GRID INTEGRATION CONFORMITY TESTING PROCEDURES FOR VOLTAGE REGULATED DISTRIBUTION TRANSFORMERS (VRDT)

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ABSTRACT

The German distribution grids are penetrated by an increasing amount of distributed generators (DG). The compliance with the voltage limits requires further grid expansions. The voltage regulated distribution transformer (VRDT), as a new component for voltage regulation, must fulfil the grid code and interact with DG. Therefore, test procedures to investigate the grid conformity are needed to secure safe grid integration. Low-voltage-ride through (LVRT) is a test procedure for generators connected at medium-voltage (MV) level. This paper presents the results of LVRT test procedures for VRDT in combination with load and feed-in of DG.

INTRODUCTION

The German *Energiewende* includes a massive integration of DG, especially of photovoltaic (PV) modules, into the low and medium voltage (LV/ MV) grids. The uncoordinated connection is highly challenging to the voltage regulation of distribution grids. A reversal of the power flow can cause a violation of the upper limit of the voltage according to EN 50160. Besides conventional grid reinforcement, an alternative is the voltage regulated distribution transformer [1]. Furthermore, reactive power support by PV-inverters is requested in VDE AR-N 4105 [2]. The experience with these new components is limited to few research projects, yet. For a broad application, test series for critical grid situations are needed to secure a valid system behavior. Voltage dips and grid faults disturb customers and are difficult to be applied to new components in real grids. Thus, the investigation of current and future voltage control strategies for VRDT requires laboratory test procedures.

MOTIVATION

VRDT as voltage controller for public LV-grids have to be integrated into grids already in existence. Thereby, grid operators need a high reliability and predictable behavior in order to secure functional and safe operation. Voltage dips caused by self-extinguishing faults leads to pre-fault conditions [3]. Thus, a switching of the VRDT in case of a short voltage dip is not desirable. The VRDT controller contains an integrated under-voltage blocking function. LVRT is a test procedure for generators and is stipulated in several national grid codes. As a VRDT connects grids containing DG, a VRDT must fulfil the same requirements. Until now, VRDT are not part of the standardization as unit, but as components (distribution transformer, on-load tap changer (OLTC). Thus, this paper firstly introduces a methodology for testing VRDT in a test environment, consisting of real cables, DG, load and VRDT itself. The goal is to investigate the grid conformity of VRDT in case of voltage dips.

VOLTAGE CONTROLLER

Voltage controllers in distribution grids can be distinguished by their position inside the grid and by their owners. Central controllers (e.g. inside substations) are usually owned by grid operators. Regulated HV/MV- transformers with OLTC regulate the medium-voltage, depending on the loading or generation. Decentralized voltage controllers are pre-dominantly used by customers in combination with generators (e.g. wind turbine, PV). The focus of this paper is the VRDT as part of the grid and all its relevant components. Hence, in the following the VRDT and inverters are introduced.

Voltage regulated distribution transformer

The VRDT consists of a standard distribution transformer with an OLTC at the MV-side and a controller unit for an activation of the OLTC. Hence, the voltage ratio can be changed by switching the OLTC stepwise according to the additional regulating windings of the transformer.

A voltage controller is required in any kind of VRDT in order to keep the voltage within predefined tolerable limits and to initiate the required switching actions of the OLTC. Busbar voltage control is most commonly used for available VRDT and is also implemented in the controller of the device under test (DUT), which is described here. The controller compares the voltage at the busbar on the LV-side of the transformer to a specified tolerance band, which is typically set to have total range of about 1.2 … 2 times the size of the step voltage of the OLTC ($1.2\ V_{step} \leq 2\ V_B \leq 2\ V_{step}$).

A delay time T_d is introduced in order to prevent unnecessary switching actions close to the limits of the

tolerance band and therefore to reduce the total number of switching actions. If the voltage exceeds the limits of the tolerance band for the duration of T_d, the controller activates a switching command to the OLTC. Thus, the voltage ratio of the transformer is changed and the voltage returns to a value between the given limits.
Sudden and large changes of the voltage will be detected by the voltage controller and immediate switching actions will be initiated if the voltage exceeds the limits of $V_n - V_{B,fast} \leq V_n \leq V_n + V_{B,fast}$. Figure 1 illustrates the voltage regulation.

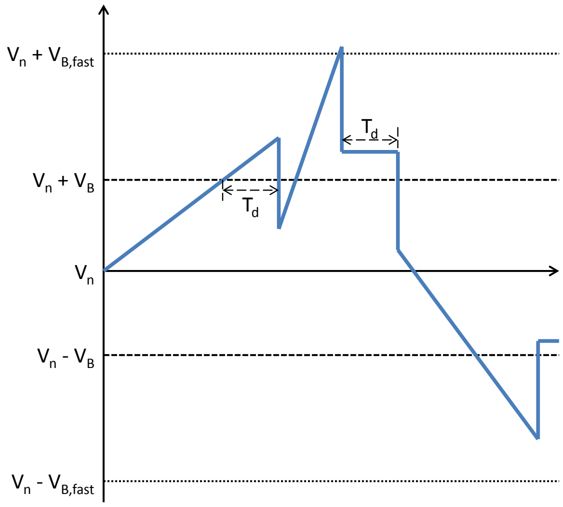

Figure 1 – Voltage regulation of VRDT controller

Finally, voltage controllers are usually equipped with under-voltage blocking, preventing the OLTC from stepping up the voltage in case of unusual voltage drops in the super-ordinated voltage levels.
The FGH Certification Office certified the DUT as a component in December 2013 according to the test reference *Z 417*. Thereby, several type-tests for transformer, OLTC and controller are fulfilled [4].

<u>Inverters</u>

Power electronic inverters are normally used to connect solar panels and other DG. Reactive power support is requested as a contribution to the static voltage control, in VDE AR-N 4105 [2]. The voltage V_{PCC} at the point of common coupling (PCC) depends on the feed-in of active and reactive power of the DG. Hence, the voltage can be controlled by reactive power feed-in at the PCC [2]. Different control schemes for reactive power are in use, a minimal cos φ is defined by the grid operator inside the limits of table 1.

S_{DG} [kVA]	cos $\varphi_{underexcited}$		cos $\varphi_{overexcited}$
≤13.8	0.95≤	cos φ	≥0.95
>13.8	0.90≤	cos φ	≥0.90

Table 1 – Parameter cos φ [2]

The standard for reactive power control follows a characteristic cos φ(P) static, cos φ=1 for $P < 0.5 \cdot P_{max}$ and for $0.5 \cdot P_{max} \leq P \leq P_{max}$ cos φ is calculated by:

$$\cos\varphi(P) = 1 + \cos\varphi_{min} - \frac{1 - \cos\varphi_{min}}{0.5 \cdot P_{max}} \cdot P \qquad (1)$$

As a disadvantage of this method, the reactive power is independent of the actual voltage V_{PCC}. Another control scheme is the voltage dependent reactive power control Q(V). The Q(V) control can be defined by a linear characteristic, the curve used within the test setup is shown in Figure 2.

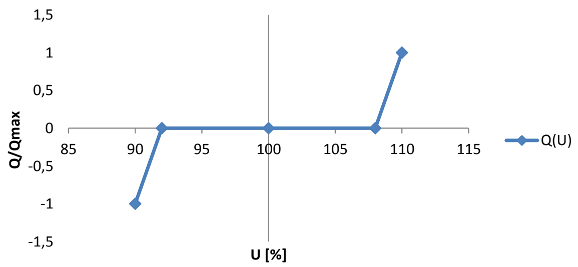

Figure 2 – Q(V)-curve for test setup

TEST SETUP

The Center for Grid Integration and Storage Technologies of RWTH Aachen University operates a 10 kV medium-voltage grid (200 MVA short-circuit power, open or closed ring structure). Different MV/LV substations and a configurable LV-grid with a total line length of more than 2000 m (150 and 35 mm² NAYY) can be connected to the MV grid. Different loads and inverters fed by 16 DC-sources (total power of 150 kW) can be installed at various positions within the LV-grid.
In order to investigate the behavior of the VRDT under real load and grid fault conditions, the DUT is connected to the public 10 kV-grid via an LVRT test system feeding different inverters and a high power load on the LV side. The test setup is shown in Figure 3, the measurement positions are marked with V_{MV}, V_{LV} and V_{PCC}.

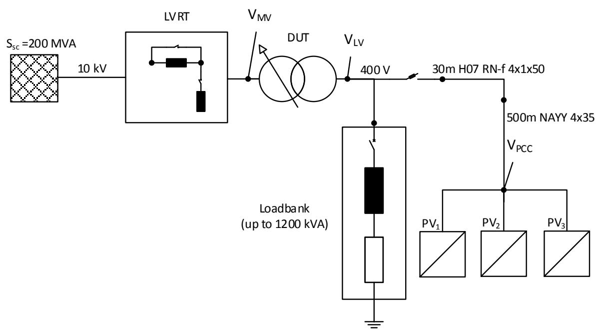

Figure 3 – Test setup

The LVRT test system generates voltage dips (0.92 to 0 p.u.) at the MV-side of a DUT (generators up to 4 MW). An inductive voltage divider, defined by Xsr and Xsc, obtains the required voltage dip. The series inductance Xsr reduces the short circuit current and

hence the voltage reduction in the public grid. Figure 4 shows the principle.
The isolator switch IS enables three-phase and two-phase dips by disconnecting of phase 2 from the short circuit. The switching of circuit breaker CB_2 defines the start time and the duration of the voltage dip [5].

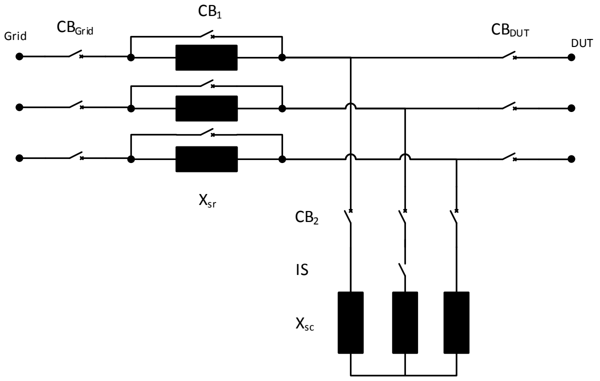

Figure 4 – LVRT test system

A cable (500 m NAYY 4x35SE) connects three three-phase PV-inverters (2x10 kVA, 1x30 kVA) to the VRDT. A programmable load is connected directly to the VRDT. Different heating resistors and inductances are switched independently to obtain a load in steps of 0.8 kW and 0.6 kVAr. The maximum power consumption is 1200 kVA (3x320 kW and 3x240 kVAr).
Three different high-resolution measurement devices (sampling rate up to 100 kHz) enable for the analysis of the tests. On the LV-side, one DEWE-571 is installed at the busbar of the DUT (V_{LV}), one at the grid connection of the inverters in parallel (V_{PCC}). Inside the LVRT test system, a DEWE-800 measurement device monitors voltage and current of the grid, of the DUT (V_{MV}) and of X_{sc}.
The DUT is a 400 kVA 10/0.4 kV Dy5 transformer, with a short-circuit voltage of 3.7 % and no-load losses of 641 W. Hence, the series impedance (400 V) is (4.34+j 15) mΩ. The OLTC of the DUT follows the reactor principle and regulates the voltage in +/-4 steps of 2.5 % each. Parameters given by the manufacturer are shown in Table 2.

Parameter	Value
Voltage set point [V]	230
Bandwidth [%]	2.5
Delay time T_d [s]	10
Under-voltage blocking [% of voltage set point]	80

Table 2 – Parameter VRDT controller

The transformer LV-busbar feeds the voltage controller unit of the VRDT. Hence, the LVRT test stresses the VRDT controller as well. A data connection of a control system to the VRDT controller reads out tap position and busbar voltages at the VRDT every second. Errors and interruptions of the data connection are an indicator for the malfunction of the VRDT controller.

TEST CASES

Technical guidelines and standards for DG in Germany and Europe define requirements for the grid integration. The requirements depend on the maximum power capacity and the related voltage level for the grid connection of the DG. Fault-ride-through (FRT) capability in Continental Europe is requested for DG with an installed capacity of more than 1 MW [6]. In Germany, FRT is standard for DG directly connected to the MV-grid or higher voltage levels [7]. DG connected to an LV-grid shall disconnect in case of voltage dips below 80 % nominal voltage within 200 ms, a dynamic grid support is not requested yet [2]. Equipment and installations must have immunity for defined voltage dips and interruptions, testing techniques for LV-components are given in [8].
Since the application of VRDT includes grids with high DG penetration, they must fulfil at least the same standards to operate safely. Although an FRT-capability for LV-connected DG is not requested by now, it is discussed as a future challenge [9].
Therefore, three different residual voltage levels are chosen as test cases for LVRT. 0.85 p.u is a basis scenario to prove the functionality of the VRDT (Dip No.1). The residual voltage of 0.73 p.u. for Dip No.2 is below the level of the under-voltage blocking. The automatic disconnection of the PV-inverters is tested by a minimum voltage of 0.05 p.u. (Dip No.3). Furthermore, the VRDT controller unit is tested in parallel to validate its immunity against voltage dips.
The timing of CB_2 is according to the standards and additionally set to 15 s in order to exceed T_D (10 s). CB_1 is opened 5 s before the voltage dip and is closed 5 s after it. All test scenarios are performed three-phase as well as two-phase. The transformer connection type Dy5 causes a phase shift in case of two-phase dips. On the LV-side, a two-phase dip transforms to a one-phase dip with voltage depending angles between the line voltages [10]. The depth and duration of the voltage dips are shown in table 3.

No.	depth [%]	duration [ms]
1	85	2000
		5000
		15000
2	73	1400
		5000
		15000
3	5	100
		150

Table 3 – Parameter LVRT tests

In order to secure a functional behavior for any kind of load situation, three different load scenarios are investigated. Firstly, a no-load test enables the verification of the test settings and a test of the VRDT as a component (scenario 1). Within scenario 2, the loadbank reduces the busbar voltage by drawing a constant load of 240 kVA and a power factor (PF) of 0.9_{ind}. Hence, the controller activates a switching of the VRDT. For customer installations, a minimal tolerable PF of 0.9 is defined [11]. In scenario 3 the VRDT is tested in combination with feed-in of DG and a reversal of the power flow in the grid. A long cable (500 m) connects three PV-inverters. Thereby, a total active power of 40 kW increase the voltage at the PCC to 1.095 p.u. PV_1 and PV_2 are two standard inverters with constant cos(φ) control. PV_3 uses a Q(V)-control in this setup. The parameters are shown in Table 4.

PV	P_{DC} [kW]	S_{max} [kVA]	PF
1	10	10	0.95
2	10	10	0.95
3	20	30	Q(V)

Table 4 – Parameter PV-inverter

The parameters of the Q(V)-curve of PV_3, are shown in Figure 2. The reactive power support starts above 1.08 and below 0.92 p.u. The maximum reactive power Q_{max} of the inverter is given by:

$$Q_{max} = sin(\varphi_{max}) \cdot S_{max} \approx 13\ kVA \qquad (2)$$

MAIN RESULTS

In total, 48 different voltage dips are applied to the VRDT and its controller. Figure 6 shows the 0.85 p.u./15000 ms/2ph dip with all voltages (200 ms average of periodic values) of the VRDT. The upper plot represents the neutral-earth voltage of the VRDT on the MV-side (unit 10 kV/$\sqrt{3}$), whereas the lower plot shows the equivalent voltages on the LV-side (unit 230 V).

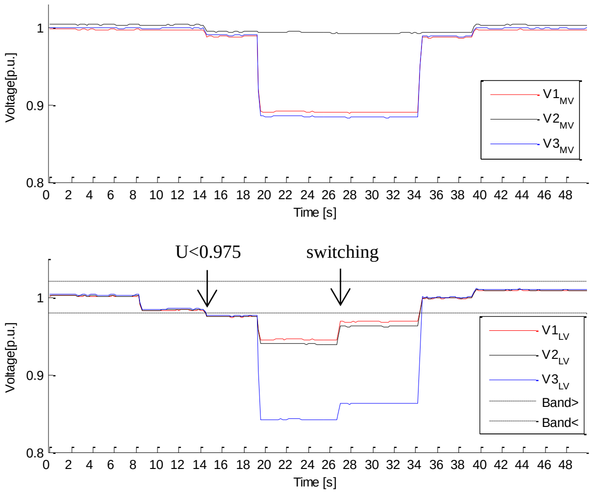

Figure 6 – 0.85 p.u./15000 ms/2ph, scenario 2

The load is switched on at 8 s, at 14 s CB_1 opens and the voltage reduces across the series inductance of the LVRT test system. Now the voltage exceeds the lower limit of the tolerance band and the timer of 10 s duration starts. During the dip in phase 1 and 3 from 19 to 34 s, the VRDT switches at 27 s to $V1_{LV}$=0.967 p.u.. Hence, the total delay of 12 s contains 10 s T_D and 2 s additional for the external switching process (drive, controller). Finally, the voltage $V1_{LV}$=1.01 p.u. is inside the bandwidth of the controller. The VRDT switches as expected, no anomalies occur. Hence, the VRDT operates normally in case of high load.

Figure 7 shows the result for the 0.73/15000 ms/3ph dip. The feed-in of 40 kW raises the voltage at PCC of the inverters to $V1_{PCC}$ =1.095 p.u.. The Q(V)-regulation sets the total PF to 0.9_{ind}. The grid and busbar voltages are about 1.0 p.u.. As the voltage drops, the total PF rises to 1 within 5 s and drops back to 0.9 p.u. again within 5 s after the voltage recovers.

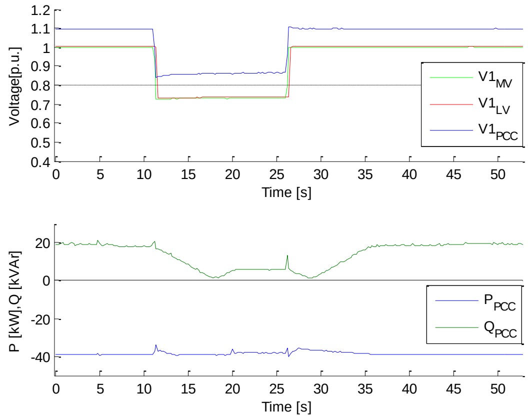

Figure 7 – 0.73 p.u./15000 ms/3ph, scenario 3

During the voltage dip, the delay time T_d is reached, but the VRDT holds the tap position. Thus, the requirement for under-voltage blocking of the VRDT is satisfied. Furthermore, the Q(V)-regulation supports the voltage in the grid by reducing the consumption of reactive power.

In case of the dip 0.05 p.u./100 ms/3ph, the automatic disconnection of each PV-inverter is activated. Figure 8 shows the single-phase voltages.

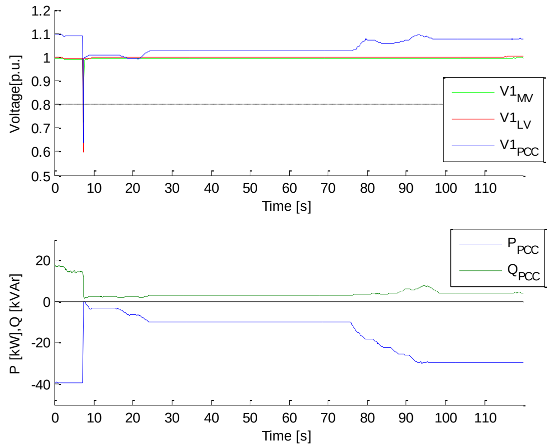

Figure 8 – 0.05 p.u./100 ms/3ph, scenario 3

After the voltage dip, all inverters decrease their active power feed-in. Furthermore, the reactive power consumption is at its minimum. The recovery of PV_1 to the maximum power of 10 kW takes 15 s, whereas PV_3 needs 67 s to restart. PV_2 causes an overvoltage error on the DC-side and an interruption of the DC-source. The characteristics of the inverter PV_2 must be investigated further, in order to secure a valid laboratory simulation.
Figure 9 shows a high resolution diagram of voltages and currents at the PCC of the inverters for the 0.05/150 ms/2ph dip.

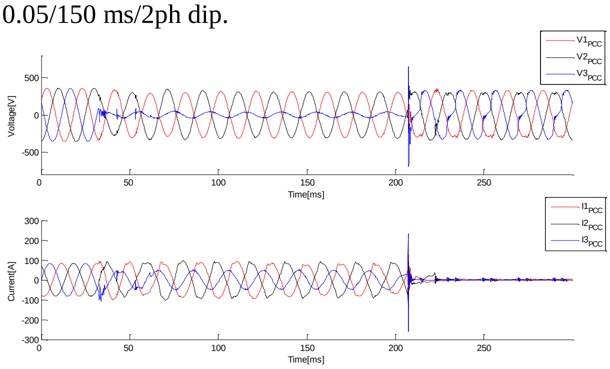

Figure 9 – 0.05 p.u./150 ms/2ph, scenario 3

The voltage dip starts at 34 ms and ends at 207 ms. During the dip, all inverters stay connected. Thereby, a high current (260 A) and a voltage peak (650 V) in phase 3 is measured. All inverters simultaneously disconnect within 175 ms. Hence, the inverters feed-in a fault current and disconnect when the voltage recovers. Thus, a more specific voltage/time characteristic is needed, to reduce an unnecessary disconnection of DG in LV-grids.

CONCLUSION AND OUTLOOK

The tests showed that the VRDT fulfills the requirements for DG in case of voltage dips. In every test scenario, the VRDT functions without interruption, no malfunction or unintended switching occurs during the operation. Furthermore, the data-connection to the VRDT controller remains. Thus, the VRDT reacts immune to the applied dips. The voltage V_{PCC} at the PV-inverters in the test setup is up to 1.1 p.u., but it does not lead to a switching of the VRDT. The integration of additional measurement positions (e.g. at the end of the line) into the control of the VRDT could indicate the increased voltage and start a switching. This application of the VRDT must be tested separately in order to investigate the characteristics of the VRDT controller in case of communication failures of an external sensor or in case of switching operations by the grid operator. The PV-inverters interrupt the feed-in after the short (100 ms and 150 ms) dips to 0.05 p.u.. Although this is required, in case of a massive integration of DG in LV-grids, a huge power loss after an overlaying voltage dip is possible.

First insights into the system performance of VRDT and DG have been obtained. However, further investigations are needed to investigate the voltage control of LV-grids. Thereby, the investigation of innovative algorithms for VRDT controllers in combination with additional sensors is of interest. Furthermore, the parameterization of controllers for VRDT and DG has to be researched.

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