Testing procedure for the evaluation of grid compliance of power generating units according to the requirements of the Indian Grid Code

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Abstract—**This paper introduces a systematic testing procedure to be applied to power generating units (mainly wind and inverter-based stations), which will contribute to the sufficient evaluation of grid compliance, by covering all the relevant requirements imposed by the Central Electricity Authority of India (CEA).**

Keywords-component; Central Electricity Authority (CEA); Fault Ride Through; grid compliance; harmonics, IEC, IEEE

I. Introduction

Evaluation of grid code compliance of power generating units (PGUs) in power systems with increasing renewable energy penetration, has become a challenging task for the grid operators. Transient behavior and power quality performance of PGUs often raise questions on the static and dynamic security of the power systems, especially in case of units using power converters, which do not have an inherent capability to resist or slow down frequency deviations, like the wind turbines (WTs) and photovoltaics (PVs).

The main concern of all grid codes is to impose limits for the acceptable behavior of PGUs at the point of connection but they do not necessarily include any compliance process for the verification of grid compatibility. This issue is often covered on a universal basis by the IEC 61400-21 standard [1], the new edition of which is expected to be released until beginning of 2018 [2]. However, this standard refers purely to WTs while, in certain cases, it is necessary that further testing and evaluation specifications are set in order to demonstrate adequately the successful performance of the tested units according to a specific grid code of interest.

This gap is already recognized by several countries, which have developed particular testing procedures to assist the grid compliance process. In Germany, FGW has issued the Technical Guideline 3 (FGW-TR3, [3]), which describes in detail all the necessary tests needed to be performed on PGUs (including WTs and PVs) in order to verify compliance with the German medium and high voltage grid codes. FGW-TR3 is also supported by particular guidelines for the simulation and the certification of PGUs and Systems [4]-[5]. In Spain, the Spanish Wind Energy Association (AEE) has prepared a dedicated procedure for measuring and assessing the response of wind farms in the event of voltage dips [6]. In UK, National Grid Electricity Transmission (NGET) has issued a special guide for Power Parks Modules to describe to stakeholders how the grid compliance process should work [7]. In Denmark, special guidelines on the calculation of the power quality parameters are issued to support testing of wind power plants [8], which is mainly based on the IEC 61400-21 standard [1].

In India, the Central Electricity Authority (CEA) has put into force certain specifications for the connection of wind generating stations and stations using inverters [9]-[10]. A wide revision of these specifications is recently proposed by the CEA and is currently under public consultation [11]. The main scope is to ensure that wind and solar stations behave similar to conventional power stations with regard to frequency and voltage stability, robustness and power quality. However, a dedicated testing and assessment procedure is still missing, which sometimes leads to ambiguous interpretations by the Testing Laboratories and the Certification Bodies. The aim of this paper is to exploit the experience of UL DEWI in the grid code compliance testing and assessment in India and worldwide, in order to propose a concrete testing procedure for assessing compliance with the Indian Grid Code. Due to the fact that the expected new amendment Regulation [11] is still not finalized, the proposed procedure is mainly based on the current one [10]. Nevertheless, assuming that some of the proposed changes or additional provisions are likely to be finally incorporated, a relevant reference is occasionally included.

Regarding the structure of the paper, in Section II, the current requirements of the CEA standard for grid connectivity are presented. Section III includes proposals for the necessary tests for each particular electrical characteristic (fault ride through capability (FRT), flicker, harmonics, grid protection and control requirements). In Section IV, a brief discussion on the certification procedure for the assessment of grid compliance is included, while the conclusions of the present work are summarized in Section V.

II. CEA Standard for Grid Connectivity

The Indian regulatory framework for the connection of PGUs is mainly included in the CEA Regulations of 2007 [9], where the general standards for grid connectivity are prescribed, and the Amendment Regulations of 2013 [10], where separate requirements for wind and power converter based generating stations are amended. The latter requirements refer to the electrical characteristics during normal operation, the frequency and voltage support capability of the PGUs and, especially for WTs, the transient performance and their capability to control active and reactive power, as described in detail below.

A. Electrical characteristics in normal operation

The power quality parameters that are mentioned in the CEA Regulation [10] are the harmonics, DC current injection and flicker. The Regulation does not refer to any measurement guideline but incorporates the following provisions:

- With regard to harmonic current emissions, they should not violate the limits specified in the standard 519 of the Institute of Electrical and Electronics Engineers (IEEE), [12]
- The DC current injection of the PGUs at the point of connection should not be greater than 0.5% of the rated current
- The flicker emissions should be kept within the limits specified in the IEC 61000, which refers to the IEC Technical Report 61000-3-7 [15]

The above requirements are expected to remain unchanged in the new CEA amendment [11].

B. Control capability

The following requirements apply:

- The PGUs shall be capable of supplying the necessary reactive power in order to ensure that power factor is kept within the limits of 0.95 lagging and 0.95 leading, which must be achieved even if power system voltage varies in the range of up to ±5%.
- With regard to frequency stability, the PGUs 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 and solar radiation). This performance shall be also achieved with a voltage variation of up to ± 5 %, a condition which is proposed to be eliminated from the new CEA amendment [11].
- In particular, wind generating stations shall have the capability of set-point control of the active power following the orders given the relevant Load Dispatch Centre. The new CEA amendment [11], includes also solar stations under this requirement and refers to all stations with installed capacity of more than 10 MW connected at voltage level of 33 kV.

C. Fault-ride-though-capability

Fault-ride-through (FRT) capability in current CEA Regulation [10], is related only to wind generating stations, connected at voltage level of 66 kV and above. However, it is worth mentioning that in the new amendment [11], both wind and solar stations connected at any voltage level are included under the same requirement. The following rules apply:

TABLE I. MINIMUM REQUIREMENTS OF LVRT CAPABILITY OF WIND GENERATING STATONS ACCORDING TO CEA REQUIREMENTS

Percentage voltage at the interconnection point V_T/V_N[a]	**Fault duration [ms]**
0.15	300
0.85	3000

a. VT/Vn is the ratio of the actual voltage to the nominal system voltage.

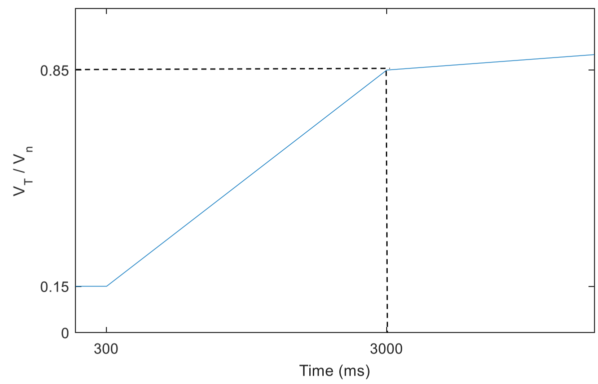

Fig. 1. Lower limit of the voltage-against-time profile of any or all at the interconnection point, above which wind generating stations at voltage level of 66 kV and above shall remain connected to the grid, according to the current CEA Grid Connectivity Standard [10]. In the new CEA amendment, solar stations are also expected to be considered while PGUs at all voltage levels shall fulfil the requirement.

- PGUs shall remain connected to the grid when voltage at the interconnection points on any or all phases drops down to the level depicted in Fig. 1. The exact lower voltage levels along with the corresponding minimum fault durations are also shown in TABLE I.
- During the voltage dip, the PGUs shall generate active power in proportion to the retained voltage while maximizing the supply of reactive current till the time voltage starts recovering or for 300 ms, which ever time is lower.

D. Grid protection system

According to CEA initial Technical Standard [9], the protection system shall reliably detect faults on various abnormal conditions.

III. PROPOSED TESTING PROCEDURE

Certification according to CEA requirements presented in Section II, requires the availability of a proper measurement and testing procedure. The current practice for this, is to follow the testing procedure of IEC 61400-21 [1], which refers exclusively to WTs but it is often also applied to other converter-based generating units, like PVs. However, there are still some CEA requirements not adequately addressed in IEC 61400-21, while additional specifications for evaluation and reporting are necessary to constitute a concrete and undisputed testing procedure. In the next paragraphs, a relevant procedure is proposed and deployed, based on the experience and know-how of UL DEWI over the last years.

A. Testing of Fault Ride Through behavior

Although the current CEA requirement refers only to wind generating stations, it is reasonably assumed that the same requirements are valid also for other PGUs, like PVs, as proposed in the new CEA amendment [11]. The basic steps of the relevant testing procedure are given in the next.

The measurements shall be performed at the high voltage side of the transformer which may coincide or not with the point of common coupling (PCC) of the Wind/PV unit. Measurement at the plant level, could be also acceptable but it should be taken into account that it is difficult to meet any test equipment with nominal capacity larger than 8-10 MW in the wind industry worldwide. In any case, it should be stressed that the measurement at the terminals of the single unit (e.g. WT or PV) provides results on the safe side.

Regarding the configuration of the testing equipment, the test can be carried out using for instance a set-up such as the one illustrated in Fig. 2. Under all circumstances, the specifications and the configuration of the used equipment must meet the operational and accuracy requirements of IEC 61400-21 [1]. The voltage drops are created by a short-circuit emulator that connects the phases together through an impedance. The impedance Z_1 is used for limiting the effect of the short circuit on the up-stream grid. The size of the impedance must be properly selected so that the voltage drop testing is not causing an unacceptable situation at the upstream grid, and at the same time not significantly affecting the transient response of the tested unit. The minimum acceptable requirements for the acceptable voltage drop at the grid side depend on the characteristics of the PCC and have to be provided by the local grid operator, prior to the performance of the tests. It is recommended to apply a by-pass connection of Z_1 prior and after the drop.

Regarding the necessary measuring points, it is recommended to measure voltages and currents at all three phases at least at MP2, which corresponds to the point of connection between the WT/PV unit and the grid (PCC). Optional measuring points are at the LV side (MP1), grid side (MP3) and short-circuit branch side (MP4), as shown in Fig.2. Measuring at the latter points is not strictly recommended but it is advisable, in order to provide additional information to the Certification Body and the grid operator.

The impedances employed in the testing equipment for a voltage dip must have an X/R ratio of at least 3. The short circuit apparent power at the testing point must be at least three times the nominal power of the generating station/plant. This represents a grid impedance with a maximum short-circuit voltage of 33%. The correct configuration of the testing equipment for each specific voltage dip must be tested with a no load test. In order to calculate the impact of the emulated voltage dips on the grid, reliable information concerning the grid short-circuit power and grid impedance angle have to be provided by the grid operator.

Testing procedure

The on-site tests must be carried out in accordance with IEC 61400-21 [1]. The on-site test is performed on the complete PGU. A test bench test is permissible for PV units, where the existence of PV modules is not a necessary requirement as the power may be provided by a suitable DC source.

Fault ride through tests pose significant burden on both the grid and the tested components. Therefore proper protective devices must be used in both sides. It is recommended to agree the tests and the protective devices in advance with the local grid operator.

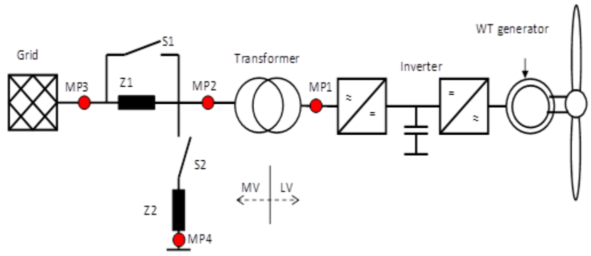

Fig. 2. Example of low voltage ride through test setup at the point of connection of a single WT. The configuration is valid also for PV and other power generating units as well as for power plants < 10 MW

The LVRT tests to be performed, should be selected in accordance with the voltage profile of Fig.1. In order to obtain a representative view of the behavior of the PGU under the complete range of voltage drops, at least three voltage levels in the linear area of the relevant curve of Fig.1 between 300ms and 3000ms should be examined. The lowest voltage level during the dip should be ≤ 15% of the nominal system voltage (V_T) while the maximum fault voltage should be selected as close as possible to the limit of 85% of V_T. Tests at voltage levels greater than 85% (area above 3000ms in Fig.1) are difficult to be implemented because these levels are very close to the normal operating ranges of the units. An indicative list of tests including desirable voltage levels and minimum fault durations is given in TABLE II. . The tests must be carried out for both three-phase and two-phase faults, with the PGU/plant operating at:

- between 0.1 Pn and 0.3 Pn (partial load) and
- above 0.9 Pn
- Especially for inverter based units tested at a test bench it is required that the tests are performed at an active power of 100% ± 2% Pn instead of > 0.9 Pn

  P_n is the nominal power of the tested unit

It should be mentioned that, especially for partial load tests, the new IEC 61400-21-1 [2] suggests that the operating point at partial load should be between 0.25 P_n and 0.5 P_n. Two consecutive tests are foreseen for each case.

The operational mode of the tested units shall be explicitly specified. For each voltage dip level and fault type, the relevant testing equipment configuration must be tested with a no load test. The no load tests should be performed shortly before the relevant under-load tests, in order to ensure that the same grid conditions apply.

Regarding the necessity of performing single phase LVRT tests, the following should be taken into account:

- Due to the protection settings at the circuit breakers at the grid side, it is often not possible to perform these tests without putting the security of grid supply at risk
- In principle, faults to ground impose higher danger than the phase-to-phase ones on people working in the area and the equipment.

Based on the above remarks and considering that the single phase fault ride through capability is related more to the proper settings and the cooperation of the protection systems than to the injection of the proper amounts of active and reactive power, it is suggested that single phase dips are not strictly required to be included within the relevant LVRT certification campaigns.

To summarize, a graphical overview of the tests recommended in TABLE II. in conjunction with the actual CEA grid code requirements is presented in Fig.3.

TABLE II. OVERVIEW SUGGESTED TESTS FOR THE LVRT CAPABILITY OF WIND/PV UNITS

Voltage magnitude[a] [pu]	Minimum Duration[a] [ms]	Fault Type	WT/PV load	Number of tests
≤ 0.15	≥ 300	3-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2[b]
			$P \geq 0{,}9P_n$	2
		2-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
0.30 – 0.40	≥ 1340	3-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
		2-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
0.50 – 0.60	≥ 2170	3-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
		2-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
0.70 – 0.85	≥ 3000	3-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
		2-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
0.85 – 0.90[c]	>> 3000	3-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2
		2-ph	No load	1
			$0.1\ P_n \leq P \leq 0.3\ P_n$	2
			$P \geq 0{,}9P_n$	2

a. The specified magnitudes and durations refer to the voltage drop occurring when the unit or plant under test is not connected.
b. Two consecutive tests must be performed for each partial and full load case.
c. This test is optional because the voltage dip level is very close to the normal operating range of the units

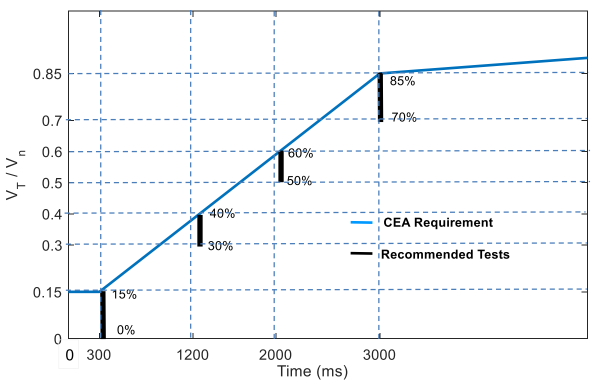

Fig. 3. Overview of the recommended low voltage ride through tests in conjunction with the CEA grid code requirements

Finally, according to the current CEA requirements, testing of overvoltage ride through (OVRT) capability is not necessary though being included in the proposed new amendment [11]. The OVRT testing procedure is already introduced in the FGW TR3 guideline [3] and will be also included in the expected new IEC 61400-21-1 [2]. However, the decision if such a requirement is necessary or not for India has to be taken by the Central Electricity Regulatory Commission (CERC), depending on the particular characteristics and the transient stability margins of the power system.

B. Harmonic measurements

The harmonics measurement procedure described in the current edition of IEC 61400-21 [1] is not fully compatible with the contents of the IEEE standard 519, the latter being requested by CEA ([10], [11]). The instrumentation specifications are common in both standards and should comply with the IEC 61000-4-7 [13] and IEC 61000-4-30 [14]. However, notable differences appear in the assessment method and the harmonic results are not directly comparable. This has to be taken into account when assessing the relevant grid compatibility. The basic differences between the two guidelines are presented in TABLE III. In the same table, the relevant modifications expected in the new IEC 61400-21-1 standard [2] are also included, for informative purposes.

It should be stressed at this point, that the harmonic measurement method proposed by the IEEE 519 standard is mainly oriented to loads operating at contact power. From that perspective, measurement on daily and weekly basis may not cover all power levels in case of WTs and may not be sufficient. Therefore, it is recommended that the power-bin-wise measurement procedure is adopted, as per IEC 61400-21. The averaging time and the aggregation method of IEEE 519 can be applied afterwards for the evaluation of the harmonic results.

C. Measurement of DC current injection

Measurement of DC current injection is not addressed in the IEC 61400-21 [1]. Nevertheless, the raw data derived from the standard harmonic measurements can be used for the evaluation of the zero-Hz component. This will be extracted through the Fast Fourier Transform (FFT) and can be averaged for example over 10 min, like in the normal IEC harmonic evaluations. In the final report, either the maximum or the 95^{th} percentile for each power bin can be presented at a

TABLE III. COMPARISON BETWEEN IEC AND IEEE STANDARDS WITH REGARD TO THE HARMONIC EVALUATION PROCEDURE

Parameter / procedure	IEC 61400-21, Ed.2	IEC 61400-21-1, Ed.1, CDV	IEEE Std519
Instrumentation	Compatible with IEC 61000-4-7 and 61000-4-30		
Averaging time	10 min	10 min	3s / 10 min
Number of measurements	≥ 3 for each 10 % power bin	≥ 7 for each 10 % power bin	≥ 24h[a] for 3s and ≥ 7days[a] for 10min
Aggregation method	Arithmetic	Arithmetic	Geometric
Statistical assessment	Max of all measurements per power bin	95^{th} percentiles of all measurements per power bin	95^{th} and 99^{th} percentiles for each 24h
Parameter	Current	Current	Current / Voltage

separate position in the relevant results table. This approach is also applicable to existing harmonic measurement data.

As an alternative, IEEE standard 1547.1 [17] includes a detailed procedure for the measurement and the data analysis of *dc* current injection, proposed for inverters that connect to the grid without the use of *dc*-isolation output transformers, which may serve as a guide. Taking this standard into account a dedicated test can be alternatively executed, as described in paragraph 5.6 of IEEE 1547.1 standard, where it is asked to measure harmonics for a 5-min period at three different power levels (33%, 66% and as close to 100% of P_n as possible) and then calculate the *dc* component. Obviously this presupposes that the PGU has to operate with a set-point power.

It is important to note that the current sensors used in either of these approaches should be capable of measuring the zero Hz component correctly.

D. Flicker measurements

According to the CEA requirements, the flicker emissions of wind and converter-based generating stations should comply with the limits imposed in IEC 61000 series of standards, which in turn corresponds to IEC TR 61000-3-7 [15]. The measurement and evaluation procedure as per IEC 61000-3-7 is in line with the basic principles of IEC 61400-21 standard [1] and this means that the test procedure of IEC 61400-21 is sufficient. The flicker report can be based on measurements of flicker of a duration, which is long enough so that sufficient data in all 10% power bins from 0% to 100% of the nominal power are collected. The measurement reports, typically do not include any assessment of compliance with the limits included in the IEC 61000-3-7.

E. Testing of control requirements

According to CEA requirements, special control features of the units under certification have to be demonstrated. These features are not fully covered by the testing procedure of the IEC 61400-21 standard and certain points need to be addressed separately, as explained below:

- *Reactive power capability to maintain power factor within the limits of 0.95 lagging and 0.95 leading, provided that this performance is achieved with a voltage variation of up to ± 5% of U_n*

The relevant test procedure is not defined in detail in the CEA standard. Ideally, test results are expected to cover a voltage range of ± 5% of nominal system voltage and a power factor range between 0.95 lagging and 0.95 leading. Based on this, the following procedure is identified:

Step 1: Active power and reactive power measurements as 1-minute values will be taken at standard (nominal) voltage and at three different reactive power modes (zero, max inductive and max capacitive). Analysis will be done according to the existing procedure of IEC 61400-21 [1].

Step 2a: The standard voltage of the terminals of the tested unit has to be changed at the limits of ± 5%. This can be achieved with the use of certain methods such as the use of a tap changer of the step-up transformer, the use of the LVRT-test equipment etc. Measurements and analysis may be performed as described in Step 1.

Step 2b: As an alternative to *Step 2a*, sub-system test may be performed (involving the controller plus the generator and the inverter) on a test bench, but this presupposes the availability and provision of such facility, preferably in India.

As a general comment on this specific requirement of the CEA standard, the performance of the test under different voltage levels (*Steps 2a or 2b*) is not a straightforward procedure and it increases the complexity, the duration and the cost of the relevant certification. Instead, following the standard procedure of IEC 61400-21 [1] (*Step 1*) the basic features of the tested units are adequately tested and demonstrated.

- *Capability of remaining connected to the network and operate within the frequency range of 47.5 Hz to 52 Hz and able to deliver rated power in the frequency range of 49.5 to 50.5 Hz provided that this performance is achieved with a voltage variation of up to ± 5% of U_n*

As a prerequisite of this test, grid protection tests according to IEC 61400-21 [1] must be performed to ensure the correct functionality of the grid protection system, as described in paragraph F. The following further options are identified for its execution:

Option 1: During the normal PQ measurement campaign, the grid frequency is recorded and presented. However, the potential frequency deviations are expected to lie within a more narrow frequency range than the one required by the CEA (i.e. between 47.5 Hz and 52 Hz) and therefore the efficient performance of the tested unit cannot be fully demonstrated.

Option 2a: This test may be also implemented virtually by providing the relevant dummy input signals directly to the controller of the unit under test (apparently through the use of the grid simulator). The active involvement of the manufacturer is definitely necessary for the effective execution of this test.

Option 2b: A sub-system test (controller plus generator and inverter) on a test bench, is also possible but this is but this presupposes the availability and provision of such facility, preferably in India.

Finally, it should be mentioned that the condition about the voltage range of up to ± 5% is proposed to be eliminated in the new CEA amendment [11].

- *Active power set-point control*

The standard procedure of the IEC 61400-21 [1] is sufficient for this test and can be expanded also to solar stations.

F. Functionality of the protection system

The aim of this test is to demonstrate the PGU ability to disconnect from the grid if the voltage or frequency for a given time exceeds a given limit (upper or lower). The intention is to focus on the functionality of the protection system rather than on documenting specific protection levels and times. For this specific test, the procedure described in the IEC 61400-21 [1] is sufficient. The tests can be performed either on-site or at a test bench, by applying variable voltage/frequency signals, through a proper grid simulator coupled to the protection device. By all means, a separate test of the complete trip circuit has to be performed on-site, in order to demonstrate the efficient performance of the complete PGU protection system, including the response of the relevant circuit breaker. It should be mentioned at this point, that with the expected new IEC 61400-21-1 [2] minor

TABLE IV. SUMMARY OF THE SUGGESTED TESTS ACCORDING TO THE CEA GRID CODE AND RELEVANCE TO THE IEC 61400-21 STANDARD

No	Current CEA Requirement	Proposed test procedure	Covered by IEC 61400-21
1	Harmonics according to IEEE 519	According to IEEE 519 and IEC 61400-21	No
2	DC current > 0.5% of P_n	Evaluation with FFT transform and reporting according to IEC	No
3	Flicker according to IEC 61000-3-7	According to IEC 61400-21	Yes
4	Reactive power support	Reactive power capability according to IEC 61400-21	Yes
5	Operation within specific frequency range	- Grid protection test acc. to IEC (see point 8) - Use of grid simulator (optional)	No
6	Fault Ride Through Capability	Acc. to IEC	Yes
7	Active power set-point control	Acc. to IEC	Yes
8	Functionality of grid protection system	Acc. to IEC	Yes

changes are foreseen in the testing procedure, mainly related to the form of the input test signal.

G. General Measurement Requirements

To ensure transparency and traceability of the certification tests, the tests and measurements described in the previous paragraphs must be performed by measuring institutes accredited for the relevant services according to ISO/IEC 17025 [18].

The measurement equipment shall meet the accuracy requirements of IEC 61400-21 [1]. All currents and voltages must be recorded with a sampling rate ≥4 kHz for flicker and switchings and ≥10 kHz for harmonics and FRT testing.

In TABLE IV. an overview of the suggested certification tests according to the CEA Grid Connectivity Standard is given in relation to the tests included in the IEC 61400-21 [1]. It is worth mentioning that some further tests of the IEC 61400-21, like the *active power ramp rate limitation*, the *reactive power set-point control* and the *reconnection time* are not explicitly referenced inside the current CEA Grid Connectivity Standard. However, the new CEA amendment [11] includes specific proposals for these requirements. Therefore, it is already recommended to follow the complete IEC 61400-21 measurement procedure and include these tests in the relevant certification reports.

IV. ASSESSMENT OF GRID COMPLIANCE

The tests proposed in the previous Section have to be properly evaluated in order to facilitate the assessment of grid code compliance. Although the certification process is a task accomplished by the Certification Bodies, this Section includes some basic suggestions for the formatting of the Test Reports and the display and interpretation of the measurement results, based on the long-term experience of UL DEWI in the field.

TABLE V. INDICATIVE RESULTS TABLE WITH THE REQUIRED LVRT CHARACTERISTIC VALUES MEASURED FROM THE LVRT TESTS

	No	Parameter	Relevant time
General	1	Date	-
	2	Time	-
	3	Operational mode of WT	-
	4	Active power range	-
	5	Three phase/ two phase voltage dip/swell	-
	6	Wind speed / available power	-
	7	WT tripped (Y/N)	-
	8	Time of entrance of voltage dip	-
	9	Time of clearance of voltage dip	-
	10	Fault duration (measured from test)	-
	11	Magnitude of voltage dip / swell (measured from test)	-
Before voltage dip	12	Voltage	Indicatively, between 500ms and 100ms before fault entry
	13	Active power	
	14	Reactive power	
	15	Active current	
	16	Reactive current	
During voltage dip	17	Voltage	Indicatively, 100ms after fault entry until 20ms before fault clearance
	18	Active power	
	19	Reactive power	
	20	Active current	
	21	Reactive current	
	22	Active power ratio (During/Before voltage dip)	-
After voltage dip	23	Voltage	When steady state value is reached (e.g. 5s after fault clearance)
	24	Active power	
	25	Reactive power	
	26	Active current	
	27	Reactive current	

A. LVRT Report compilation requirements

The results must be included in a Test Report which fulfills the requirements of IEC 61400-21 and IEC 61400-21-1 ([1], [2]). For convenience reasons, the LVRT reports are usually compiled separately from the rest PQ, Control and Grid protection reports.

As a basic rule, the location of the measuring point and the specific configuration of the involved unit/plant, including the relevant control parameter settings are essential for the completeness of the test report.

The stated response shall include time-series and graphs of the following parameters, for the time at least 30 seconds prior to the voltage drop and until at least 10 seconds after the fault clearance, given that the effect of the voltage drop has abated:

- positive and negative sequence voltage
- positive and negative sequence currents
- positive sequence active power

- positive sequence reactive power
- active current
- reactive current
- wind speed or available power

Positive and negative sequences must be calculated according to IEC 61400-21, Annex C [1].

TABLE V. summarizes the necessary parameters which have to be presented for each performed test, along with the recommended averaging times. These parameters must be included in a results table in the Test Report.

An LVRT test report can be considered as complete, if the following basic criteria are met:

- All tests required by this procedure should be carried out (according to TABLE II.
- A diagram which shows the ratio of active power during and before the voltage dip as a function of voltage dip level is included, similar to the example of Fig. 4.
- The measured the reactive current is presented graphically in the report.
- The test report additionally includes the following graphs for one of the two consecutive tests in each case:
- RMS value of voltage, positive and negative sequence voltage, instantaneous phase to phase voltages
- Active and reactive power of positive sequence, active and reactive current of positive sequence, voltage of positive sequence and wind speed (in case of wind turbines).
- Instantaneous and effective values of currents of each phase.

Note for Fig.4: Especially, concerning the active power production of the tested unit during the dip, in the example of Fig. 4, it is recognized that the actual field measurements do not necessarily lie on the target line of 1:1 proportion between active power and voltage, as required by CEA. Instead, a reasonable variance of the measured values is noticed, which represents reality and has to be taken into account during the assessment phase. To facilitate certification phase, a tolerance band of 0.1 p.u. is proposed to be introduced and displayed together with the measurement results, as seen in Fig. 4. Further details concerning the evaluation of the relevant quantities need also to be clarified. A common query is if the results should be expressed as positive sequence values or the standard RMS ones. Since this is not directly derived from the CEA Standard, it is recommended that the calculation method is clearly described inside the test report.

B. *Reporting of PQ, Control and Grid Protection tests*

In principle, the standard template according to IEC 61400-21 [1] is sufficient and could be used for the reporting of the power quality, control behavior and grid protection tests of the PGU. Especially for harmonics, it should be taken into account that the evaluation method of IEEE 519 is different from the one of IEC 61400-21. The relevant report should clearly encounter these differences.

C. *Compliance review checklist*

As a summary of the suggested compliance assessment procedure, presented in this Section, an indicative checklist

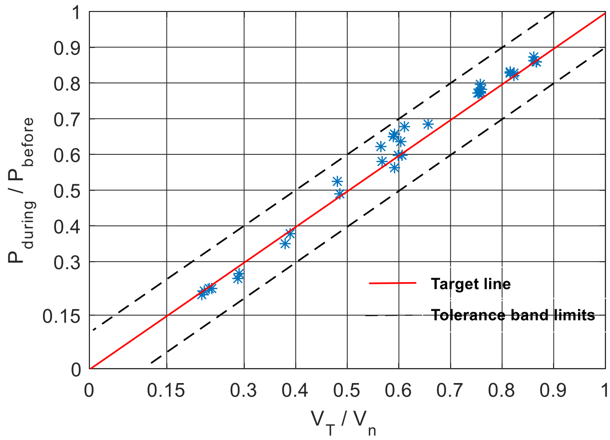

Fig. 4. Ratio of the measured active power during and before the dip as a function of voltage dip level (example from actual field

TABLE VI. INDICATIVE COMPLIANCE REVIEW TABLE

	No	CEE requirement	Requirements	Passed?
PQ	1	Harmonic currents	Limits of IEEE 519	Yes/No
	2	DC current	> 0.5% of P_n	Yes/No
	3	Flicker	Limits of IEC TR 61000-3-7	Yes/No
Control & Prot.	4	Reactive power support	Reported according to IEC 61400-21	Yes/No
	5	Operation within specific frequency range	Successful operation of the protection system, as per IEC 61400-21 grid protection report	Yes/No
	6	Active power set-point control	Reported according to IEC 61400-21	Yes/No
	7	Functionality of grid protection system	Same as in point 5	Yes/No
Fault Ride Through	8	Remained connected during and after the dip?	Should remain connected	Yes/No
	9	Fault duration determined from test	≥ times defined in TABLE II.	Yes/No
	10	Voltage drop level defined by the test[a]	within voltage ranges of TABLE II.	Yes/No
	11	Ratio of active power during and before the dip determined from test	Should be in proportion to the retained voltage [b]	Yes/No
	12	Active power before fault entry	At partial load: $0,1\ P_n$ - $0,3\ P_n$ At full load: $\geq 0,9\ P_n$	Yes/No

a. to be confirmed based on the no load test because of the voltage change under load conditions
b. real measurement do not usually lie on a straight line. A reasonable tolerance band is suggested for the acceptance of the measured behavior (typically a width of ± 10% P_n should be sufficient).

for compliance review of the tested units is included in TABLE VI.

V. CONCLUSIONS

In this paper, a testing procedure to determine the electrical characteristics of wind turbines and inverter-based generating stations in accordance to the CEA requirements is proposed. As far as possible, this testing procedure follows the existing international standards and guidelines, like the IEC 61400-21. However, some additional specifications are imposed by CEA, which need to be sufficiently addressed through dedicated tests.

The paper specifies the type and number of field tests that have to be performed, the measurement and evaluation specifications (duration of measurements, statistical evaluation process etc.) as well as reporting requirements. In some cases, further discussion on the interpretation of certain CEA requirements is included. In addition, the paper contains proposals for the efficient assessment and interpretation of the results to ensure that the final decision is according to CEA requirements. The proposals are being supported by selected examples from actual tests performed by UL DEWI in India in the last years.

It is believed that the proposed procedure will contribute to the alignment of the testing procedures among the involved testing institutes, will facilitate the work of the Certification Bodies on a basis of fairness and transparency, will support the manufacturers in the proper manufacturing of their new models and will speed-up the grid compliance evaluation process followed by the grid operators in India.

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