EXPERIMENTAL INVESTIGATION OF DISTRIBUTION GRID RESTORATION CONCEPTS USING NEIGHBORING ISLANDED LV-MICROGRIDS

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ABSTRACT

Nowadays low voltage microgrids can be used for the emergency power supply of local loads. To reduce downtime and to increase the security of supply of the surrounding distribution grid, these microgrids might be connected via the medium voltage grid to neighboring low voltage grids as part of a bottom-up grid restoration concept. That way the potential of distributed energy resources installed in the distribution grid can be used to prolong the time of emergency power supply and expand the area to more customers.

In this paper, a bottom-up grid restoration concept is experimentally investigated with special focus on the startup process of a microgrid and the distribution transformers until the successful synchronization of a neighboring microgrid.

Central results are that with the investigated grid-forming units the energizing of the distribution transformers as well as the synchronization of a neighboring microgrid is possible. However, special attention has to be drawn to the high peak values of the inrush currents of the distribution transformers and to the according design of the grid-forming unit to endure or mitigate these phenomena (e.g. using a voltage soft-start function).

1. INTRODUCTION

Motivation

Due to the rising penetration of decentralized energy resources (DER), microgrid (MG) concepts have been a major focus in the field of power engineering research over the last years. Nowadays, the increasing number of especially photovoltaic (PV) [1] and storage systems [2] in the public low voltage (LV) distribution grids enables theoretically the formation of local MGs. One potential use case for islanded LV-MGs is the public temporary emergency power supply for local loads, e.g. in case of a major disturbance in the transmission grid, resulting in a local blackout. To further reduce the downtime and to increase the security of supply in the surrounding parts of the distribution grid, it may be useful to combine emergency LV-MGs and neighboring LV-grids (containing loads and DERs but not necessarily grid-forming units) via existing medium voltage (MV) infrastructure as part of future grid restoration concepts. That way, a quick and stable partial distribution grid restoration may be achieved. Using all available DERs the chance of the emergency power supply lasting until the transmission grid is restored by the transmission system operator (TSO) may increase. The optimal use of already existing assets may also reduce costs of otherwise necessary upgrades or retrofitted applications.

Grid Restoration Concepts

Today's grid restoration procedure after a huge blackout follows plans that have been prepared in advance. It is controlled and coordinated by TSOs in cooperation with power plant- and distribution system operators (DSOs) [3]. The transmission grid is divided into subnetworks by circuit breakers in substations and the distribution grids are detached [4]. Depending on the situation, the restoration process follows either a "top-down" or a "bottom-up" concept. In addition, a combination of both concepts is possible [3]. In the first case, sections of the overlaying transmission grid are energized by an external voltage source e.g. neighboring TSO with power plants with high nominal power (PP) and black start capability, such as pumped hydro PP. Afterwards, additional PPs and loads (e.g. in form of distribution grids or parts of them) are reconnected step by step from the "top"-transmission level "down" the distribution level to further loads and DERs (Figure 1, blue lines).

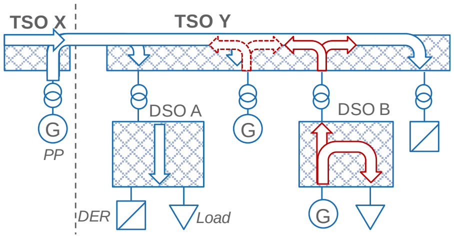

Figure 1*: Grid Restoration Concepts*

In case of no external voltage source, the bottom-up concept is applied. Here, the re-energization of the grid is initiated without an external voltage source by a unit located in the own grid section. Therefore at least one grid forming device with black-start capability is needed to start the process (Figure 1, red arrows) [4]. It is not clearly defined in the bottom-up concept, whether the black start is executed directly in the TSO grid (Figure 1, dashed red lines) or indirectly via the distribution grid. Therefore, further strategies, such as "build-down", "build-up" and "build-together", can be deduced which depend on the actual DSO and TSO relation [5].

Goal and Structure

The goal of this paper is the experimental investigation of the questions whether bottom-up grid restoration concepts for LV/MV grids using neighboring islanded MGs are a suitable approach to reduce downtime, what challenges arise with these concepts and what recommendations are to be given. The special focus herby is drawn on the first steps of the start-up process until the synchronization of a neighboring MG.

Therefore, after briefly stating fundamentals of the German distribution grid structure, MG concepts and inrush currents (chapter 2), fundamental experimental investigations of the grid restoration concepts using the Grid Integration Laboratory of the Institute for High Voltage Technology are designed (chapter 3). The results of the conducted experiments are presented and discussed pointing out the important phenomena and challenges and two possible concepts are derived (chapter 4). The conclusions are summarized and an outlook on necessary further research is given (chapter 5).

2. BACKGROUND

Distribution Grid Structure

The distribution grid in Germany can be divided into high voltage (HV), MV and LV level. For this paper, the expression distribution grid refers only to the LV and MV levels. Starting from a central busbar, MV grids have usually ring topologies, but they are operated as radial grids with a relocatable sectioning point (see Figure 2) [6].

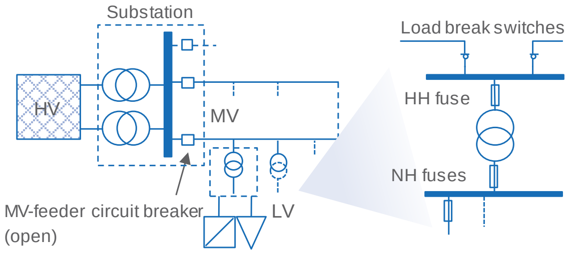

***Figure 2**: Structure of typical Distribution Grid*

Individual MV-feeders can be disconnected from the rest of the grid by circuit breakers in the HV/MV substation. Within the MV feeder, each MV/LV distribution substation can be used to move the sectioning point by load break switches on the MV side. The subordinated, radial LV feeders that supply the actual loads and DERs are typically equipped with hand-switchable NH fuses [6].

Microgrids

For the efficient and safe operation, as well as the control of the rising number of DERs in the distribution grid, MGs are a feasible approach. For the scope of this paper, a MG comprises a LV or MV grid with DERs and acts as a single producer or load [7]. It can be operated in grid-connected or islanded mode and with ac-, dc- or even both voltage types. Small MGs tend to have stability issues, for example due to unexpected high power gradients or temporary insufficient energy due to volatile power sources [8]. Therefore, several control and protection strategies have been proposed for the safe and reliable operation of MGs, which may need communication as well [9] - [11]. Due to its capability to work in islanded mode, a MG is well suited to act as emergency power supply in case of a local or global blackout. In this case, e.g. diesel generators or battery storage systems are used for the local supply of electrical energy to loads or critical infrastructure. In addition, MGs can be used for bottom-up grid restoration concepts, which is a current research topic.

Transformer Inrush Current

The transformer inrush current is the maximum instantaneous output current, drawn by a non-energized and thus fully discharged transformer, while being re-energized. Measurements show these currents to be 20-25 times higher than the rated current [12]. The peak value of the inrush current can be significantly reduced by slowly ramping up the voltage, e.g. by using a soft-start function for the voltage on the grid-forming devices [13]. Other countermeasures are the usage of switchable impedances for the start-up process, special overcurrent devices or advanced control algorithms [12]. Due to the high numbers of transformers connected to the distribution system, inrush currents have to be considered, e.g. after switching actions by the DSO, and the protection has to be designed accordingly.

3. METHODOLOGY

For the investigation of the start-up process of a bottom-up distribution grid restoration concept, using neighboring islanded LV-MGs, the experiments need to be designed. In particular, the following questions are addressed:

- What requirements can be derived for the grid-forming unit? What type of grid-forming unit (directly coupled or inverter-interfaced) is to prefer?
- What amount of active and reactive power is needed to energize and feed the distribution transformers and the MV-cable under no load conditions?
- Should the distribution transformer/s be energized during the start-up of the grid-forming unit or should they be connected later on? If latter, what inrush currents can be expected?
- Is it possible to synchronize the grid-forming unit of an islanded MG to a weak grid with minor power quality?
- Do additional disconnectors and other components need to be implemented at distribution substations?

Grid Integration Laboratory

The experimental investigations are performed in a LV/MV distribution grid laboratory with a setup shown in Figure 3. It consists of three LV/MV distribution substations T1, T2 and T3 of commonly used power ratings from 250 kVA to 1250 kVA, three grid-forming generators BSS 1, BSS 2 and CHP of different types and power ratings from 15 kVA to 100 kVA and 3 switchable ohmic-inductive loads up to 45 kW. Using these components, three separate MGs are created as indicated by the areas MG1, MG2 and MG3 in Figure 3.

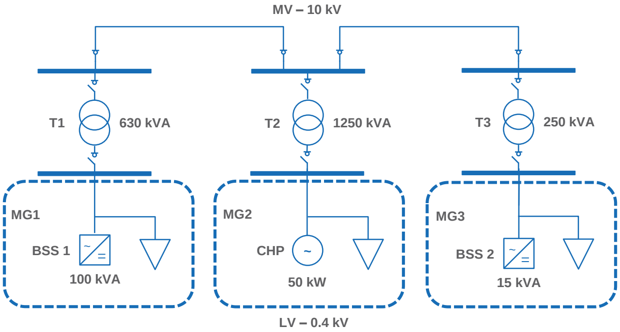

***Figure 3**: Overall laboratory setup*

The MGs can be connected using the 10 kV MV-cables between the distribution substations. Due to the restricted space of the laboratory, each MV-cable has an approximate length of 10 m. The key data of the distribution transformers is listed in Table 1.

***Table 1**: Key data of the distribution transformers*

Transformer	**T1**	**T2**	**T3**
Vector group	Dyn5	Dyn5	Dyn5
Rated power	630 kVA	1250 kVA	250 kVA
Short circuit ratio	0.042 p.u.	0.063 p.u.	0.04 p.u.
LV side resistance	2.27 mΩ	1.11 mΩ	5.15 mΩ

The difference between the grid-forming generators is as follows: BSS 1 represents a commercially available converter with a rated power of 100 kVA designed to use a battery storage system as the DC-source. It is capable to operate either in grid-connected or islanded mode. BSS 2 is a battery inverter with a rated power of 15 kVA (see Table 2), which is also commercially available. Additionally, BSS 2 is able to automatically switch from islanded and grid connected mode, if a distribution grid is detected.

***Table 2**: Key data of the BSS 2 battery inverter*

Parameter	**Value**
Rated power	4.6 kVA (per phase)
Rated voltage	230 V
Rated frequency	50 Hz
Rated current	20 A
Maximum peak current	120 A

CHP represents a combined heat and power plant emulator. It consists of a synchronous generator with a rated apparent power of 105 kVA designed to operate at a maximum active power of 50 kW. A commercial automatic voltage regulator (AVR) is used for excitation. Using an electric drive, the behavior of a gas turbine governor (GAST) is emulated. For more detailed information on the grid integration laboratory and the grid forming units see [13].

Experiments

For the scope of this paper, the following two experiments were conducted:

1. Investigation of no-load losses of the distribution transformers

For the measurement of the no-load losses of the distribution grid transformers, one grid-forming unit at a time is used to energize the corresponding distribution grid transformer and subsequently each other possible combination of distribution transformers is connected via the MV-line as shown in Figure 4 (exemplary for BSS 2).

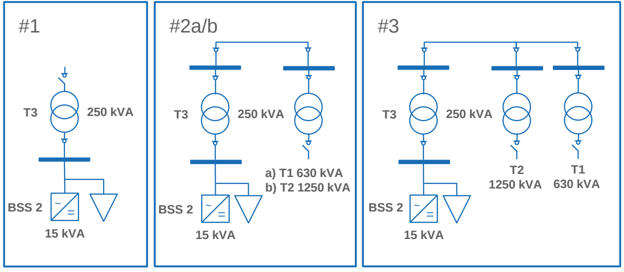

***Figure 4**: Laboratory setup for measurement of no-load losses*

To prevent high inrush currents, the voltage soft-start function of each grid-forming unit is used. Because the BSS 1 does not offer a soft-start function, only the CHP and the BSS 2 are investigated as grid-forming units. Voltage and currents at the grid-forming device are measured and the stationary power demand of the distribution transformers is calculated (active power P, total reactive power Q and deformed power D using the formula $Q = \sqrt{Q_1^2 + D^2}$).

2. Hard switching of distribution transformers

The setup for the investigation of the hard switching of distribution transformers is shown in Figure 5 exemplary for CHP as grid-forming device.

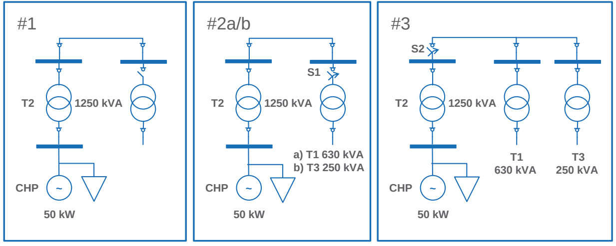

***Figure 5**: Laboratory setup for investigation of grid restoration concept*

The local distribution transformer of one MG is energized using the soft-start function (#1). Then subsequently the other distribution transformers are connected by closing the MV-switch S1 at the substations, energizing the neighboring LV-grids (#2). Finally, two distribution transformers are connected simultaneously by closing S2 (#3). The hard switching of the local distribution transformer is avoided, because of the lack of any significant impedance. In a second step, a MG is operated on the LV-side of the neighboring LV-grid using the local grid-forming device as shown in Figure 6.

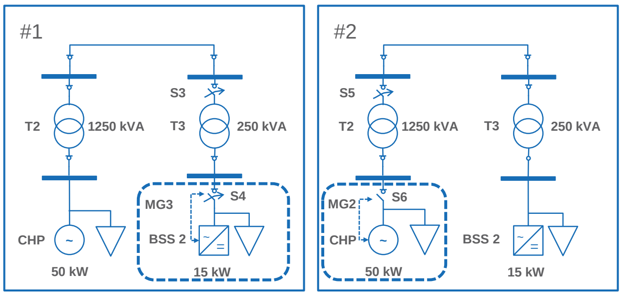

***Figure 6**: Laboratory setup for the investigation of the grid-resynchronization process of a local MG*

The aforementioned bottom-up grid restoration concept is repeated to perform the synchronization process of the local MG and its grid-forming device to the overlaying grid. For example in (#1), the transformer T2 is energized using the soft-start function of the CHP. In MG3 BSS 2 acts as grid-forming unit. Then S3 is closed and T3 is energized. After a short period the synchronous relay S4, which is controlled by BSS 2, is closed automatically and MG3 is synchronized to the grid formed by the CHP. BSS 2 should switch automatically to the grid-parallel mode.

4. RESULTS AND DISCUSSION

Experimental Results

1. Investigation of no-load losses of the distribution transformers

The no load losses of the distribution transformers are shown in Table 3 for both investigated grid-forming units.

***Table 3**: No-load losses of distribution transformers*

Grid-forming unit						
			BSS2			**CHP**
Connected transformers	T3	P	0,19 kW	T2	P	1,23 kW
		Q	0,34 kVAr		Q	3,05 kVAr
		D	0,28 kVAr		D	2,03 kVAr
	T3 + T2	P	1,39 kW	T2+T3	P	1,50 kW
		Q	2,70 kVAr		Q	3,18 kVAr
		D	1,83 kVAr		D	2,10 kVAr
	T3+T1	P	1,16 kW	T2+T1	P	2,17 kW
		Q	1,29 kVAr		Q	4,23 kVAr
		D	1,09 kVAr		D	2,57 kVAr
	all	P	2,33 kW	all	P	2,44 kW
		Q	3,64 kVAr		Q	4,35 kVAr
		D	2,28 kVAr		D	2,60 kVAr

The active power injected by the grid-forming units is in the range of the no-load losses of the transformers itself. Due to the short length of the MV- and LV-cables, cable losses are negligible. The reactive power contains a high amount of distorted power, caused by the energizing process of the distribution grid transformers under no-load conditions. By adding a resistive load to the setup, the amount of distorted power can be reduced and a higher power quality is achieved. It shall be noted, that even BSS 2 with its low rated power of 15 kW compared to the transformer ratings up to 1250 kVA is able to energize and supply up to three distribution transformers. In comparison, the synchronous generator of the CHP injects a higher amount of reactive power compared to the battery inverter of the BSS 2. Despite the use of the voltage soft-start function for both grid forming devices, due to the overall low damped system, overcurrents might arise during the soft-start period.

2. Hard switching of distribution transformers

The hard switching of distribution transformers leads to inrush currents and long enduring overcurrent and -voltage situations, regardless whether BSS 2 or CHP is used as grid forming unit. These inrush currents are exemplary shown in Figure 7 for the experiment (#2a) using BSS 2 as grid-forming unit.

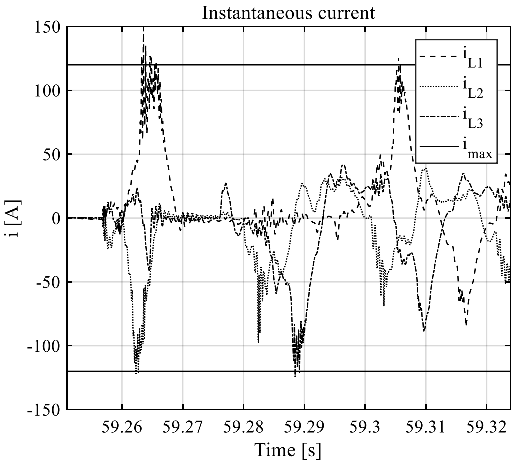

***Figure 7**: Measured inrush current at BSS 2 while energizing T1 (instantaneous values)*

Even though the inrush currents exceed the maximum short time peak current $i_{max} = 120\ A$ of BSS 2, no switch off process is initiated by the converter protection. After the initial inrush current, overcurrents up to 2.3 p.u. occur lasting 15 s (see Figure 8) and a corresponding overvoltage up to 450 V at each phase.

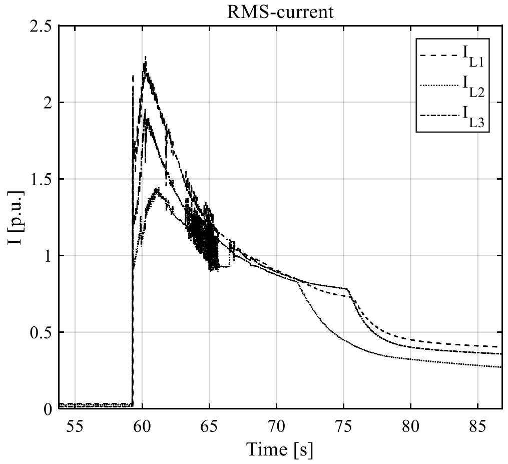

***Figure 8**: Measured inrush current at BSS 2 while energizing distribution grid transformer T1 (RMS-values)*

The investigations of the resynchronization process of a local MG are successful, since in both investigated cases the grid-forming units (CHP or BSS 2) of the MGs connect to the grid supplied via the MV-line and switch to grid-feeding mode.

Discussion

Summarizing the experiments, there can made no recommendations which type grid-forming unit is to prefer, since both are able to energize the transformer in all scenarios without tripping. However, the conducted experiments depict a worst-case scenario, since no damping is added to the grid resulting in long lasting overcurrents- and voltages. A soft-start function of the voltage is recommended for the grid-forming units, since it reduces the inrush currents. Yet, it has no effect on the occurrence of the long lasting overcurrents. The measurements of the no-load losses can be used as a first estimation for the dimensioning of grid-forming units as well as for further simulation-based research. In addition, the ability of the resynchronization of an islanded MG to a grid under no-load conditions with low power quality is confirmed using synchronous relays at the LV-side of the distribution substations.

With the results of the experiments, two concepts for the start-up process of the bottom-up grid restoration of LV grids can be distinguished:

1. Combined start-up of all distribution transformers

Assuming there is one grid-forming unit connected to the central busbar on the LV-side of one distribution substation and all other loads and grid-feeding units at this and the other substations are disconnected, the start-up of all necessary distribution transformers at once is a possible solution. Yet, this option is only feasible if the exact area to be resupplied is known beforehand and all containing MV- and LV- switches are set to the right position. Since most switches at distribution substations in Germany are not remote-controlled, technicians need to be deployed. One advantage is the avoidance of inrush currents. A soft-start function for the voltage is a mandatory feature for this concept. However, it does not always protect from long lasting overcurrents when the grid is low damped.

2. Step-by-step switching of distribution transformers

In this concept the soft-start function of the grid-feeding unit is used to energize the distribution transformer at the busbar. The other distribution transformers are energized subsequently following switching operations. Since inrush currents cannot be avoided in this concept protection and the grid-forming devices have to be designed accordingly for the grid-restoration purpose.

5. SUMMARY AND OUTLOOK

Summary

The results of the conducted experiments show, that the grid-forming units BSS 2 and CHP are able to energize distribution grid transformers using a soft-start function. They are also able to withstand the inrush-phenomena after hard switching, which leads to high peak currents. In addition, it is possible to connect two neighboring grids to one grid for grid restoration process in principle. This fact might be used in future grid restoration concepts to prolong the time of emergency power supply and expand the area to more customers, thus reducing the overall downtime.

Outlook

Additional research either in form of experiments or simulations needs to be conducted to further develop these concepts. For instance, suitable methods for the mitigation of the inrush- and overcurrents should be applied and tested. Protection schemes need to be developed to guarantee a safe operation. To scale the investigations to the level of one distribution grid, simulation scenarios may be carried out. These simulations can use the measurements of the conducted experiments for validation purposes.

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