IMPACT OF SYNCHRONOUS AND DISTRIBUTED GENERATION UNIT CHARACTERISTICS ONTO THE STABLE OPERATION OF LOW VOLTAGE ISLANDED MICROGRIDS

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ABSTRACT

In the event of an interruption of supply or a blackout the increasing number of distributed generation in the distribution grid level offers the possibility for temporary islanded microgrid operation. Due to low inertia and a high number of individually controlled distributed generation units, contingencies in the power balance may lead to unstable grid conditions. To be able to assure the stable operation of islanded microgrids, the limiting factors of synchronous and distributed generation units and their individual parameterization need to be identified.

In this paper, the impact of synchronous and distributed generation unit characteristics in low voltage islanded microgrids is evaluated focussing on the influence of the frequency dependent active power reduction of photovoltaic converters. In an experimental and simulative way the impact of e.g. the installed active power of photovoltaic converters with different active power reduction parameterizations is evaluated.

On basis of the conducted investigations, oversizing the grid-forming synchronous generators or increasing the settling time of the frequency dependent active power reduction of photovoltaic converters leads to a stable islanded microgrid operation.

INTRODUCTION

Due to the increased penetration level of distributed generation (DG) units, in Germany especially in low (LV) and medium voltage (MV) levels, the generation may exceed the consumption locally [1]. In addition, the prices for photovoltaics and battery cells are continuously decreasing [1], which may lead to a sustainable further increase of inverter-interfaced DG (IIDG) units connected to the distribution grid level. In case of an interruption of supply or a blackout, all these developments offer the opportunity for a temporary islanded microgrid (IM) operation in the distribution grid level. DG units with grid-forming (GF) capability, e.g. a synchronous generator in a combined heat and power plant (CHP), are able to contribute to the grid restoration process [2].

In this paper, an exemplary synchronous generator is considered as GF unit for a stable IM operation. With the increase of IIDG units in LV and MV levels, the inertia of the grid decreases – especially in islanded microgrids (IMs). Therefore, changes in the power balance of the IM lead to larger frequency deviations in comparison to parallel grid operation. Because of the German grid code, IIDG units are obliged to adjust their active power infeed in case of frequency deviations. This frequency dependent active power reduction (FDAPR) may influence the grid frequency after contingency, e.g. active power changes [2], [3].

Currently there are no standards for the FDAPR in CHP-formed IMs, neither how these IMs should be structured to ensure a stable operation.

Within the project ENSURE the temporary operation of IMs in the distribution grid level is investigated, analyzed and necessary criteria for a stable operation are derived. Therefore, this paper addresses the determination of grid portfolio characteristics for a stable operation of IMs formed by GF SGs. This takes into account the impact of FDAPR controls of present DG units onto the stability in the IM – both experimental and simulative. First, an IM is set up at the testing center of the institute for High Voltage Technology at RWTH Aachen University. The impact of the FDAPR according to the German BDEW grid codes (in the following type 1) [4] is investigated depending on various occurring active power changes in the IM. In addition, the adjustment of the low voltage grid codes (in the following type 2) is implemented in the models and compared with the former BDEW grid codes regarding FDAPR [5]. Finally, a sensitivity analysis is performed in order to evaluate synchronous and distributed generation (SDG) characteristics in IMs.

LABORATORY COMPONENTS AND SETUP

The majority of DG units are connected to the low voltage level. Inverter-interfaced Photovoltaic (PV) converters, CHP and consumer loads can be connected physically to an LV IM at the testing center. To evaluate the impact of SDG characteristics in IMs, a SG, two PV converters and a resistive load are utilized. Via a laboratory control a communication link is established to all assets. E.g. certain set points for active and reactive power infeed and demand for PV converters and loads can be specified.

Laboratory setup and control

For the analysis of the impact of SDG characteristics onto the stable operation of IMs the structure in Fig.1 is used. The directly coupled SG in a CHP test bench is connected

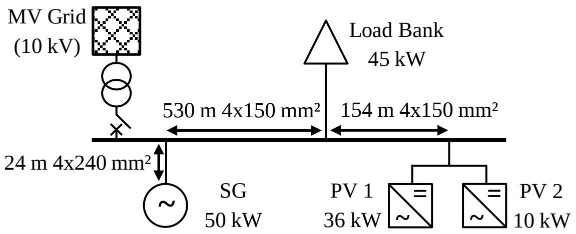

***Figure 1:** Laboratory setup for analysis of SDG characteristics*

to a bus bar via a 24 m 240 mm² aluminum cable. Via a 530 m 150 mm² aluminum cable an ohmic-inductive load bank is connected to the bus bar. In addition, two PV converters are connected via a 154 m 150 mm² aluminum cable to the bus bar. When operating the circuit breaker towards the LV/MV transformer in open position, the grid topology is operated in islanded mode.

CHP test bench

As grid-forming unit a directly coupled SG in a CHP test bench is used [6]. Although, the rated power of the SG is 105 kVA, the test bench operates with a maximum rated active power of 50 kW. The prime mover of the CHP test stand is an electrical drive machine. This machine can emulate the behavior of various prime movers (e.g. combustion engines). For the used setup an existing governor model is used and a commercial automatic voltage regulator is installed [3].

Inverter-interfaced PV converters

The IIDG units are represented by two grid-following PV converters with a maximum active power output of 36 kW (PV 1) and 10 kW (PV 2), respectively. The power factor of the PV converters can be chosen between 1 and 0.85 (PV 1) and between 1 and 0.75 inductive, respectively. Both PV converters are supplied by DC power sources to be able to perform experiments independently from solar irradiation. The PV converters are set to follow the German BDEW MV grid codes to be able to provide ancillary services such as FDAPR (type 1) [4]. At present in Germany new LV the grid codes oblige DG units to provide FDAPR (type 2) as well and their specific behavior is customized [5].

Load

The electrical loads at LV level are represented by a switchable three-phase ohmic-inductive load bank. Per phase a maximum of 15 kW of active power (45 kW in total) and 5.7 kVar inductive reactive power (17.1 kVar in total) can be set. The maximum load can be switched in 15 linear steps, resulting in 1 kW and 0.38 kVar steps.

Laboratory experiment and results

For the evaluation of the impact of SDG characteristics onto the stable operation of IMs ohmic load steps are performed. Special focus is given to the influence of PV converters with FDAPR. The SG in the CHP test bench is used as grid-forming unit. The PV converters are parameterized according to the former MV grid code with FDAPR type 1 [4]. Only an ohmic load is used and 45 kW is applied to the grid. The active power output of the two PV converters is set to 38 kW. A load step of -3 kW, from 45 kW to 42 kW, is performed after 3.2 s (Fig. 2).

Due to the reduction of the ohmic load, the frequency increases above 50.2 Hz. As a result, the PV converters reduce their active power output according to FDAPR type 1. Because of the slow speed control and initially missing mechanical power of the SG, the SG reacts with a delayed increase of active power output. At this point, the frequency has already fallen below 50 Hz again, so that the PV converters increase their active power output to nominal power. The resulting active power input from SG and PV converters leads to an increase in frequency above 50.2 Hz, whereby the reduction of the active power output from the PV converters starts again from the beginning.

The reference active power output of the PV converters which is used for the determination of the amount of active power reduction is identified at that point when 50.2 Hz is exceeded. Since the PV converters do not have reached their nominal active power when the frequency exceeds 50.2 Hz again, the reference active power output is reduced in comparison with the previous excess of 50.2 Hz. The interaction of the speed control of the SG and the power reduction of the PV converters impairs a stable IM operation. Small load changes (here 3 kW) may lead to an unstable grid situation. In order to be able to avoid such grid states in IMs, time domain simulation models are extended and compared with the laboratory results with regards to the FDAPR type 2. The prior goal is the identification if the observed interactions in the laboratory setup can be replicated in simulation.

MODELLING APPROACH

As a next step, the impact of the new LV grid codes, including an adjusted FDAPR behavior of DG units is modelled. In addition, the former specification of the FDAPR type 1 investigated in the laboratory setup is compared with the FDAPR type 2. Therefore, the dynamic behavior of the SG, PV converters and load is modelled. In order to ensure comparability of the results of the laboratory setup and the simulations, the modelling of the SG and load is comparable to the dynamic behavior of the laboratory setup. Also the equal grid topology is used. The time domain simulations are carried out in the sym metric RMS time domain simulation environment "MatPAT with an implicit-explicit solver [7].

Synchronous generator (SG)

The used model for the SG bases on the fundamental machine equations, which include stator and rotor voltage equations as well as the related flux equations [7]. Preliminary investigations showed that a 4^{th} order model is sufficient for implementation. In addition, the used generic excitation system IEEE DC1A model showed an appropriate dynamic behavior. For the modelling of the governor a simplified steam turbine governor is used [8].

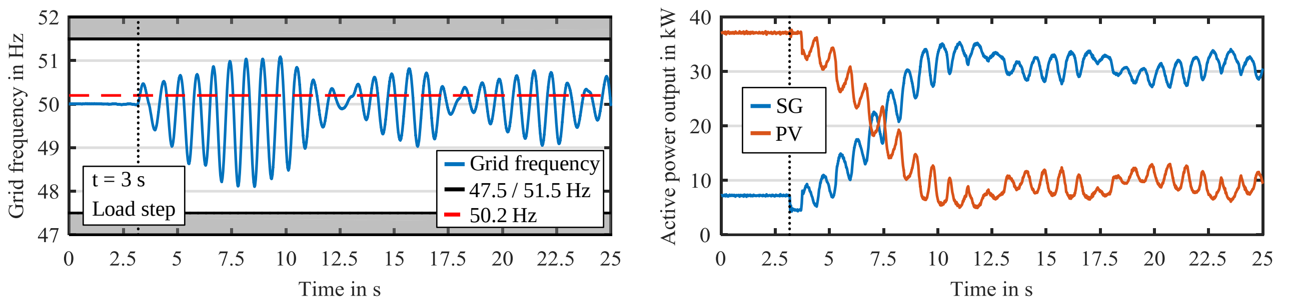

Figure 2: *Grid frequency (left) and active power output (right) of synchronous generator and photovoltaic converters at load step of -3 kW (after 3.2 seconds) with FDAPR type 1*

Modelling of IIDG PV converters

On the DC side the modelling of the PV converters is represented by a current source. Depending on the available power due to maximum power point tracking the DC current fed into the grid is determined. Via additional controls, voltage and current control, the output AC current fed into the grid is controlled. In order to cope for the FDAPR control type 2 an additional control is implemented. Fig. 3a depicts the used control structure.

Modelling of FDAPR type 2: VDE 4105

Due to the new German grid codes for DG units connected to LV level, a FDAPR is implemented [5]. The FDAPR leads to a power reduction above 50.2 Hz according to the following equations:

$$\Delta P = 20\ P_{ref} * \frac{50.2\ Hz - f}{50\ Hz} \qquad (1)$$

$$with\ 50.2\ Hz \leq f \leq 51.5 Hz \qquad (2)$$

where ΔP describes the reduction of the active power output depending on the active power output P_{ref}, when the grid frequency f exceeds 50.2 Hz. Since the PV converters are forced to feed in their maximum active power to the grid, only the active power reduction is considered. In the range from 49.8 and 50.2 Hz no adjustment of the active power output takes place. In order to cope for the internal processing of the phase locked-loop (PLL) to determine the change in frequency and the calculation of the necessary power reduction a dead time T_{dead} is implemented in the FDAPR. Moreover, a delay time T_{delay} is implemented so that the rate of change of active power output can be varied. The corresponding control structure can be seen in Fig. 3b.

The voltage control is modelled as ideal PI controller and adjusts the current reference values depending on the chosen target. In this case, the active power output and the AC voltage are controlled. E.g. if the active power output deviates from the active power output set point adjusted by the FDAPR control, the reference value of the active current I_d^{ref} is customized according to the PI control characteristics. In the next step, the adjusted refer ence current values are forwarded to the current control. The current control regulates the AC current fed into the grid. The current control is represented by first-order lag blocks [9].

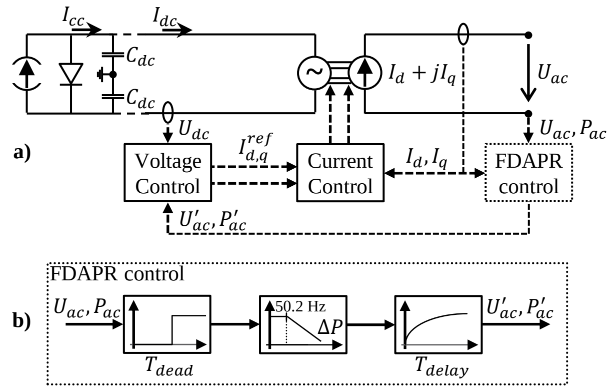

Figure 3: *Control structure of PV converter with FDAPR*

Load

For the representation of the load bank the ZIP load model is used. Since the load bank is a constant impedance load in the simulation, a constant impedance load is modelled. The corresponding equations can be found in [8].

Grid Model

The resistance, reactance and susceptance of the LV lines are modelled via the standard pi equivalent circuit model. This way, a constant admittance matrix is constructed, which allows a continuous calculation of the power flows during the dynamic simulation. The results of a prior power flow calculation serve as initial operating point and input for the dynamic simulation.

Comparison of dynamic behavior

The simulation results for grid frequency and active power output, when simulating equal conditions as established in the laboratory setup, but with the utilization of the FDAPR type 2 (see Fig. 1), are shown in Fig. 4.

Again a load step from 45 kW to 42 kW after 3.2 s is performed. The values for T_{dead} and T_{delay} are set to 0.43 and 0.05 s, respectively, which have been derived from the laboratory results of FDAPR type 1. The active power output of both PV converters is 38 kW. Therefore, the grid-forming SG has to supply 4 kW to the IM, when the load is reduced to 42 kW. Analogous to the laboratory experiment the results of the simulation show interactions between the SG and the PV converters caused by the load step. In comparison to the laboratory results, the frequency exceeds the frequency limits 47.5 Hz and 51.5 Hz for

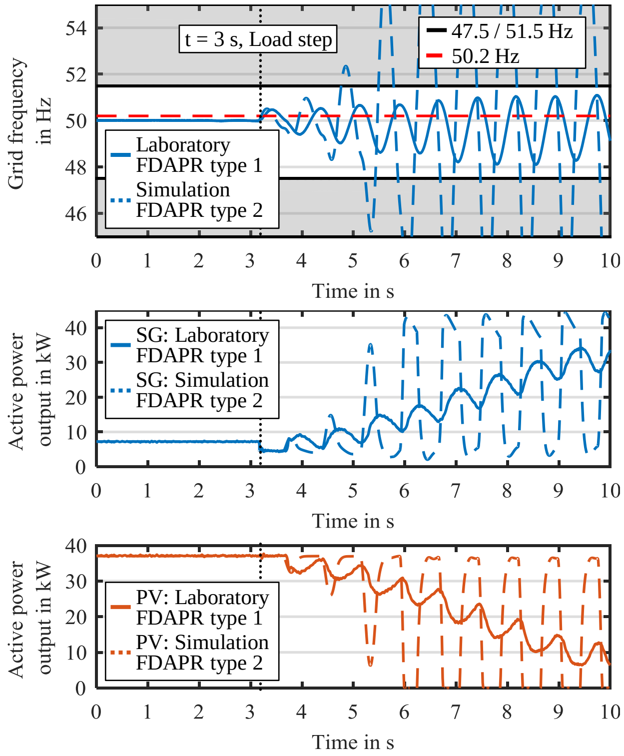

Figure 4: *Comparison of grid frequency (top), active power output of synchronous generator (center) and PV converters (bottom) at load step of -3 kW (after 3.2 seconds) with FDAPR type 1 (laboratory) and type 2 (simulation)*

normal operation after 4.8 seconds. The FDAPR type 1 increases its active power output to nominal active power when the frequency is lower than 50.05 Hz. Like this an "artificial" time delay is included in the FDAPR type 1. Since FDAPR type 2 adjusts its active power output when the frequency changes above 50.2 Hz, no additional "artificial" time delay is included. Due to the increase of the frequency above 51.5 Hz all DG units would disconnect from the grid, when using FDAPR type 2. For the simulation no disconnection of the DG units due to frequencies higher than 51.5 Hz or lower than 47.5 Hz is considered. Like this it can be observed whether the interactions remain or terminate. The simulation results show that FDAPR type 2 would lead to a disconnection and there with a loss of active power from DG units. This instant loss would lead to even larger frequency deviations, in this case caused by the loss of 38 kW of active power. In comparison to FDAPR type 1, type 2 causes stronger deviations from nominal grid frequency. DG units would disconnect from the IM, which could lead to a shutdown of the IM. Since the simulated setup represents an exemplary grid situation, further simulations have been conducted in order to evaluate certain limits for the operation of LV IMs in case of GF SGs.

COMPONENT CHARACTERISTICS

For the evaluation of a stable IM operation with an SG in GF control three study cases are further investigated:

- Case 1: Impact of the load step depending on the nominal apparent power of the GF SG
- Case 2: The impact of installed active power of the PV converters depending on the nominal apparent power of the GF SG
- Case 3: The influence of time constants T_{dead} and T_{delay}

When the frequency in the IM exceeds the frequency limits 47.5 and 51.5 Hz, no stable operation of the IM is assumed in the following investigations [10]. Therefore, when the IM can be operated between 47.5 and 51.5 Hz, normal operation is given, which is highlighted in the following figures by a black dot and by a red dot, when the frequency exceeds the mentioned limits. The same setup as in Fig. 1 is used for all study cases and the varied parameters for the three study cases are shown in table 1. For the scaling of the nominal apparent power of the SG different SGs and the corresponding dynamic parameters are used [11].

Study case 1: Load step and nominal apparent power of SG

In Fig. 5a the variation of the load step and the nominal apparent power of the GF SG is shown. For small load steps $\Delta P_{load\ step}$ below 1.5 kW no impact on the stable operation of the IM can be observed. Moreover, in case of the investigated setups, a stable operation of the IM can be ensured when the nominal apparent power S_{nom} of the grid-forming SG follows this equation:

$$S_{nom} > 96 * \Delta P_{load\ step} + 70\ kVA \quad (3)$$

$$with\ \Delta P_{load\ step} > 1.5\ kW \quad (4)$$

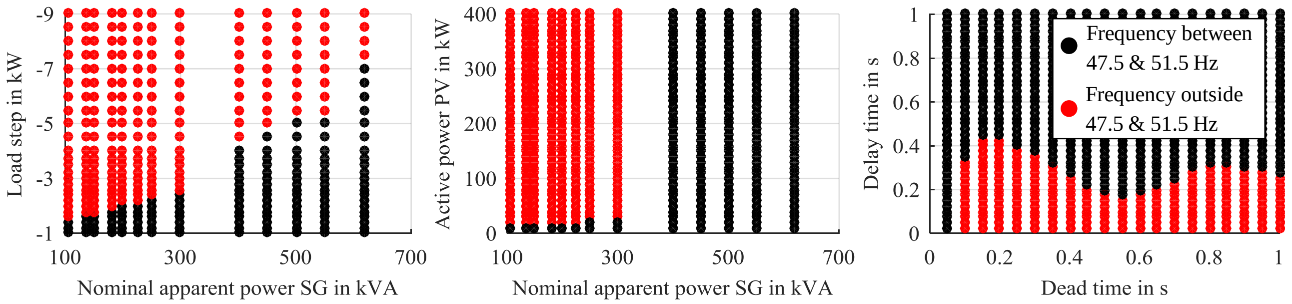

Figure 5: *Illustration of the variation of parameters:* ***left)*** *Load Step and Nominal Apparent Power of SG,* ***center)*** *Installed Active Power PV Converters and Nominal Apparent Power of SG and* ***right)*** *Influence of Time Constants* T_{dead} *and* T_{delay}

Table 1: *Varied parameters of the investigated study cases*

Parameters	**Study case 1**	**Study case 2**	**Study case 3**
Load step	-1 to -9 kW	-3 kW	-3 kW
Nominal apparent power SG	105 – 620 kVA	105 – 620 kVA	105 kVA
Installed active power PV	50 kW	10 – 400 kW	50 kW
Base load	50 kW	10 – 400 kW	50 kW
T_{dead}	0.43 s	0.43 s	0.05 – 1 s
T_{delay}	0.05 s	0.05 s	0.025 – 1 s

Study case 2: Installed active power PV converters vs. nominal apparent power of SG

In Fig. 5b the variation of the installed active power the PV converters and the nominal apparent power of the GF SG is displayed. The results show the share of active power fed into the grid by PV converters has a comparably small influence on the stable operation of the IM. If the nominal apparent power of the SG is larger than 400 kVA a stable IM operation is ensured because load steps of 3 kW lead to comparable small deviations in grid frequency when using SGs with higher nominal power.

Study Case 3: Influence of Time Constants

In Fig. 5c the variation of the time constants T_{dead} and T_{delay} of the FDAPR type 2 is illustrated. As long as T_{delay} is larger than 0.4 s a stable operation of the IM is ensured. Since larger T_{delay} result in smaller changes of the active power output of the PV converter, the SG is able to compensate this power imbalance without large frequency deviations. The influence of T_{dead} is negligible since a beneficial operation is reached only in the case when T_{dead} is equal to zero.

CONCLUSION & OUTLOOK

The impact of SDG characteristics with special focus on the FDAPR control of PV converters in LV IMs have been presented and evaluated. First, a laboratory LV IM has been set up with a SG as GF unit, PV converters and an ohmic load. A load step of -3 kW has been conducted and the resulting deviations in grid frequency and active power output are presented. Due to interactions between the FDAPR control specified by the former German grid code and the speed control of the SG a stable operation of the IM is impaired. Because of new German LV grid codes and therewith an adaption of the FDAPR of PV converters the new FDAPR behavior is implemented in existing time domain simulation models. The utilization of the new FDAPR leads to a larger impact on the grid frequency when implementing equal conditions as in the laboratory setup. That's why parameter variations including the nominal apparent power of the SG, the installed active power of the PV converters, the height of load steps and the time constant of the new FDAPR are performed. The results show that, the GF SG should be scaled depending on the expectable load steps in the IM and almost independently from the installed active power of PV converters. The larger the time delay of the FDAPR control is, the better load steps can be handled within the frequency operational limits. The results show that for future standardization and to ensure a stable temporary IM operation an additional time delay should be taken into consideration.

In future work additional criteria like operational limits for voltage and maximum line currents have to be evaluated. Also, the influence of battery storages, the type of the load, or the interactions of control parameters of the SG and the PV converters should be considered. In addition, the real dynamic behavior of PV converters with the new FDAPR needs to be analyzed and evaluated.

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