RELEVANCE OF HIGH-VOLTAGE-RIDE-THROUGH CAPABILITY AND TESTING

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ABSTRACT

Withstanding voltage dips without disconnection for certain time durations is state-of-the-art among manufacturers of wind turbine generators. Meanwhile, new challenges evolved along with the sustained connection of dispersed power generators to medium and high voltage systems. 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. 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. Insights and experiences are demonstrated based on successful pilot project testing of a wind turbine. Derived from the results recommendations for HVRT testing procedures can be provided for guideline proposals as well as the drafting of the requirement within the codes.

INTRODUCTION

Resisting voltage dips in the system is commonly known as Low-Voltage-Ride-Through Capability (LVRT) and mandatory basic requirement for dispersed power generators (DPG) in almost every international grid code, nowadays. The utilized LVRT testing equipment as well as corresponding testing procedure 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. The LVRT requirement became necessary due to the increasing penetration of DPG and their associated significant share of power supply. By then, a critical level was reached when disconnection of wind turbines during system faults was not acceptable anymore and threatened the systems robustness in terms of frequency stability. Since incidents in Germany and Spain underlined the fundamental relevance of LVRT, transient stability analyses were carried out in several countries. Even when the amount of installed wind power was on comparably small level, the impact of wind power outages potentially caused serious system shut downs due to their geographic location and distribution [1]. Thus, extensive retrofittting measures took place and manufacturers had to adapt their power generating units (PGU) accordingly. This happened in Germany and Spain in the past and the technical justification is generally accepted.

Today, system operators and power producers have to deal with new challenges while requirements become more advanced and more stringent. In addition, further sophisticated services are needed in order to maintain security of supply. In this context, overvoltage is an issue and increasingly discussed in the development of modern grid codes such as the German VDE-AR-N 4120. In the final version of this standard for the connection of power generators to German high voltage system (mainly 110 kV, but also 60 to 150 kV) the ability of DPG to resist overvoltage is nationally firstly introduced with a High-Voltage-Ride-Through (HVRT) requirement [2].

MOTIVATION 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 [3]. However, very short swells also might occur after a system fault clearance because of reactive power injection from the DPG 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 40 Hertz (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 [4].
The fault occurred on a 380 kV transmission line near Schwerin in the northeast of Germany. The resulting voltage dip with a residual voltage of 48% of nominal voltage ($U_n = 110$ 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 TSO 50hertz ca. 1.400 MW of installed wind power capacity is connected to the medium voltage level. However, due to their old age only approximately 200 MW of them are certified according to German SDLWindV and 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 of 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, e.g. Canada, Australia or USA.

**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 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. The newly published version of the German grid code VDE-AR-N 4120 is valid for customer installations that are connected to 110 kV voltage level in Germany. With its publication at the beginning of 2015 this technical standard has a transition period of 2 years for its full application to new power plants [2]. It describes the required dynamic system support of DPG’s with specifications in terms of a combined LVRT and HVRT capability. The HVRT profile of type 2 power generating plants (meaning plants that include PGUs which are not equipped with directly grid connected synchronous generators) 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 DPG is 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 some other international grid codes. Likewise Germany, countries like Italy, South Africa or Australia already require HVRT capability of DPG, while others like the USA or Denmark consider an inclusion in future codes. Comparable to LVRT the requirements differ 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 the PGU has to be able to stabilize the system voltage during the fault by injecting a fast acting dynamic reactive current according to a newly defined characteristic (Fig. 2).

In contrast to events of voltage dips, the PGU 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 \( \Delta i_t \) 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 \( (\Delta U = k \times \Delta u) \).

In 2013 the European Network of Transmission System Operators developed a pan-European Network Code on Requirements for Grid Connection Applicable to all Generators (ENTSO-E NC RfG) that has not been adopted by the regulatory and legal institutions, yet. Based on the explanations above an adequate consideration and inclusion is strongly recommended.

**TESTING OF HVRT CAPABILITY**

In Germany the compliance with the HVRT requirement has to be shown by the manufacturer of the PGU 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. In a pilot prototype project with the wind turbine manufacturer ENERCON, again FGH designed the first mobile HVRT testing container which can easily be added to existing LVRT testing containers and realizes very flexible operation and testing possibilities.

**Configuration of the HVRT testing setup**

For testing LVRT behavior of an entire wind turbine generator 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. 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 inserted 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).

![Configuration of LVRT, HVRT and combined setup](image)

**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 existing LVRT containers (retrofit). In such combined LVRT/HVRT solutions a switching between HVRT and LVRT testing can be ensured very flexible without reconstructions. Advantageously, both circuits use relevant 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 is 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 until 35kV and power of the DUT up to 10 MVA.
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% \( U_{in} \). Even then the repercussion on the system voltage was negligible.

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 a modified switching sequence of the installed circuit breakers. Additional advantages of this adapted switching sequence are reduced overshooting and reduced transients of the testing voltage. Furthermore, a lower stress to the test circuit breakers can be realized.

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 \( U_{in} \). 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. 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% \( U_{in} \) the transformer is saturated and a peak magnetizing current up to 100 A occurred (Fig. 4). Such continuous stress might damage to the power transformer.

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 ohmics 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. The operating range of the circuit’s resonance frequency is always higher than the power system’s frequency (50 / 60 Hz). For a power system’s frequency of 50 Hz the operating range of the test circuit is in the range of the third and fifth harmonic frequencies, corresponding to the circuit amplification (voltage gain) of 1.12 and 1.05 p.u. (Fig. 5).

![Figure 4: Magnetizing current and distorted voltage at HVRT](image)

![Figure 5: Amplification of fundamental (blue), third (red) and fifth (yellow) harmonic frequencies at different parameterization of the ohmic resistance](image)

In addition to an increased fundamental voltage, an operating point of the test circuit near a harmonic frequency will result in an even stronger increased harmonic voltage applied to the DUT. To avoid this, 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.

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. 6 was performed at a three phase overvoltage of ca. 118% \( U_{in,LV} \) 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.

Fig. 6: Required reactive current infeed during the fault with tolerance bands according to FGW-TR8

As it can be seen in Fig. 6, 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. 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.

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 PGUs 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. However, the drafting 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 PGU 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. Based on the characteristic with initialized k=2 the generating plant is able to provide 40% I/I\(_{n}\) at its maximum since the positive sequence voltage at the terminals of the PGU is restricted in any case. 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 further HVRT testing the behavior of doubly-fed induction generator 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 the new VDE-AR-N 4120 requires also negative-sequence current injection.

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