well. For units the protection at the unit is relevant and for stations both, the protection at the unit as well as the protection at the POI are relevant. For the compliance certification DNVGL-SE- 0124 shall be used together with the CEA [2,7 and 8].

2. Control behaviour & Power quality assessment

For the frequency withstand ability the capability of the unit to operate within the specified frequency range shall be verified. Therefore, manufacturer documentation or corresponding measurement reports shall be submitted for each unit or component under assessment.
For the evaluation of the operability of the plant with decreased or increased grid frequency the protection settings at the POI shall be assessed according to the requirements of the relevant grid code.
For the frequency droop control the assessment shall be made on unit level. For assessment on plant level each unit and the relevant plant control shall be assessed. Therefore, manufacturer documentation, measurement reports of the testing with injected frequency signal according to FGW TR-3 [3], or test bench records shall be submitted for each unit or component under assessment.
For units the reactive power capability shall be measured under rated voltage conditions as described in FGW TR-3 [4]. For the withstand capability regarding the voltage range the assessment is based on manufacturer declarations. The assessment shall cover the complete operational area of voltage and active power. For stations the capability at POI shall be determined with complex load flow calculations based on the capability test results of the single units and all relevant components like plant control, cables, transformers and reactive power compensation equipment.

For the power quality assessment, the certification body assess the measurement report for the harmonic, DC current injection and flicker. The certification report properly documents all observations and gives comments. Any deviation from the limits which adversely affect the grid performance would be conveyed to the customer and in such case no certificate would be issued.

IV. CONCLUSIONS

In this paper, the requirements of the Indian grid code, testing and measurement procedure and the certification procedure on how to proof it are described. The testing is usually according to international standards like IEC 61400-21, FGW TR-3 etc. We used mainly the German measurement guidelines usually referred as FGW TR-3 for the FRT and control behaviour requirements, and IEE 519 for the power quality. This paper specifies test types which need to be performed, care needed to be taken during the testing and how to report the measurement values. This paper also contains the efficient assessment and interpretation of the results to ensure that the CEA requirements are fulfilled. This will ultimately benefit the Indian grid with respect to stability and thereby continuance of the power supply.

ACKNOWLEDGMENT

The authors would like to recognize the contribution and express appreciation to the colleagues of DNV GL Hamburg who continuously support the certification projects in India.

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