Testing Renewable Power Plants on High-Voltage-Ride-Through Capability

Grid Code Requirements and Testing Procedure

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When penetration of distributed generators (DG) reach significant shares in the power supply, provisions of system services become increasingly important. Withstanding voltage dips is a crucial feature in this context and commonly known as Low-Voltage-Ride-Through capability (LVRT). Meanwhile, this mandatory requirement can be found in almost every international grid code – also in India. The utilized LVRT testing equipment and procedure is worldwide state of the art. However, resulting from further DG installations new challenges evolve that threaten the system stability. In this regard, overvoltage is an issue and frequently discussed in terms of grid code requirements for High-Voltage-Ride-Through (HVRT) and adequate testing. Also in the current draft of the amendment 2016 "Technical Standards for Connectivity to the Grid" of the Indian Central Electricity Authority such HVRT requirement can be found. Thus, there is an ongoing discussion among relevant market players with respect to compliance and testing. The paper therefore emphasizes both technical relevance of HVRT within grid codes and testing configurations.

High-Voltage-Ride-Through, HVRT, Over-Voltage-Ride-Through, OVRT, Fault-Ride-Through, FRT, grid integration, grid codes, compliance, testing, test system

I. INTRODUCTION

Resisting voltage dips without disconnection for certain time durations is state-of-the-art of wind turbine generators (WTG). In India the Central Electricity Authority (CEA) introduced the LVRT requirement in the connection standards in 2013 for wind power plants [1], [2]. In a petition the CEA clarified in this regard the application and validity of the requirement. Wind turbines that have been commissioned after 15/04/2014 are required to be LVRT compliant. The compliance shall be tested and verified by a third party and shall be included as a part of type certification of wind turbines in India. Furthermore, the state electricity boards will work on phasing out the older stall regulated turbines. Also, turbines that do not have LVRT feature has to be retrofitted with LVRT capability and the state electricity boards have to proof it. The grid code is applied nationwide and the CEA will make amendments in the future to clarify the grid codes for connectivity of wind turbines. In this context, not only the resistance against voltage dips but also the fault-ride-through-capability in terms of overvoltage gets increasingly important. Temporary overvoltage may occur in the system because of load shedding, phase-to-earth faults or generation losses combined with dynamic variations in loadings and huge transmission line capacitances. In India, the latest draft of the amendment includes new provisions regarding HVRT capability for wind as well as solar power generating plants [3]. Since this feature is only addressed in very few technical guidelines, yet, the article therefore emphasizes on the one hand the technical relevance of such HVRT requirement within grid codes and on the other hand the configuration of the testing setup and used procedure.

II. BACKGROUND AND RELEVANCE OF HVRT

Overvoltage in the power system may take place due to high transmission line capacities in combination with load shedding or generation tripping because of e.g. lacking LVRT capability, which causes temporary load rejection particularly in rural areas. Another reason for high voltage excursions can be found when the system voltage recovers following a fault clearing. This event is on the one hand caused by stalling and subsequent tripping of a high penetration of line connected induction engines, and on the other due to the acceleration and inertia of the generators which force reactive power oscillations with low damping [4]. However, very short swells also might occur after a system fault clearance because of reactive power injection from the DG for stabilizing the disturbed voltage during the fault. These phenomena for voltage variations differ in terms of time duration, ranging from a few milliseconds to some minutes, as well as in location and system propagation. Nevertheless, such very short and local voltage swells do not threaten the system security in any case. The impacts of wide-spread overvoltage in the transmission and distribution system are much more serious, though.

In praxis, a high voltage excursion in the transmission system of Germany e.g. happened during an incident in 2012 with relatively long increase in voltage and regional system wide impact. The capacitive voltage boost occurred following a two phase fault on a transmission line in the grid section of the German TSO 50Hertz (see Fig. 1). After the fault was cleared almost 1.7 GW of generation was lost because of tripping of wind turbines without LVRT capability as well as lacking resistance of withstanding overvoltage [5].

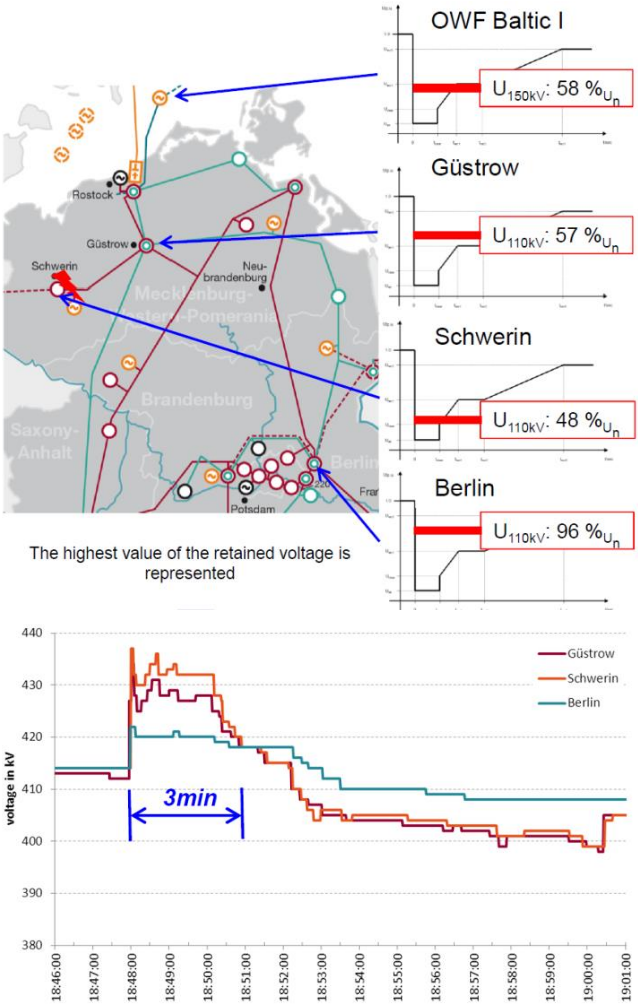

Figure 1 Incident in Germany and subsequent overvoltage [5]

The fault occurred on a 380 kV transmission line near the city of Schwerin in northeast of Germany. The resulting voltage dip with a residual voltage of 48% of nominal voltage ($U_n := V_n$; $U_n = 110$ kV) at the substation close to the fault location spread in a wide area and reached even Berlin in a distance of approximately 200 km. Before the incident, the compensation reactors in the northern grid section were disabled because of high amounts of wind power infeed and normal grid voltage. Thus, a conventional coal-fired power plant with 550 MW located in Rostock was shut down as well. In the northern section of the German TSO 50Hertz there was almost 1.400 MW of installed wind power capacity connected to the medium voltage level at that time. However, due to the old age only a minor share of these turbines meet the LVRT requirement. Therefore, lots of wind power plants disconnected from the MV system as a result from the voltage dip. This led to a temporary increase of the vertical net load from 1.300 MW up to 3.000 MW. After the fault was cleared within approximately 70 ms, the sudden loss of generation capacity in distribution systems and corresponding unloading of grid sections caused immediately rise in voltage within the 380, 220 and 110 kV levels. In the 420 kV transmission network the voltage increased considerably up to 435 kV for approximately 3 minutes as well as in the 110 kV system by ca. 8% U_n. As a consequence, additional WTG disconnected because a non-existing HVRT requirement and their lacking capability to resist such overvoltage. By enabling compensation reactors in the transmission system the voltage was restored to its normal operation band again. However, the described situation demonstrates the danger of potential chain reactions and it is crucial to counteract such phenomena and avoid its occurrence in every manner. Hence, the technical justification of the HVRT requirement is given in systems with either strongly distributed generation or long transmission distances like in India, Australia or USA.

III. HVRT Requirements in Grid Codes

In order to avoid critical situations caused by overvoltage, system operators sensitize to introduce specific HVRT requirements in recent grid codes. Comparable to the situation in 2003 when the German TSO E.ON published the first grid code including a generally valid LVRT capability profile for wind turbines, it can be expected that also HVRT capability will become state-of-the-art in the next few years and many international system operators will make use of it by adapting their grid codes with corresponding requirements. In Germany the newly published grid code VDE-AR-N 4120 is valid for customer installations that are newly connected to the 110 kV systems [6]. The requirements in the code describe the dynamic system support of DG's with specifications in terms of a combined LVRT and HVRT capability. The HVRT profile for wind and solar power plants requires resistance against overvoltage up to 130% U_n for 100 ms and following 125% U_n until 60 s. The fault is defined by the appearance of an abrupt voltage change or by the criteria that the voltage increases to values of more than 110% of $U_{n,MV}$. As long as all phase to phase voltages at the point of common coupling (PCC) remain within the illustrated thresholds of the HVRT profile, the DG are supposed to ensure a stable operation without disconnection from the grid. Therefore, in terms of overvoltage consideration the highest of the three phase to phase voltages has to be evaluated in this context.

Similar profiles can also be found in other international grid codes. Likewise Germany, countries like Italy, South Africa or Australia already require HVRT capability of DG, while others like the India or the USA consider an inclusion in future codes. According to the draft of the 2nd amendment of the Indian CEA, wind and solar generating units/stations at all voltage levels shall remain connected to the grid, when voltage at the PCC rise above the specified value given below for specified time [3].

TABLE I. CEA HVRT Proposal

Overvoltage (p.u.)	*Minimum time to remain connected (seconds)*
$1.3 < U \leq 1.4$	1
$1.1 < U \leq 1.3$	3
1.1 or below	Continuous

Comparable to LVRT the requirements differ internationally according to the local needs of the system operators in terms of time periods, maximum voltage magnitudes, references and fault types. Besides the capability to remain connected to the grid, in Germany for instance the WTG has to be able to stabilize the system voltage during the fault by injecting a fast acting dynamic reactive current according to a defined characteristic (Fig. 2).

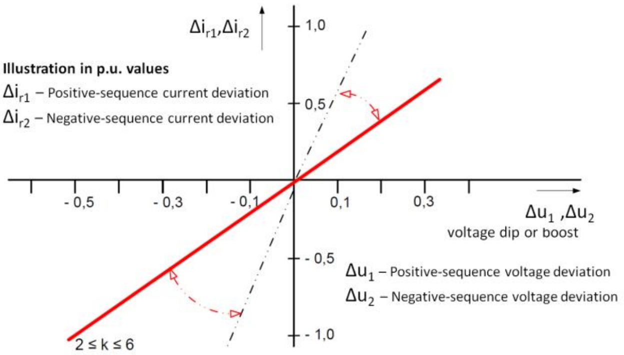

Figure 2 Required dynamic reactive current injection during fault events according to German VDE-AR-N 4120 [6]

In contrast to events of voltage dips, the WTG is required to absorb reactive power in case of voltage boosts by injecting a capacitive reactive current (under-excitation). The current must reach 90% of its designated value within 30 ms (response time) and its tolerated stationary value not later than 60 ms (transient time). The measurement of the voltage deviation and calculation of the resulting reactive current Δi_r is usually located at the terminals of the power generation unit, which means low voltage side of the unit's machine transformer. The magnitude of the additional reactive current is predefined and proportional to the voltage deviation ($\Delta i_r = k^* \Delta u$).

IV. TESTING OF HVRT CAPABILITY

The utilized testing equipment as well as corresponding testing procedure for verifying the LVRT capability of WTG is worldwide state of the art since more than 10 years. The methods of application and performance have been incorporated in the standard of the IEC 61400-21 for wind turbines [7]. HVRT capability is supposed to be verified similarly and tests are already carried out successfully.

In Germany the compliance with the HVRT requirement has to be shown by the manufacturer of the WTG by performing corresponding measurements and testing. For the purpose of adequate testing appropriate test equipment is needed. Recent approaches and ideas were related to special transformers with diverse tapping, or transformers combined with specific power electronics. Disadvantageously these solutions do not use standard components which cause high costs in development and implementation. Often they can also not be used for combined LVRT and HVRT testing or do not represent the system behavior under realistic conditions. Analogous to the development of the first mobile LVRT testing container, it was again FGH and the wind turbine manufacturer ENERCON who designed the first mobile HVRT testing container in 2013 which can easily be added to existing LVRT testing containers and realizes very flexible operation and testing possibilities.

A. *Configuration of the HVRT testing setup*

For testing LVRT behavior of a WTG a mobile testing device containing an inductive voltage divider is commonly used. The setup and corresponding testing guideline was developed by FGH in 2003 and is today incorporated in the standard IEC 61400-21 for wind turbines. In order to realize a test configuration for creating short term overvoltage, the existing container setup was modified. The constellation includes a serial oscillator circuit, consisting of an inductor, a capacitor and a resistor (Fig. 3). The inductor is identical with the serial impedance of the inductive voltage divider that is integrated in LVRT test systems which is a strong benefit in combined LVRT/HVRT testing setups. With this electric circuit overvoltage can be provoked by making use of capacitive charging (Ferranti effect).

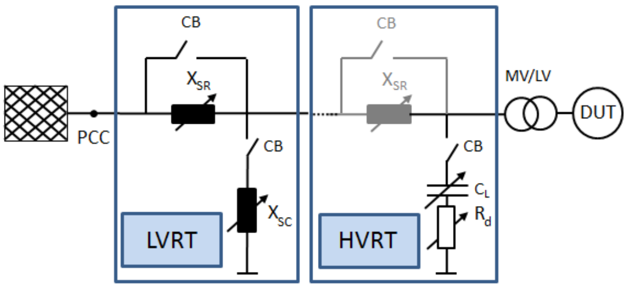

Figure 3 Configuration of LVRT, HVRT and combined setup

With the replacement of the short-circuit impedance by a capacitor, the test configuration characterizes the equivalent electrical representation of a transmission line. The charging current of the capacitor causes a voltage drop at the inductor which adds up the grid voltage at the output. The resistor prevents the uncontrolled oscillation of voltage at the point of connection. Several surge arresters protect the components of the test system.

B. *Benefits*

The HVRT test setup can either be implemented as a stand-alone with own switch gear and full test circuit, or as add-on system for LVRT test containers (even retrofitting possible). In such combined LVRT/HVRT solutions a switching between HVRT and LVRT testing can be ensured very flexible without reconstructions. Advantageously, both circuits use redundant components which provide synergies and reduce costs. Based on the needs of testing overvoltage, the components can easily be adjusted in very small steps until voltage up to 200%, if desired. Due to the modular and scalable design the equipment is very flexible and can be delivered and operated all over the world which might be a problem for oil transformer approaches. In contrast to other solutions based on power electronics the grid is represented realistically because of the usage of passive elements. By using the serial impedance the authentic control behavior of the device under test (DUT) can be observed accurately at different voltage levels up to 36 kV and power of the testing devices up to 8 MVA.

V. HVRT PROTOTYPE AND EXPERIENCES

The prototype of the HVRT testing laboratory was integrated in a 20 feet standard container and combined with an existing LVRT setup. For testing a wind turbine connected to a 10 kV medium voltage level was used. More than 100 HVRT tests were performed with overvoltage up to 140% U_n. Even then the repercussion on the voltage of the connected power system was negligible.

A. Voltage Drop after Capacitor Switching

During the prototype testing a short voltage drop at the moment of switching the capacitor was observed. After that voltage drop the testing voltage increases to the adjusted value. In some cases the required rectangular shape of the test voltage in terms of an abrupt ideal voltage change with tolerances of maximum 20 ms according IEC 61400-21 could not be reached. An investigation proved that the short voltage drop can be avoided by using adapted and modified switching sequences of the installed circuit breakers. Additional advantages were reduced overshooting and reduced transients of the testing voltage. Furthermore, a lower stress to the test circuit breakers can be realized.

B. Magnetizing Current of Power Transformer

A typical medium voltage power transformer is designed to operate in the linear range of the magnetizing curve for voltages up to 1.05 or 1.10 p.u. of U_n. If the operating voltage exceeds these values, saturation effects of the power transformer occur. On the primary side of the transformer a very high magnetizing current can appear, while on the secondary side to the voltage is significantly lower compared to the normal voltage ratio. Additionally, the secondary voltage is strongly distorted by harmonics.

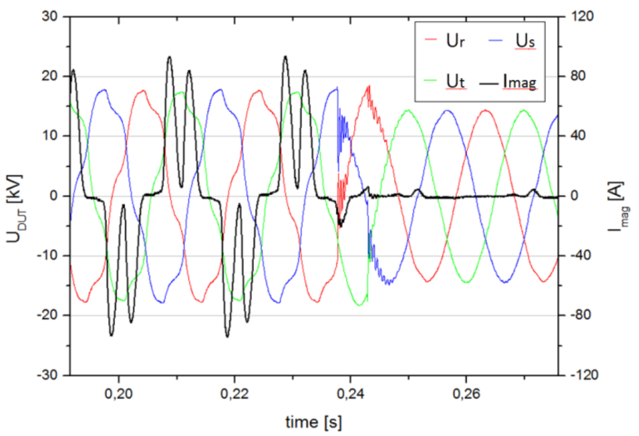

Figure 4 Magnetizing current and distorted voltage during HVRT

The magnetizing current of the power transformer is an inductive current. Therefore, the transformer itself helps inherently to reduce overvoltage from the grid by consuming reactive power. By increasing the operating voltage of the transformer the magnetizing current increases even more, without resulting in higher voltages on the secondary side. During the fault, at measured values of 124% U_n the utilized transformer is saturated and a peak magnetizing current up to 100 A occurred (Fig. 4). Such continuous stress might damage to the power transformer.

C. Harmonics and Resonances at HVRT Testing

A serial connection of an inductance and a capacitance is commonly used as absorption circuit to filter undesired frequencies, such as harmonics. To reduce a voltage of a specific frequency the resonance frequency of the circuit has to comply with that frequency. When doing so, the inductive and capacitive reactance deletes each other. If there are no other ohmic resistances connected, the circuit behaves like a short circuit for the undesired frequency. Although the voltage of the entire circuit is low, the voltage at the circuit components can be very high. This behavior has to be considered, if the recommended HVRT test circuit is used for testing.

In order to avoid undesired amplification of harmonics, enough damping resistance has to be added. In this context, ripple control frequencies used for remote control connected consumers and power plants needs to be taken into account. A test circuit matching with the ripple frequency will behave as a filter, if the damping resistance is inadequately selected. Generally an operation point around the ripple frequency should be excluded, to prevent influencing these systems.

D. Reactive Current Injection during HVRT

Although the transformer is operated in its non-linear range during the overvoltage, the resulting distorted testing voltage at the wind turbines terminals shall not influence its dynamic system support. The following measurement of Fig. 5 was performed at a three phase overvoltage of ca. 118% $U_{n,LV}$ while the wind turbine control was configured according to the reactive current injection of German SDLWindV and k=2. This characteristic is similar to the new VDE-AR-N 4120 requirement but it includes a +/-10% voltage deadband. Moreover, the positive-sequence voltage is illustrated which is used as a reference for the triggered reactive current according to the requirement.

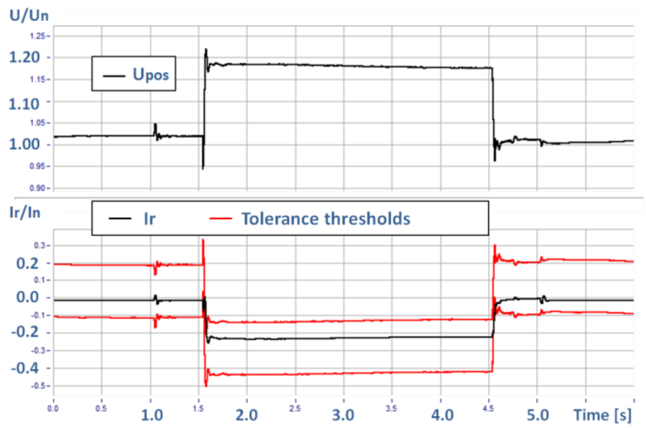

Figure 5 Required reactive current infeed during the fault with tolerance bands according to ^German FGW-TR8

As it can be seen in Fig. 5, despite the strongly distorted phase testing voltage (cp. Fig. 4) the reactive current infeed complies fully with the desired behavior and the certification tolerances according to FGW-TR8 [8]. The shape of the sinusoidal current injected by the converter is however distorted in the grid filters because of the testing voltage. Nevertheless, the HVRT grid code requirement is successfully fulfilled.

VI. CONCLUSION

The HVRT capability and formulation of corresponding requirement in today's grid codes are crucial aspects and increasingly spotlighted in the context of stability assessments of international power systems. Relevant systems are characterized by not only high penetration of dispersed power generators but also long transmission distances where capacitive overvoltage can occur easier in case of load shedding or generator tripping. The described phenomena justify the resistance of WTG against such faults under predefined conditions, and testing for the verification of its compliance is needed. The paper discussed an appropriate solution for the HVRT testing configuration and verified its applicability in pilot prototype testing which provided valuable experiences and findings. Today, it is applied successfully in testing campaigns for grid code compliance of different WTG manufacturers. In the next edition of the IEC 61400-21 the testing procedure and the setup will be incorporated.

However, with respect to grid code drafting the definition of the HVRT requirement is subject to careful consideration. As the results from testing show, the effects of overvoltage can spread widely in the systems but their magnitude is limited at power generation level because of saturation effects of interconnected transformers. Due to the transformer designs, the saturation generally restricts the secondary voltage to maximum values of 120% U_n. That means system overvoltage above 120% to 130% U_n will not be handled differently by the generating unit with standard technologies. At the development of grid code as well as corresponding testing guidelines this should be taken into account. Additionally, if the WTG measures the restricted secondary voltage, any other requirement that is based on this reference voltage is also restricted to its maximum value. This applies e.g. to the German grid code in the definition of the infeed of reactive current. This does not cause any problems but it is an aspect that system operators should keep in mind. If higher currents are desired, the k-factor must be increased. Nevertheless, a factor for the entire power generating plant with PCC reference voltage cannot be implemented in this way.

At testing two phase faults, higher voltages than 130% U_n in two phases are often needed to exceed values of 1.1 p.u. of secondary positive sequence voltage. Hence, it is recommended limiting two phase HVRT testing to 110% of the nominal positive sequence voltage. Furthermore, due to the commonly used Dyn5 configuration of the unit transformer, any one phase fault will be transferred as two phase fault to the secondary side. Thus, explicit testing of one phase faults is not needed in continental Europe. A different concept for protection and neutral point treatment along with earthing may change this consideration, however. This may apply to India should be scrutinized carefully when different fault types are to be taken into account.

In further HVRT testing the behavior of doubly-fed induction generators has to be analyzed. In particular the effects of utilized three-winding transformers need to be verified. Depending on its configuration also one phase overvoltage should be considered and hence considered when testing setups are designed. Furthermore, similar to the discussed aspects of the dynamic system support, the precise reactive current should be investigated profoundly as well. It must be avoided that influence of the strongly distorted voltage affects the performance of the power converter incorrectly. Especially the different control strategies and concepts among the manufacturers are subject to further examination since newest grid codes require also negative-sequence current injection. It should be verified where the WTG detects the voltage disturbance.

Acknowledgment

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References

[1] Central Electricity Authority (CEA), Technical requirements for connectivity of Generators - Indian Electricity Grid Codes, 2010

[2] Central Electricity Authority (CEA), Technical standards for connectivity to the Grid – Amendment Regulations, 2013

[3] Central Electricity Authority (CEA), Technical standards for connectivity to the Grid, Draft Regulation 2016

[4] Western Electricity Coordinating Council (WECC), 2013, WECC Variable Generation Planning Reference Book, Salt Lake City, Utah

[5] European Network of Transmission System Operators (ENTSO-E), Justification of the FRT-Requirement for Type B Units in the RfG Network Code, Meeting with DSO Technical Expert Group, Brussels, Belgium, 2012

[6] VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., VDE-AR-N 4120 - Technische Bedingungen für den Anschluss und Betrieb von Kundenanlagen an das Hochspannungsnetz (TAB Hochspannung), Berlin, Germany, 2015

[7] International Electrotechnical Commission (IEC), IEC 61400-21 Edition 2, Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines, 2008

[8] Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW) e.V. „Technische Richtlinien für Erzeugungseinheiten und -anlagen, Teil 8: Zertifizierung der Elektrischen Eigenschaften von Erzeugungseinheiten und –anlagen am Nieder-, Mittel-, Hoch- und Höchstspannungsnetz“, Revision 8, 2016