Active Power Sharing in Microgrids Using Multiple Grid-Forming Inverters

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Abstract—**Within the scope of the "3DMicroGrid" project different concepts to control microgrids have been investigated. The concept presented here is a strategy to balance active power in purely inverter-based microgrids using multiple grid-forming inverters in parallel. A generic simulation model of a grid-forming inverter was set up in DIgSILENT PowerFactory and its functionality was tested in different microgrids. If more than one grid-forming inverter is used, they all act as voltage sources and share their active power according to the grid impedance at their terminals, while respecting their individual power limits and adjusting frequency with a f(P)-characteristic. Simulations demonstrate that the grid-forming inverter model can run as a master together with grid-following inverters, as well as in parallel with other grid-forming inverters or synchronous machines.**

Keywords—microgrids; modelling and simulation; renewable energy; efficiency; grid-forming inverter

I. INTRODUCTION

Microgrids (MGs) have been gaining more and more attention over the last decade with more real case applications taking place all over the world [1].

One important goal in the design of microgrids is the integration of renewable energies, while ensuring a highly reliable operation. With rising share of variable renewable energies (VREs), situations where the instantaneous VRE penetration is higher than the load can occur easily – e.g., in systems with a low mid-day load but with a high share of solar photovoltaic (PV) generation. In island grids and islanded microgrids, in such situations there is typically still at least one conventional generator connected to the grid (e.g., a diesel generator). This generator is responsible to be "grid-forming", that means to set the voltage and frequency in the grid. VRE units with a conventional grid-feeding control scheme cannot provide this service.

The disadvantage of this practice is that in the absence of energy storage, it implies VRE curtailment as well as avoidable fuel costs, CO2 emissions, and wear and tear of the diesel generator. If the control scheme of one or more inverters in the grid could be adapted to operate grid-forming, this could enable the system operator to switch off the diesel completely in some situations. This control scheme thus enables systems with 100% VRE-based generation, only relying on wind and/or PV and a battery.

For this paper, a generic inverter model that can be used to represent each kind of inverter-based generation in dynamic grid studies was set up in DIgSILENT

PowerFactory. The concept as well as the proposed control scheme is demonstrated in example simulations.

II. Comparison of grid-feeding and grid-forming inverter control

Currently most inverters are controlled with a grid-feeding control scheme, which means that they act as controlled current sources to the grid. They are equipped with a phase-locked loop (PLL) that measures the frequency and the angle of the grid voltage, and the controller adjusts the inverter current so as to inject the desired active and reactive power. Grid-supporting controls such as frequency droop or voltage droop can be applied. However, the grid-feeding control approach only works reliably if there is sufficient short-circuit power in the grid, provided by grid-forming elements.

In a purely inverter-based grid at least one inverter is required to provide the voltage reference, meaning its amplitude and frequency. In this grid-forming control scheme, the inverter acts as voltage source to the grid. It will try to keep the voltage and frequency at its terminals according to the setpoint, and the active and reactive power output depends entirely on the grid. In this mode of operation, the frequency and voltage can be adjusted to signal information to other grid users. However, grid-forming inverter control designs are not necessarily restricted to this mode of operation. They can also follow active/reactive power setpoints and implement droops. Grid-forming control schemes are typically designed to emulate the behavior of synchronous generators [2].

III. Review of Inverter Control Schemes to achieve active and reactive power sharing

Several different control schemes for grid forming inverters in islanded microgrids are reviewed in detail in [3]. Different control concepts are classified there as follows:

- Communication-based concepts
- Droop-characteristic-based concepts
- Virtual-structure-based concepts
- Signal-injection-based concepts
- Hybrid concepts

The purpose of our investigations was to find a simple yet functional control concept applicable in a wide range of grids. The disadvantage of communication-based methods is that they require communication infrastructure, which can make them costly and prone to communication failure. Virtual-structure based concepts require a good knowledge of the grid impedance, which can be hard to obtain or may change over time due to outages and new switching states in the grid. Signal-injection-based concepts require a more complex control and measurement structure and the capability to inject high frequency signals.

Consequently, the most suitable concepts for our purpose are droop-characteristic-based concepts. These concepts have the advantage that they can be easily implemented without (or with only minimum) communication, and they are highly modular. However, the main disadvantage is that it is not easy (or even impossible) to achieve good active and reactive power sharing and narrow operation ranges of voltage and frequency at the same time.

IV. Review of Concepts using Grid-Forimng Inverters

The control of inverters, including in particular different concepts for grid-forming control, has been investigated extensively, e.g. in [2], [3] or [4]. There are also concepts presented on how to use grid-forming inverters in large power systems, e.g. in [4] and [5].

In island or microgrids grid-forming inverters are already in use today, as shown in [6] and [7]. In [6], a battery-PV-diesel system is operated without the diesel generator, and with the battery in grid-forming mode, when PV excess energy is available. In [7], an islanded mini grid is operated with PV and batteries, where one of the batteries is operated grid-forming. This battery modifies the frequency depending on its SOC and thereby sends signals to other batteries and grid users to adapt their power. Both of these concepts rely on a single grid-forming battery. If not only small micro- or island grids, but also large grids shall be operated with (almost) 100% inverters, one grid-forming entity will not be sufficient.

The following main challenges occur when a grid (micro- or island grid as well as large interconnected systems) is operated with up to 100% inverters using grid-forming control:

1. Compared to synchronous generators, inverters have very limited capability to provide short-time overcurrents. Since using larger and more expensive inverters is normally not feasible, grid-forming inverters switch to grid-feeding when their current limits are reached, temporarily losing their grid-forming behavior. Load balancing schemes must be established to ensure that these limits are not reached in normal operation, and protection schemes must be designed to cope with the resulting behavior during faults.
2. VRE generation such as wind and solar power is not well suited for providing power balancing services, due to the inherent variability of primary resource. Using it for this purpose during sufficient resource availability is possible, but competes with other solutions on economic terms.
3. If batteries are used, they need to be prevented from reaching the upper or lower limit of their state of charge (SOC). In this case they would lose their controllability and consequently they would not be grid-forming anymore.

For 100% inverter-based island grids and microgrid applications, battery inverters are the most suitable candidates for grid-forming operation. Compared to VREs, batteries have the additional advantage that they can be operated with negative active power. Batteries are also advantageous for other services, such as primary reserve and load shifting.

V. Developed concepts

Summarizing the advantages and disadvantages of the previous chapters, we believe it is beneficial to use batteries as grid-forming elements in inverter-based grids. These batteries should be operated with a simple droop control to not be dependent on communication and have an easy to implement and expandable system.

The control of the grid-forming elements must be slightly different depending on whether there is only one or several of them in the system.

A. Single grid-forming battery in small island grid

In this case, the battery works as a voltage source. It will not control active and reactive power, but inject whatever is needed to maintain the voltage and the power balance. It is possible to adjust frequency and voltage with droop characteristics, such as f(P), f(SOC) or U(Q), whereas in highly resistive grids an U(P) and a f(Q) droop is more appropriate [8]. By adapting frequency and/or voltage, the grid-forming inverter signals all other elements in the grid that there is a power mismatch. The grid-following inverters can then support the grid by adapting their output power accordingly (e.g. P(f) droop).

As soon as the grid-forming battery approaches its current limit or the SOC reaches its lower limit, the load needs to be reduced or more generation must be connected. If the SOC reaches its upper limit renewables have to be curtailed.

The first set of simulations covered in this paper is focused on this concept and its interactions with grid-following inverters and a load shedding scheme.

B. More than one grid-forming inverter in a larger island or microgrid

Even when more than one battery is operated grid-forming, they can be operated as voltage sources without active or reactive power setpoint. They will typically apply droop characteristics, such as f(P) to share power. When different amounts of power are drawn from them for a short time when the load changes, this will not lead to different inverters trying to imprint different frequencies; instead they will swing and settle on a common frequency depending on all individual droop characteristics, just like synchronous generators would do.

When different batteries with different sizes and different droop characteristics are used, they will usually reach their upper or lower SOC limits at different times. As mentioned before, also batteries that are at their limits have to switch to grid-following mode. Since more than one battery is operated grid-forming, the frequency cannot easily be used to alert other batteries and grid users of such events. Hence, a minimum of communication is required to ensure stability by shifting the P(f) droop characteristic to keep the batteries away from their operation limits.

Simulation results of this concept in a simple test grid are shown in section VII. Those focus in the active power sharing between grid-forming inverters and their interaction with grid-following inverters.

VI. Inverter Simulation Model

A. Grid-forming models

Two models of grid-forming inverters have been developed in PowerFactory. Both variants are optimized for simple application in island systems, and are based on the droop characteristics concept described in section II. The models are equipped with a current limiter inserted within the inner current loop.

They main difference between the models is the type of droop characteristic used for the frequency outer loop control. The first of the models is intended for the “Single grid-forming battery” concept and is equipped with a f(SOC) characteristic that sets the frequency of the entire island system. The other variant of the model is intended for active power sharing of parallel grid-forming inverters and uses a f(P) characteristic.

B. Grid-following models

In many 100% inverter based systems, grid-forming inverters will only represent a portion of the generation connected. Therefore their interaction with the rest of the inverter based generation, operating in a grid-following mode, must be checked. The simulations carried out in this study are performed with both grid-following inverters and grid-forming inverters connected to the modelled grids.

The models for grid-following units correspond to a PV inverter model with a P(f) characteristic parametrized for providing both underfrequency and overfrequency support to the system. Overfrequency support is achieved by reducing the active power output of the inverter when the frequency increases above the nominal value; underfrequency support is achieved by increasing the active power output when the frequency drops below the nominal value. This functionality implies a reduced power output at the nominal frequency compared to primary resource availability, leaving a margin to the maximum power point.

VII. Simulation Results

The feasibility of the concepts was tested in different test grids via dynamic simulations in PowerFactory. The simulation results are presented in the following.

A. Single grid-forming battery in small island grid

This first set of simulations focus on the “single grid-forming battery” concept. A simple small island grid model with a radial layout was set up in PowerFactory. The generation consists of one grid-forming inverter that generates the voltage and frequency (f(SOC)) of the system, and one PV grid-following inverter that provides active power support to the system via P(f) droop characteristics. Moreover, three loads are connected to the system, and two of them (corresponding to non-essential loads) are equipped with a load frequency relay that triggers the connection or the disconnection of the loads depending on the frequency of the system. The model of the grid and its main parameters can be seen in Figure 1 and in TABLE I. respectively.

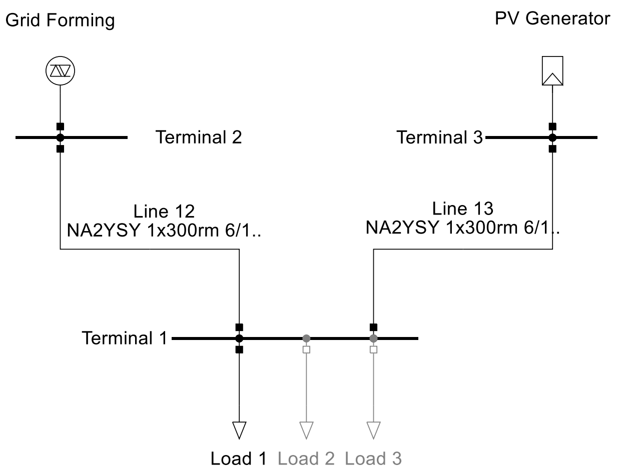

FIGURE 1: POWERFACTORY GRID MODEL USED FOR THE SIMULATIONS IN SECTION VII.A

TABLE I. SMALL ISLAND GRID: ASSET RATINGS AND LOAD ASSUMPTIONS USED IN THE SIMULATIONS IN SECTION VII.A.

ASSETS		RATINGS
Grid-forming battery inverter	Nominal active power	10 MW
Grid-following PV inverter	Nominal active power	6.9 MW
Load 1	Active power	3.45 MW
Load 2 (non-essential)	Active power	1.715 MW
	Disconnection threshold	49 Hz
	Reconnection threshold	49.65 Hz
Load 3 (non-essential)	Active Power	1.715 MW
	Disconnection threshold	48.75 Hz
	Reconnection threshold	49.7 Hz
Line 12	Type	NA2YSY 1X300 6/10kV it
	Length	2 km
Line 23	Type	NA2YSY 1X300 6/10kV it
	Length	2 km

Please notice that the different elements in this test system have been sized only with the purpose of demonstrating how the different inverter types and the load shedding scheme interact; the system does not represent a real island case and no optimization has been made to supply the load in the most economic manner.

The simulation is initialized with a *SOC* of the battery connected to the grid-forming inverter equal to 50%, which according to the f(SOC) characteristic sets a frequency for the system equal to 50Hz. For the grid-feeding PV plant, primary resource conditions are ideal, but the plant is operating at 50% of its nominal power at 3.45 MW according to its P(f) characteristic. With these initial conditions, the solar PV plant generation exactly matches the load, and the grid-forming battery inverter's active power output is zero. Hence, the *SOC* of the battery stays at 50% and the frequency of the system at 50 Hz. This situation remains unchanged for the first period of the simulation as can be seen in Figure 2. It is then changed by a sequence of events marked with times *t*1 through *t*7.

At *t*1, load 2 is connected to the system. Initially, its power is completely supplied by the grid-forming inverter whose *SOC* starts decreasing, and thus the frequency of the grid. The solar PV plant's grid-feeding inverter responds to the change of frequency by increasing its active power output. The frequency settles at 49.75 Hz, which corresponds to the value at which the PV plant's power output has increased enough to cover both load 1 and load 2. This operation point then remains unaltered until load 3 is connected at *t*2. After this event, the available solar PV power is still sufficient to cover all loads in the system, but there is no remaining power margin. The P(f) characteristics has been set so that the maximum power output is reached at a system frequency equal to 49.5 Hz. At *t*3, a sudden decrease in the irradiation changes the PV plant's power output to 70% of its previous value. The power output is no longer sufficient to cover all the loads and thus part of the load is fed by the grid-forming inverter. Since the *SOC* now keeps decreasing, the frequency of the system enters the frequency range where the load shedding scheme is activated.

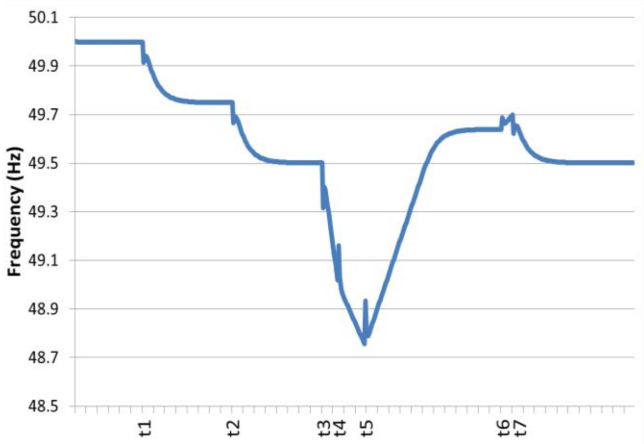

FIGURE 2: FREQUENCY OF GENERATED BY THE SINGLE GRID-FORMING INVERTER

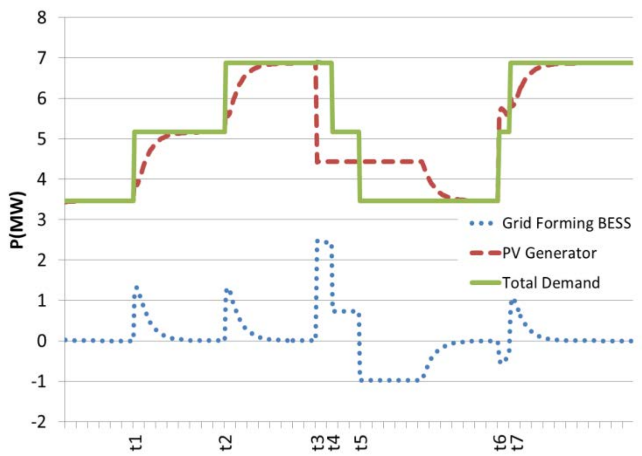

FIGURE 3: DEMAND AND GENERATION IN THE SIMULATIONS OF THE SINGLE GRID-FORMING BATTERY IN SMALL ISLAND CONCEPT

At the frequency threshold of 49 Hz, reached at *t*4, load 3 is disconnected. However, after the disconnection the loads in the system are still larger than available PV power and the frequency keeps decreasing, although its rate of decrease is now smaller. When the frequency reaches the next threshold, 48.75 Hz, the non-essential load 2 is disconnected as well. After the disconnection of this second load, the available PV power is now larger than the load and the frequency of the system starts increasing. It keeps increasing until the frequency of the system enters the range where the PV plant's power output is curtailed according to the P(f) characteristic. For a frequency equal to 49.65 Hz, 22% of the available PV power output is curtailed and the system is balanced, with the frequency of the system remaining constant. Although the frequency is no longer within the load shedding range, the non-essential loads are still disconnected. This is because the scheme was set up for the non-essential loads 2 and 3 to be reconnected automatically at frequency thresholds 49.65 Hz and 49.70 Hz respectively.

At *t*6, the available PV power increases again to its maximum value. Hence the frequency of the system rises, and more PV power is curtailed in order to balance the system. The frequency rise makes the non-essential loads 2 and 3 reconnect. Finally the system frequency settles at 49.5 Hz.

B. More than one grid-forming inverter in a larger island or microgrid

The second set of simulations focuses on demonstrating the active power sharing capabilities with multiple grid-forming inverters. The topology of the model grid is similar to the one used in the previous section, except in this case there are no grid-feeding, but two grid-forming inverters connected to the grid. The parameters and the topology of the grid are shown in TABLE II. and in Figure 4.

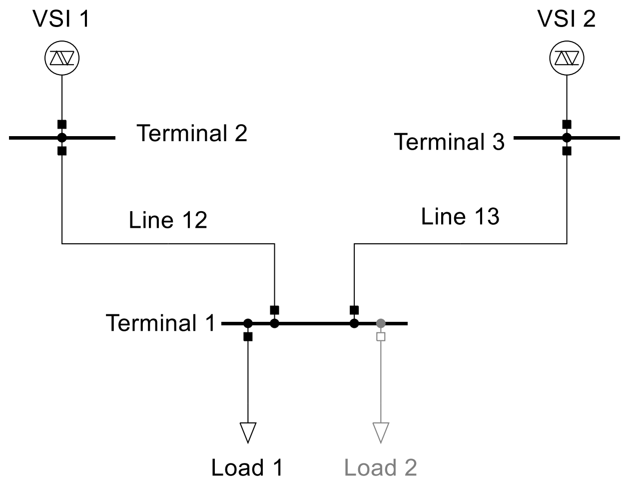

FIGURE 4: POWERFACTORY GRID MODEL USED FOR THE SIMULATIONS IN SECTION VII.B

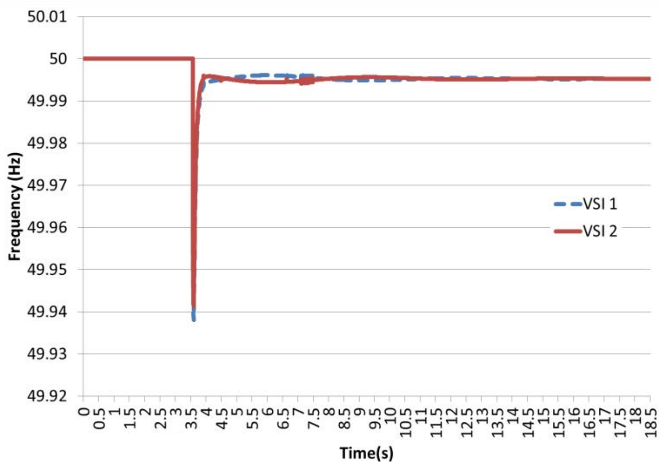

FIGURE 5: FREQUENCY OF THE GRID-FORMING INVERTERS VS1 AND VS2 FOR THE SIMULATION WITH SAME F(P) DROOP

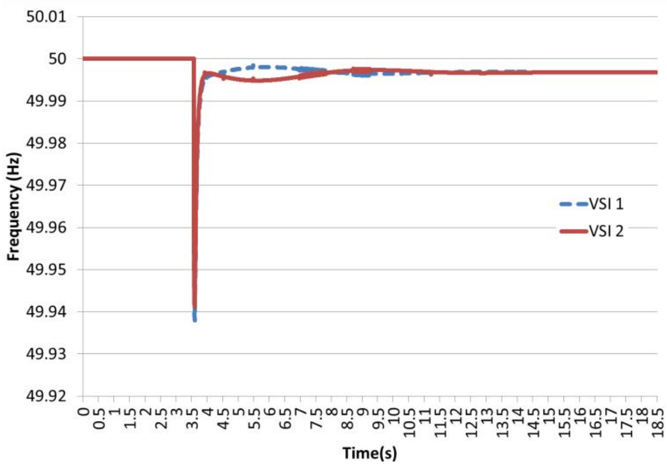

FIGURE 6: FREQUENCY OF THE GRID-FORMING INVERTERS VS1 AND VS2 FOR THE SIMULATION WITH DIFFERENT F(P) DROOP

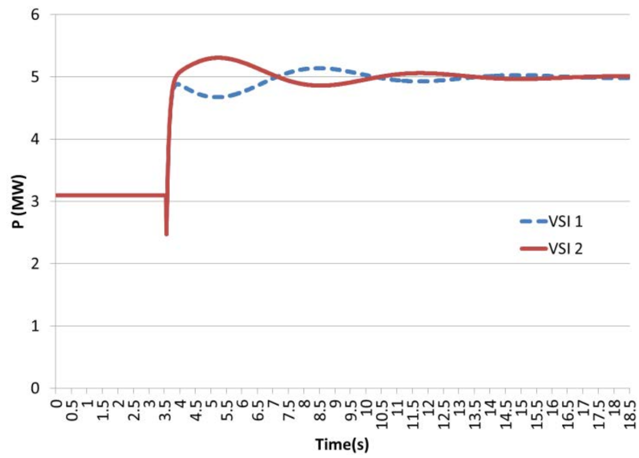

FIGURE 7: ACTIVE POWER OF THE GRID-FORMING INVERTERS VS1 AND VS2 FOR THE SIMULATION WITH SAME F(P) DROOP

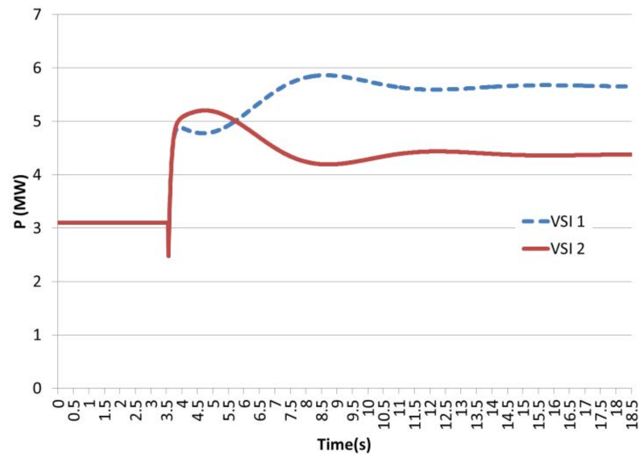

FIGURE 8: ACTIVE POWER OF THE GRID-FORMING INVERTERS VS1 AND VS2 FOR THE SIMULATION WITH DIFFERENT F(P) DROOP

First the active power sharing capability of two grid-forming inverters operating with a f(P) characteristic is tested in simulations. Both inverters VS1 and VS2 share the same droop setting of 0.1%. The simulation is initialized with both grid-forming inverters supplying equal shares of the system demand. Both inverters have the same size and f(P) characteristic, the initial frequency in the simulation is 50 Hz.

TABLE II. MEDIUM SIZE ISLAND GRID: ASSET RATINGS AND LOAD ASSUMPTIONS USED IN THE SIMULATIONS IN SECTION VII.B.

ASSETS		RATINGS
Grid-forming inverter VS1	Nominal active power	10 MW
Grid-forming inverter VS1	Nominal active power	6.9 MW
Load 1	Active power	3.45 MW
Load 2	Active power	1.715 MW
Line 12	Type	NA2YSY 1X400 6/10kV it
	Length	15 km
Line 23	Type	NA2YSY 1X400 6/10kV it
	Length	10 km

At 3.5 seconds, a new load gets connected to Terminal 1. As can be seen in Figure 7, the load step is not equally fed by VS1 and VS2 at the instant it is connected. The reason for that is that VS1 and VS2 operate as voltage sources and in the absence of a coordinating control system the current injected by them is determined by the grid impedance at their terminals. When the impedance of the grid suddenly changes, and before the inverter control responds, the power drawn from VS2 is larger because its connecting line 13 is shorter than the line connecting VS1. The resulting frequency change between both inverters again results in changing voltage angles and power contributions, until both inverters settle on equal power shares again. The damped oscillations that can be seen in Figure 5 and Figure 7 during the instants after the load connection are due to this effect. Once the oscillations disappear, the frequency of the system settles at 49.996 Hz. This value corresponds to the frequency set point determined by the f(P) characteristic of both inverters.

In a second variant of this simulation the influence of the f(P) droop on the active power sharing is demonstrated. All the simulation parameters are the same except for the f(P) droop of inverter VS1, which in this case is set to 0.05%. Starting from the same initialization as in the previous case, the inverters generate the same active power at a frequency of 50 Hz before the load is connected. When the load is connected at 3.5 seconds, the different grid impedance causes an initial power difference between both inverters. However, when the inverter control responds, the effect of the different droop can be seen: At the settling frequency the active power injected by one inverter is smaller than for the other inverter. This is expected since a smaller droop is translated into a larger active power difference for a given frequency delta.

VIII. SUMMARY AND CONCLUSION

In this paper the feasibility of completely inverter-based grids using grid-forming inverter has been illustrated. The focus has been put on small island grids. Whether the concepts presented here can be applied in real systems depends on the individual application case, which typically starts from a specific electricity supply task and includes economic constraints in design and operation. Detailed system studies are used to determine the best suited technology options on a case-by-case basis.

IX. ACKNOWLEDGEMENT

The authors acknowledge the financial support of EC FP7 ERANETMED partners, project number: ERANETMED_ENERG-11-286. The work is supported by the Federal Ministry of Education and Research of Germany in the framework of 3D-Mgrid (support ID: 01DH16019).

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