ABSTRACT: In order to validate the different functions of a low voltage microgrid, a specific test configuration has been set up in the Design Centre for Modular Systems Technology (“DeMoTec”) of the Institut für Solare Energieversorgungstechnik (ISET). In this highly innovative microgrid configuration, the grid control is distributed among three distant inverters which are not linked by any fast communication link. For primary control purposes, the sharing of power between these different grid-forming inverters is made possible using the selfsync\textsuperscript{TM} algorithm. Several critical situations have been successfully tested, which included the transition from interconnected to island operation after a fault on the main grid or the transition from island to interconnected operation (Re-connection to mains after fault, microgrid black start). In all these situations, the microgrid has demonstrated that it is today possible to combine a reliable uninterruptible power supply with the integration of a high penetration level of renewable energy sources (wind and PV).

Keywords: Microgrid, Islanding, Stability

1 INTRODUCTION

Microgrids comprise electrical distribution systems with distributed energy sources, storage devices and controllable loads, operated connected to the main power network or islanded, in a controlled and coordinated way. The operation of microgrids offers distinct advantages to customers and utilities, i.e. improved energy efficiency, minimisation of overall energy consumption, reduced environmental impact, improvement of reliability and resilience, network operational benefits and more cost efficient electricity infrastructure replacement.

In order to validate the different functions of a low voltage microgrid, a specific test configuration has been set up in the Design Centre for Modular Systems Technology (“DeMoTec”) of the Institut für Solare Energieversorgungstechnik (ISET). In this highly innovative microgrid configuration, the grid control is distributed among three distant inverters which are not linked by any fast communication link. For primary control purposes, the sharing of power between these different grid-forming inverters is made possible using the selfsync\textsuperscript{TM} algorithm.

Concerning the secondary control of the inverters, the implementation of a microgrid supervisory controller was a crucial task for the demonstration of the microgrid. An adapted communication environment based on internet and XML-RPC has been set up in order to allow the microgrid supervisory controller to send control set points to the local generator controllers (Remote Terminal Units) of the different power units (Figure 1).

Several critical situations have been studied, which included the transition from interconnected to island operation after a fault on the main grid or the transition from island to interconnected operation (Re-connection to mains after fault, microgrid black start).

![Figure 1: Communication infrastructure in the DeMoTec laboratory](image-url)
2 MICROGRID TEST CONFIGURATION

The three-phase microgrid under test includes the following components:

- 3 grid forming units (2 battery units and 1 diesel generator set)
- 2 renewable energy generators: PV (inverter) and wind (asynchronous generator)
- several loads with different priority levels
- several automatic switches for sectionalizing the microgrid into up to 3 island grids, in order to increase the reliability.
- supervisory control for a fully automatic operation of the microgrid (disconnection, re-connection, black-start, optimal dispatch)
- Connection to main medium voltage grid via a 100 kVA transformer
- A purely resistive line simulator with a resistance of 230 mOhms, representing about 400 meters of a weak low voltage line (NAYY 4*50 SE) has been inserted between the microgrid bus and the Battery Inverter 1.

3 TESTING THE ISLAND MODE

The island mode of operation has been validated on the DeMoTec microgrid. The test has demonstrated that two battery inverters with active power/frequency droops can share their active power in island mode even if the distance from the main load to each battery unit is very different. As is shown on Figure 2, a simulated low voltage line has been inserted between the battery unit 1 and the microgrid bus. The battery unit 2 is directly connected to the microgrid bus. Two strategies for the secondary control in island mode have been tested:

1. The microgrid supervisor always starts the diesel generator and regulates its power to keep the average power output of battery units close to zero. Microgrid frequency is not regulated.
2. The microgrid supervisor starts the diesel generator only if a battery state of charge is too low or if the power output of the storage units is too high. New droop setpoints are sent to the batteries for regulating the frequency at 50 Hz.

Figure 3a and Figure 3b present the results of the islanding test with secondary control strategy 1. The actions of the supervisory controller are also visible. The high impedance fault on the main grid with the consequent islanding of the microgrid happens at time t1=2083 s. At time t2=2400 s, after the diesel start, the supervisory controller, sends a new setpoint to the diesel in order to reduce the power of the battery units to zero. The remaining power fluctuations are due to the variations of both the load profile and the wind power production. A new event was an increase of the microgrid load by 6 kW (2 kW per phase). We can see the immediate response of the battery inverters which take each half of the new load. After a while, the new set point of the diesel is sent by the supervisory controller and battery powers are close to zero. The last event at time t3=2500 s is the reduction of the microgrid load by 6 kW (2 kW per phase). Again, instant response of the battery inverters, which take each half of the extra energy till the supervisory controller sends a new power setpoint to the diesel unit.

![Figure 3a: Inverters sharing power on phase L1 before and after microgrid islanding](image-url)
Figure 3b: Frequencies of mains (f_Mains) and microgrid (f_MG) before and after microgrid islanding (no secondary control of frequency).

In Figure 4, a screenshot of DeMoTec SCADA presents the impact of implementing the islanding test with the secondary control strategy 2. The microgrid frequency is controlled at 50 Hz, by sending new droop setpoints to the battery inverters. After the increase of the load by 6 kW, the frequency drops very fast to 49.4 Hz due to the primary control and is restored to 50 Hz by the secondary control. After disconnecting the 6 kW load, frequency now increases to 50.6 Hz. Figure 4 presents the situation at the time when the secondary control has again restored the 50 Hz.

Figure 4: Islanding test with secondary control strategy 2. The microgrid frequency is controlled at 50 Hz. (screenshot of DeMoTec SCADA)

4 VALIDATION OF EMERGENCY FUNCTIONS

The supervisory controller’s emergency functions have been validated on the microgrid described in Figure 2. The black-start procedure is well illustrated by the frequency plot in Figure 5a. At the start, the microgrid is split in three island systems. Each battery inverter is powering its own grid and the main microgrid bus is out of voltage. We assume also a power failure on the main grid. The first action of the microgrid supervisory controller is to start the back-up diesel unit, which restores the voltage on the microgrid bus (light blue line). The two battery inverters then automatically synchronize to the microgrid bus. In order to do this reconnection smoothly, they reduce their frequency. The batteries are then charged by the diesel unit. After restoration of the mains, the microgrid central controller activates the synchronizer of the microgrid switch and after a few seconds, the whole microgrid is reconnected.

Figure 5a: Black-start test: frequency of phase L1

Figure 5b: Black-start test: active power of phase L1

Figure 5b presents the active power on phase L1 during black-start. Power is provided to both inverters firstly by the diesel unit (370 s < time < 485 s), and secondly by the main grid. After restoration of mains and before synchronization (455 s < time < 485 s), the little power provided by the mains is due to the losses in the 0.4/10 kV transformer.

5 POWER QUALITY ISSUES

During emergency states, power quality issues have been investigated. No significant voltage dips have been recorded during these procedures. The two plots in Figure 6a and Figure 6b present the current and voltage wave forms on phase L1 during the synchronization procedure to the main grid. The microgrid main switch is closed at time tclose=484.93 s, without any dip in the voltage. The transients during an unintentional islanding event are presented on Figure 7a and Figure 7b. The current wave form shows also how the two battery inverters, which are connected with very different LV line length to the microgrid bus, are sharing the active power.
6 CONCLUSIONS

A three phase microgrid has been installed with three grid forming units (one diesel 16 kW and two battery units 12 kW each), a wind generator 15 kVA and several photovoltaic generators. Several switches have been installed in order to increase the reliability of the microgrid, which can be sectionalized into up to three island systems. The communication infrastructure allowed to implement a microgrid supervisory controller. Normal and emergency microgrid functionalities (black-start, island mode, islanding, reconnection, frequency control, power sharing,...) have been successfully tested. During microgrid islanding or reconnection phases, smooth voltage transitions were measured without any power quality problem.

In all these situations, the microgrid has demonstrated that it is today possible to combine a reliable uninterruptible power supply with the integration of a high penetration level of renewable energy sources (wind and PV).

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