INFLUENCE OF LVRT TEST EQUIPMENT CHARACTERISTICS ON THE DYNAMIC PERFORMANCE OF A POWER GENERATION UNIT

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ABSTRACT

Decentralized power plants have to stay connected to the grid during grid disturbances. Only under certain conditions they are allowed to trip. The capability of power generation units (PGU) to withstand a defined voltage-against-time-profile, the so called "low voltage ride through (LVRT)" capability, has to be proven by type testing or unit testing before they are allowed to be connected to the grid. The most common way to test PGUs is using a test container, which is emulating a fault event in the grid with reduced short circuit power. Simulations with different setups with and without LVRT test container and variation of the fault location, but always keeping the same short circuit ratio and remaining voltage at the PGU's connection point, reveal different transient behavior of the device under test. In this paper the influence of the LVRT test equipment is analyzed in detail and recommendations for modifications of the test procedure are given.

INTRODUCTION

Grid codes require decentralized power plants to stay connected to the grid during grid disturbances. Only under certain conditions the PGU is allowed to disconnect from the grid. Requirements and operating limits regarding voltage, frequency, power factor and active and reactive power control are defined in grid codes. In terms of the LVRT capability, voltage-against-time-profiles are given, varying in voltage dip depth and length, type of fault (e.g. 3-phase or 2-phase fault) and sometimes in voltage recovery shape. In order to verify the LVRT capability of a PGU, it either has to be tested on-site with certain test equipment or simulations using a validated simulation model of the PGU have to be performed. A so-called voltage sag generator is used to emulate voltage sags. The following chapter presents different types of voltage sag generators.

LVRT capability test methods

There are several test methods to emulate a fault event. There are mainly four different types of voltage sag generators:

- synchronous generator with fast voltage control
- series/shunt impedance forming a voltage divider
- tap changing transformer
- full power converter

In Figure 1 the principle of these four basic methods is provided.

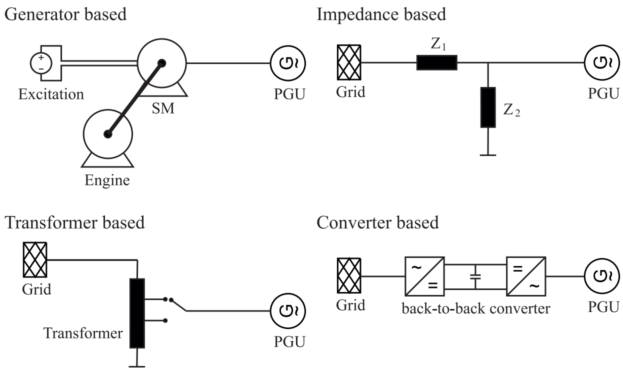

Figure 1 Overview of different types of voltage sag generators [1, 2]

In the generator based approach a diesel powered synchronous generator produces controlled symmetrical voltage sags by changing the field excitation. Hardware costs are high due to the weight and scale of the diesel engine and the synchronous generator. Only symmetrical faults can be emulated with this test method. Besides, ramp-up and ramp-down times are within several cycles of mains frequency, which is too slow to emulate realistic grid faults.

Shunt impedance based voltage sag generators create voltage dips by switching an impedance in parallel to the line. This is utilized by switching of impedances of a an impedance bank. An additional impedance is connected in series to limit the short circuit current and the influence on the feeding grid. In addition to that, the short circuit power can be adjusted by varying the value of the series impedance to emulate connection points with low short circuit power. A by-pass connection of the series impedance may be applied prior and after the voltage dip test. This test method allows for emulating 1-phase, 2-phase and 3-phase faults of variable dip depth and length. It is very easy to implement and low in cost. However, there is the risk of over-voltages caused by switching transients.

Transformer based voltage sag generators are composed of a step-down auto-transformer with on-load tap changer (OLTC). The voltage dip depth is adjusted by an appropriate tap change. Utilizing an OLTC auto-transformer is a suitable solution for building a low cost voltage sag generator. However, to emulate 3-phase faults phase individually controlled tap changers are needed.

A back-to-back converter connected between the grid and the PGU builds a full converter based voltage sag generator. This configuration has the best performance in terms of controllability and programmability. Disadvantages of this solution are high hardware costs, complexity of control and its limitations due to limited overvoltage and overcurrent capabilities, which is essential for dynamic simulation studies applying grid faults. [1–3]

Of course other solutions than the four presented ones to create voltage sags are possible. Reference [4] introduces a voltage dip generator, which utilizes an inductive divider consisting of a series impedance and a parallel branch, where a tap transformer and an impedance is located. In [5] a 3-phase induction generator with a control mechanism to modify its shaft position is presented. If voltage adaption is needed, tapped transformers are implemented. The operation is controlled by a programmable logic controller. This way any voltage-time profile is programmable, not just rectangular ones. A 4-wire matrix converter based voltage sag generator is discussed in [1]. It has basically the same characteristics as the above mentioned full converter solution, but modulation algorithms are not as complex.

Nowadays the most common method for emulating grid faults is the shunt impedance based voltage sag generator. Thus this paper is focused on this device's influence on the dynamic performance of a PGU, which applies for both simulation and on-site tests. This setup is mostly referred to as LVRT test container and therefore, will also be called by that term henceforth.

Equipment testing standard

The main purpose of the IEC 61400-21 ed2.0 standard is to provide a uniform methodology to ensure consistency and accuracy in the presentation, testing and assessment of power quality characteristics of grid connected wind turbines. The standard provides, amongst other things, an LVRT testing procedure and test setup. Although the standard is addressing wind turbines, the methodology is widely accepted for PGUs other than wind turbines, as many papers and guidelines confirm. [3] Figure 2 shows the voltage sag generator given by the standard.

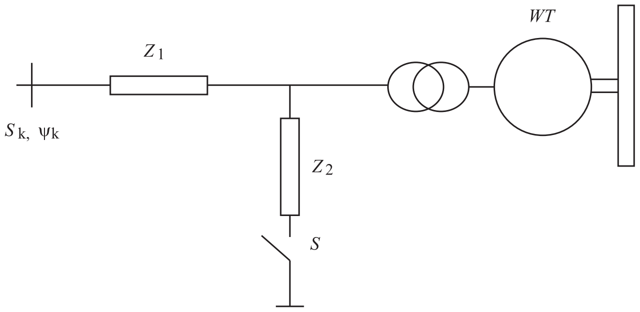

Figure 2 Short circuit emulator for wind turbine testing from IEC 61400-21 [3]

According to the standard the impedance Z_1 is for limiting the effect of the short circuit on the external grid. The size of the impedance should be selected, so that the testing procedure is not causing an unacceptable situation at the external grid and at the same time not significantly affecting the transient response of the wind turbine. A specific short circuit power is not given and may be agreed between the manufacturer, equipment test crew and utility. It has to be noted in the test report though. The voltage drop is created by connecting the impedance Z_2 by closing the switch S. The combination of Z_1 and Z_2 determines the remaining voltage during the dip. This value is defined for the PGU not connected, in order to eliminate the influence of the equipment under test. This way the same voltage dip test can be applied to different test objects without changing the settings of the test setup, unless there's a need for adapting the short circuit ratio. [3]

It has to be noted, that some grid codes and technical guidelines basically refer to the standard IEC 61400-21 ed2.0 [3], but defining differing test conditions. Mostly, the procedure is the same as outlined in the standard, but short circuit ratio, voltage dip profiles and tolerances might be defined independently. For example the technical guidelines for testing and validating the LVRT capability of PGUs by the FGW Germany [6] do not consider voltage levels at generator terminals after switching in the series impedance of the test container. It is only stated that the PGU should be able to operate permanently within a voltage range of 0.9 pu and 1.1 pu at the point of common connection (PCC) without disconnecting. [6, 7]

SIMULATION

A simulation model has been set up, using an EMT simulation method, which is in that case more appropriate than RMS methods [8]. Simulation results are going to show the influence of an LVRT test container on the dynamic performance of the PGU when facing a fault event. The simulation model of the synchronous machine including a voltage regulator and excitation system with all relevant limiters has been verified through measurements by an accredited certifier.

Simulation Setup

The configuration used for simulation is shown in Figure 3. It basically consists of a gas engine driven synchronous generator (data see Table 1), connected via cable to the low voltage side of the transformer (data see Table 2), which finally connects to the external MV grid via another cable.

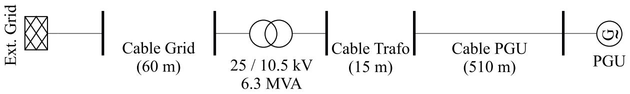

Figure 3 Grid setup for simulations

Table 1 Synchronous generator data

Parameter	Value	Unit
U_n	10.5	kV
S_n	2.492	MVA
H	0.8	MWs/MVA
xd	1.685	pu
xq	0.795	pu
xd'	0.180	pu
xd''	0.095	pu
xq''	0.129	pu
Td'	0.330	s
Td''	0.031	s
Tq''	0.025	s

Table 2 Transformer data

Parameter	Value	Unit
U_1	25	kV
U_2	10.5	kV
S_n	6.3	MVA
u_k	7.83	%
P_{fe}	27	kW
I_0	0.2	%

To achieve a worst case scenario for rotor angle excursions, the operating point of the synchronous machine is set to full load at *pf*=0.95 under-excited. In terms of the backswing phenomenon, an operating point at light machine loading with an over-excited power factor is the most severe one. Since the backswing is not the most demanding case for most setups, results for over-excited operating points are not shown here. The voltage dip was set according to ENTSO-E requirements [9] to a remaining voltage of 0.05 pu and a duration of 250 ms. The dip depth is adjusted by changing the value of the shunt impedance without the PGU connected. Following, three scenarios are defined to demonstrate the influence of the test equipment and choice of the fault location.

Scenario 1

Between the PGU and the transformer, a LVRT test container is introduced, as illustrated in Figure 4.

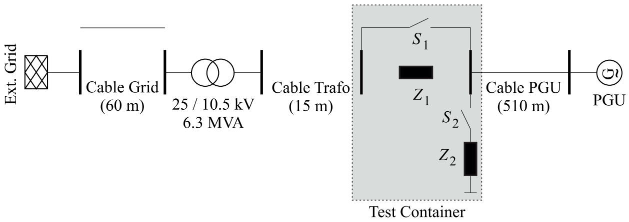

Figure 4 Test setup scenario 1

Short circuit power S_{SC}” of the supplying is fixed with S_{SC}”=263.1 MVA. As already mentioned before, the series impedance Z_1 of the test container is adjusted to achieve a certain short circuit power ratio at the generator terminals. In order to assure proper LVRT capability of the PGU in weak grids as well, short circuit power ratios are usually given by standards like in [10] in the range of S_{SC}”/P_r=3…5, with P_r being the rated power of the PGU. In this case a ratio of S_{SC}”/P_r=3.5 was chosen. This corresponds to a test container series impedance of 14 Ω (X/R=20). The series impedance Z_1 is already activated at the beginning of the simulation. The short circuit impedance Z_2 is set to 0.82 Ω (X/R=20).

Scenario 2

To compare the results with test container to a setup without test container, the short circuit power of the supplying grid has to be adjusted, to achieve the same short circuit power ratio at generator terminals. In this case this means reducing the short circuit power down to S_{SC}”=8.4 MVA. In Figure 5 the grid setup for this scenario is shown. As can be seen, the short circuit event is still created by switching an impedance for the desired fault time of 250 ms. In this case, the short circuit impedance has to be 0.76 Ω (X/R=20).

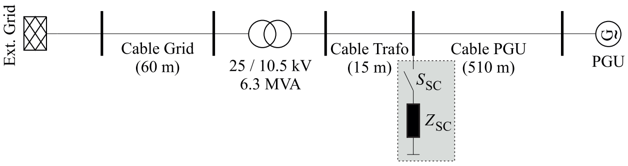

Figure 5 Test setup scenario 2

Scenario 3

Additionally a third scenario is defined. Same settings as defined in scenario 2 apply, only that the fault location has been changed from the PCC to the external grid busbar. With it the value of the short circuit impedance has to be changed as well, in order to achieve the same voltage dip depth at generator terminals. Now it has to have an impedance of 3.94 Ω (X/R=20). The grid setup for this scenario is shown in Figure 6.

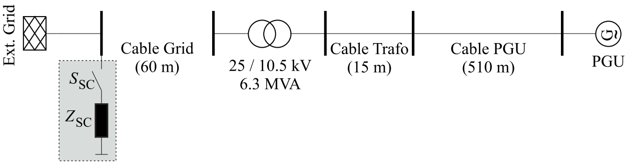

Figure 6 Test setup scenario 3

Simulation Results

The main difference between results with and without a test container lies in the fact that the series impedance of the test container, which in this case is quite big compared to grid impedances, causes a significant voltage drop. This is visualized in Figure 7, which shows the voltage profile along the network elements between the external grid and the PGU. In contrast, voltage drop between the external grid and the PGU is considerable low without a test container, which is shown in Figure 8. The voltage profile for scenario 3 is the same as for scenario 2.

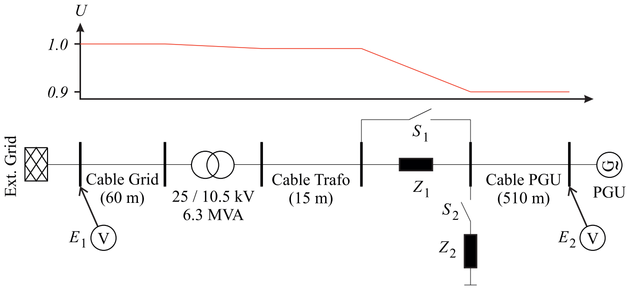

Figure 7 Voltages in test setup scenario 1

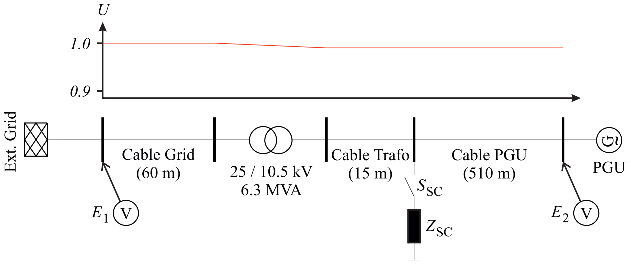

Figure 8 Voltages in test setup scenario 2

If one assumes same operating points in both scenarios, the stationary rotor angle in scenario 1 has to be higher due to the lower voltage E_2 at generator terminals, in order to achieve the same power flow P_{12}, given by

$$P_{12} = \frac{E_1 E_2}{Z_T} \cdot \sin\left(\vartheta_1 - \vartheta_2\right) \quad (1)$$

where Z_T is the total grid impedance, E_1 the external grid voltage, E_2 the PGU voltage, δ_1 the external grid reference angle and δ_2 the PGU rotor angle. Besides, in scenario 1 the retarding power in the first few cycles is not as big as in scenario 2. This is because the lower voltage at PGU terminals in scenario 1 causes a lower initial short circuit current. This effect of retardation is called backswing phenomenon. The backswing phenomenon describes the behavior of a synchronous generator in the first few milliseconds of the fault, where dissipated power is slightly increased, compared to the operating point prior to the fault. Therefore, the rotor is decelerated before being accelerated. Another disadvantage in scenario 1 presents the lower synchronizing torque due to the higher initial rotor angle.

Rotor angles of the three defined scenarios are shown in Figure 9. As can be seen the performance of the machine is different in those cases, although the same remaining voltage and the same short circuit power at generator terminals are defined.

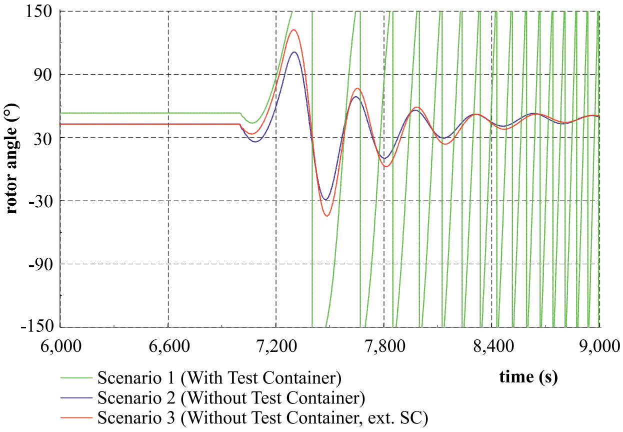

Figure 9 Rotor angle excursions for scenario 1, 2 and 3

CONCLUSION

It's been shown that an LVRT test container can have a significant influence on the dynamic performance of a PGU. Depending on the short circuit power of the grid the PGU is connected to, the influence of the container is more or less severe. Given a strong grid, where the short circuit power is high, the series impedance of the test container has to be set to a relatively high value, in order to achieve a certain low short circuit ratio at the PCC. Hence, the effect on the dynamic performance is more pronounced. On the other hand, if the short circuit power of the grid is already low, there's no need for a huge series impedance to significantly reduce the short circuit ratio and therefore, influence of the test container is lower. Although the IEC 61400-21 [3] states, that the series imedance should not affect the transient response at the terminals, no specific values or calculation methods are mentioned. As can be seen in Figure 9, the performance of the PGU is different in each scenario, although facing the same remaining voltage and short circuit power. Hence, using an LVRT test container might lead to an evaluation being too restrictive.

The method of setting the remaining voltage during a fault with the PGU disconnected has the disadvantage, that the actual remaining voltage with the PGU connected is on the one hand higher than set and on the other hand depeding on fault location and PGU operating point. Nonetheless, this is common practice and has the advantage that the voltage dip depth doesn't have to be adjusted for different scenarios or different machines. Besides, setting the actual remaining voltage during a fault event to a specific value can be quite challenging, because one has to take the dynamic behaviour of the PGU during a fault into account.

One simple solution to reduce the influence of an LVRT test container would be to adapt the tap changer positions of the transformer, in order to adjust the PGU terminal voltage. This way the results are very similar to the ones without a test container, assuming same fault event, short circuit ratio and generator terminal voltage prior to the fault event.

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