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DEVELOPMENT, VERIFICATION AND APPLICATION OF A BATTERY INVERTER MODEL FOR THE NETWORK ANALYSIS TOOL *POWERFACTORY*

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ABSTRACT

Battery inverters with adequate controls offer the fundamental possibility to form low-voltage grids, especially island- or micro-grids, which comprise distributed energy resources and renewable energies. A parallel operation of grid-forming inverters is possible with a droop-based control concept.

A suitable model to describe the battery inverter is developed and implemented in the simulation environment of *PowerFactory* from DIgSILENT, which is one professional network analysis tool for investigations of distribution networks. This simulation model is verified against laboratory measurements. The dynamics of island-grids, which are established by distributed battery inverters, are studied in an application with respect to the connection of an asynchronous motor and load sharing between battery inverters.

1 INTRODUCTION

Battery inverters with adequate controls offer the fundamental possibility to form low-voltage grids, especially island- or micro-grids, which comprise distributed energy resources and renewable energies. A parallel operation of grid-forming inverters is possible with a frequency and voltage droop control. The applicability of droops in low-voltage grids is studied by Engler in [1]. He shows that frequency and voltage droops of the conventional grid can be effectively applied in inverter-established micro-grids.

A suitable model to describe the battery inverter is developed and implemented in the simulation environment of *PowerFactory* from DIgSILENT, which is one professional network analysis tool for investigations of distribution networks. This simulation model is verified with laboratory measurements performed at the battery inverter Sunny Island 4500 from SMA AG. An extended description of the model and its verification is available in [2].

The dynamics of island grids, which are established by distributed battery inverters, are studied with respect to the connection of an asynchronous motor and load sharing between battery inverters. Transient simulations of three-phase battery inverters in droop mode are possible within the simulation environment of *PowerFactory*. In contrast to the model presented by [3], this model implements the droop control, which is based on the *selfsync*^{TM} approach [4].

2 BATTERY INVERTER MODEL

The bi-directional battery inverter Sunny Island 4500 from SMA AG is modelled. This battery inverter has three operating modes: grid-tied mode, grid-forming mode and droop mode [5].

2.1 Droop mode

The focus of this contribution is on the droop mode, which is an advanced grid-forming mode. In droop mode, the Sunny Island varies the grid's frequency f depending on its active power supply P, and the grid's voltage U depending on its reactive power supply Q (cf. [1, 5]).

2.2 Parallel operation

The droop mode with a frequency droop and a voltage droop allows to connect several Sunny Islands in parallel each acting as a grid-forming device. The share of load is automatically distributed to the connected battery inverters by using different slopes for the droops [6]. The *selfsync*^{TM} [4] control approach as proposed in [7] is utilised to achieve the parallel operation without the need for communication between the inverter units (see Figure 1).

2.3 Functional principle of the Sunny Island inverter

The principle structure of the Sunny Island battery inverter can be described as follows: The battery is connected to the grid via a bi-directional Cuk-Converter [8] which is connected to the DC link of the inverter. It boosts the DC voltage of the battery to a higher DC voltage. Therefore, it eliminates the need to use a transformer. The link between the Cuk-Converter and the AC grid forms a single-phase inverter. A control architecture and the system's management are superposed. A three-phase battery inverter is established by three single-phase inverters in Master/Slave mode. The Master forms phase A while two Slaves form phase B and phase C. Synchronizing signals which are generated by the Master define a symmetrical phase shift of 120 ° and 240 ° with the two Slaves.

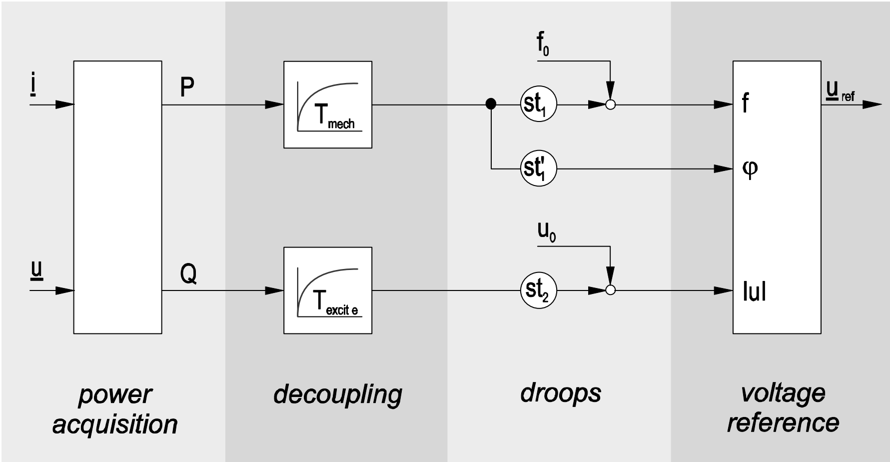

Figure 1: *Control approach selfsync™ [1, 4]. This control comprises four parts. Firstly, the active and reactive power is acquired from the current and the voltage. Secondly, the values are decoupled. Thirdly, the droops influence the frequency, phase and amplitude of the voltage reference, which is defined in the fourth part.*

2.4 Assumptions for the *PowerFactory* model

The developed model of the battery inverter is based on the following assumptions:

- **Voltage source:** The real system components of the Sunny Island battery inverter, namely the battery, the Cuk-converter, and the inverter, are considered to generate a sinusoidal AC voltage. Therefore, the implemented model uses a controlled AC voltage source representing these components of the battery inverter.
- **Sinusoidal synchronizing signals:** Since the 'Master Droop Controller' defines the grid angle for all three phases, the 'Slave Droop Controller' only adjusts the magnitude of the voltage. In reality, the synchronizing signals are signals defining the zero-crossing of the voltage curve. However, here, the synchronizing signals are sinusoidal signals, which are identical for each phase.
- **Sinusoidal voltage without offset:** The model has no voltage offset controller, which is implemented in the real battery inverter because the volt-

age generated with the droop controller block definitions is a sinusoidal wave without an offset.

- **Battery management not modelled:** As the battery is not modelled but considered as a voltage source, the battery management is beyond the scope of the model. This battery management changes the frequency depending on the battery state and the power balance in the grid.
- **No current limitation:** The parameters of the droop controllers are adjusted to the real behaviour of the Sunny Islands. However, the power supply of the voltage source used in the *PowerFactory* model is not limited. In contrast, the real Sunny Island limits the power supply to 6600 VA for 20 seconds compared to a continous output power of 3300 VA. Moreover, in case of a short circuit the Sunny Island battery inverter behaves similar to a current source, which supplies a fixed current for a limited time. This short circuit behaviour of the battery inverter is not implemented in the simulation model.
- **Discrete control partly implemented:** The discrete control of the battery inverter is only partly implemented.

2.5 Sunny Island Model in *PowerFactory*

A model implemented in *PowerFactory* is developed which enables the simulation of a three-phase Sunny Island system. The implementation follows the *selfsync*^{TM} [4] control approach. The main structure of the model in Figure 2 is divided into the three phases (A, B, C) represented by three rows. In the following, four parts of the model structure are described in more detail.

The first part of the structure shows the current and voltage measurement of each phase. The points of measurement are the output reactor, which connects the voltage source with the grid, for the current 'imeas' and the AC voltage source output for the voltage 'umeas'.

In the second part of Figure 2, the measured signals are the input to calculate the active power 'Pgrid' and the reactive power 'Qgrid' within the block 'PQdetermination'. Another output signal is the measured current 'I_Load'. The challenge of single-phase power measurement is that only sinusoidal signals of voltage and current are available over the time, in contrast to phasors that are available in three-phase systems. Burger and Engler developed a method for this task based on a 'verallgemeinerter Integrator' [9], which was developed in [10].

The third part of the main structure in Figure 2 comprises the 'Master DroopController' 'Droop Master' for phase A and two 'Slave Droop Controllers' 'DroopSlave' for phase B and phase C. Each droop controller of the respective phase defines the voltage by the droop characteristic based on the measured reactive power supply. However, only the Master defines the angle of the voltage signal. This angle results from the frequency droop characteristic and the phase correction, which are both based on the measured active power supply. The Master synchronizes the 'Slave Droop Controllers' to the grid angle with the synchronizing signals 'U_syn'.

The calculations of these droop controllers follow the control approach displayed in Figure 1.

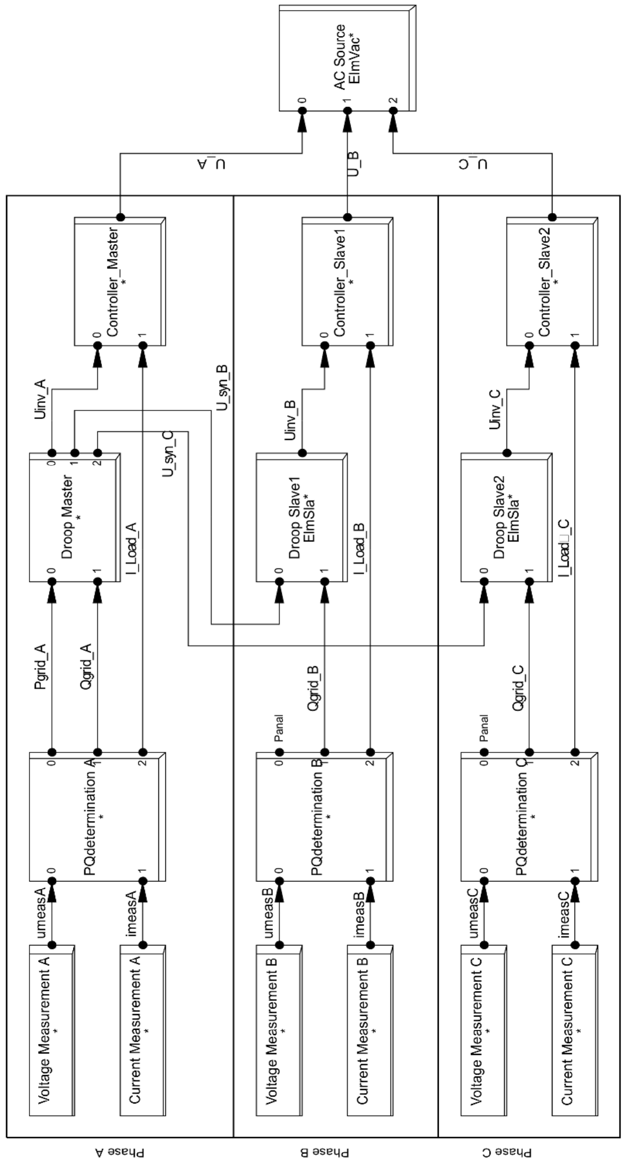

Figure 2: *Main structure of the Sunny Island model in PowerFactory. The measured values of voltage and current are the input of the 'PQdetermination', which calculates the power for the droop controllers. The droop controllers define the reference voltage by using selfsync^{TM}. Together with the measured current, the respective reference voltage is the input to the controller, which controls the voltage and the capacitor current of the included filter. The output of these controllers defines the output voltage of the AC voltage source.*

The voltage signals 'U_{inv}' of the droop controllers are the input of the 'Controller' in the fourth part of Figure 2. Each controller comprises a voltage controller and a subordinated current controller for the capacitor current of the filter, which consists of a capacitor and an inductance. The output signals of these controllers 'U_A', 'U_B' and 'U_C' are the generated voltages for the AC voltage source. Finally, the voltage source is connected via an output reactance to the grid.

3 MODEL VERIFICATION

The *PowerFactory* simulation results with the developed battery inverter model are compared to laboratory measurements of the same configuration.

3.1 Limitations of comparison

Generally, the measured values show variations between each phase, even in balanced situations. This asymmetric behaviour results from tolerances of real system components, measurement errors and influences that are not considered in this work. Consequently, there is always a small deviation between the measured and simulated values. The measured data of the transient currents of the battery inverter in connection with loads show offsets and a jagged signal with an amplitude of 0.1 A. In contrast, the simulated data of transient currents show a smoothed signal and no offset resulting from an ideal sine wave (see Figure 3).

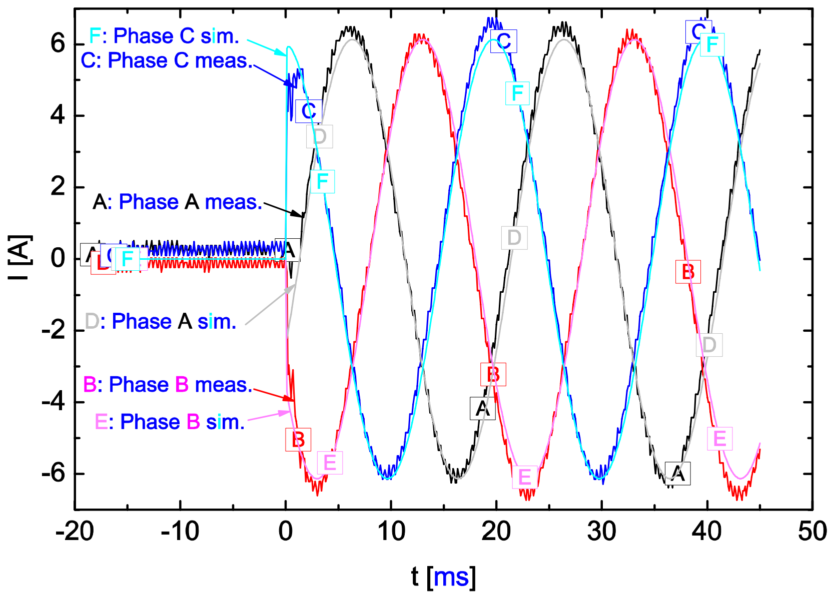

Figure 3: *Transient currents I of the battery inverter in open circuit. A 3 kW ohmic load is connected at the time t = 0 ms. Measured (meas.) values are in darker colours (A, B, C) while the simulated (sim.) values are in brighter colours (D, E, F).*

3.2 Load switching

Transient voltage drops recover faster in the simulation compared to the measured signal. This results from the assumption of an ideal voltage source, which adjusts rapidly. However, the real power electronics control needs longer to control disturbances (see Figure 4).

The *connection of an ohmic load* shows a good congruence of the simulated and measured data as displayed in Figure 3.

After the *connection of an inductive load*, the transient currents have a superposed direct current, which causes a deviation of the mean value from zero. This offset decays over some time periods of the current. In the simulation, this offset occurs similarly because of the inrush current.

After the *connection of a capacitive load*, the current oscillates and tunes within 20 ms (see Figure 5). The current progression before and after the load change shows a qualitative good congruence of the measured and simulated values.

3.3 Unbalanced conditions

An *unbalanced connection or disconnection* at one of the phases shows the same behaviour of the transient currents and transient voltages at the respective phase as in the balanced case. However, the respective other phases are not affected in the unbalanced case.

The *frequency* depends on the active power at phase A. In case that an ohmic load is connected to the battery inverter at phase A, the frequency of all three phases declines, whereas a connection at phase B and phase C does not result in a change of the frequency. This behaviour results from the implemented Master/Slave control concept. The battery management influences the measured values so that a direct comparison with the simulated values is not possible.

3.4 Load sharing

The *active power distribution* between two battery inverters based on the active power droops shows a similar behaviour in case of the measurement as well as the simulation. After the connection of an ohmic load the transients show an equal distribution of the active power in the moment after the connection. However, over the following hundreds of milliseconds, the distribution tunes to the target droop ratio. The measurement and the simulation show the same behaviour, but the simulation needs a bit longer for the tuning.

3.5 Results

The comparison between the measured data and the simulated data shows a good congruence of the signals. This illustrates the quality of the simulation. The verification for the three fundamental types of load changes, namely ohmic, inductive and capacitive load changes, verifies the model for load changes which consist of a mix of ohmic, inductive and capacitive loads. Moreover, the verification of balanced and unbalanced load changes verifies the model for load changes that occur asymmetrically distributed over the three phases.

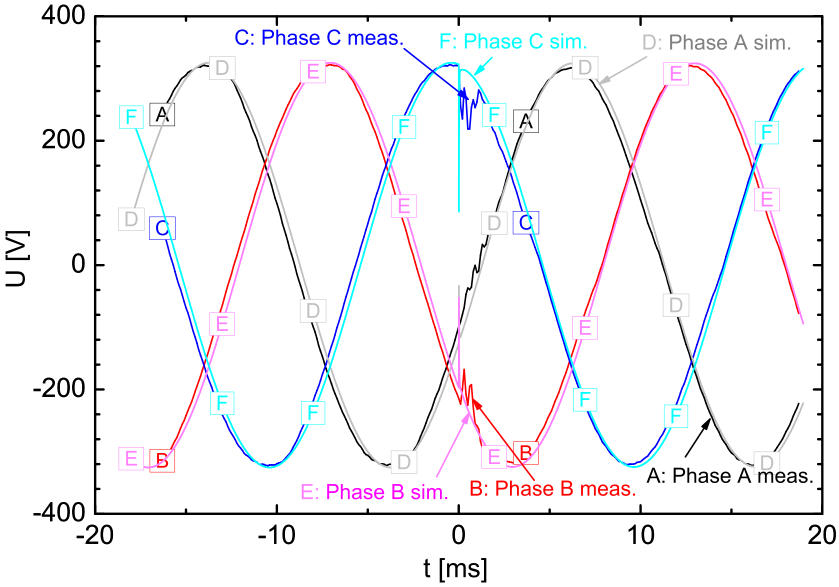

Figure 4: *Transient voltages U of the battery inverter in open circuit. A 3 kW ohmic load is connected at the time t = 0 ms. Measured (meas.) values are in darker colours (A, B, C) while the simulated (sim.) values are in brighter colours (D, E, F).*

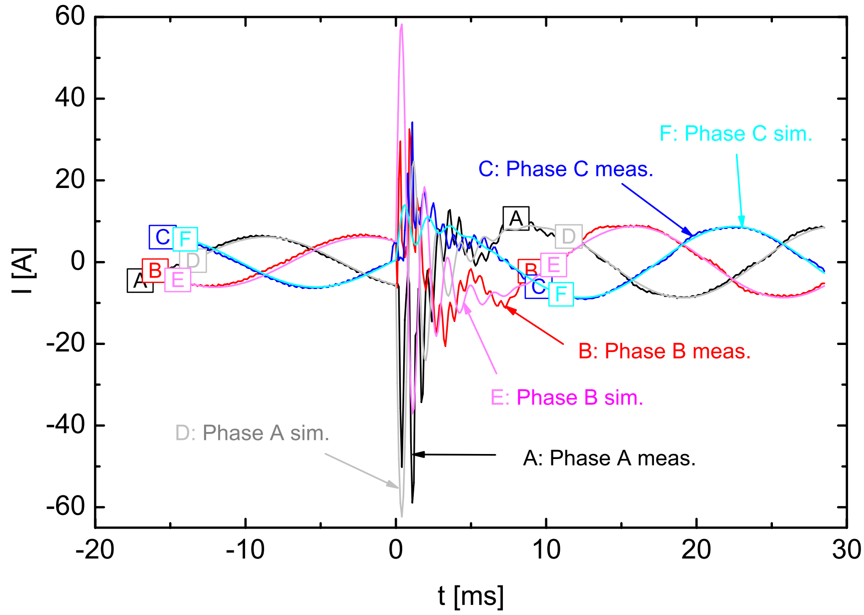

Figure 5: *Transient currents I of the battery inverter supplying a 3 kW ohmic load which is connected at the time t = 0 ms to a 3 kVAr capacitive load. Comparison between the measured (meas.) values in darker colours (A, B, C) and the simulated (sim.) values in brighter colours (D, E, F).*

4 APPLICATION

The usability of the developed model is demonstrated in the following application. The analysed island grid comprises active and reactive loads and asynchronous motors. The grid's behaviour after the connection of an asynchronous motor at a long feeder is investigated with respect to load flow analyses and transient simulations.

Figure 6 shows the analysed grid configuration. The grid comprises four busbars. Three of these four busbars (‘SI 1’, ‘SI 2’ and ‘SI 3’) are controlled by three-phase Sunny Island battery inverters, in contrast to busbar ‘Remote 4’. The battery inverter ‘Sunny Island 1’ (-0.5 Hz / 3600 W ; -3 % / 3600 VAr) has only half the droop slope of the other two battery inverters (-1 Hz / 3600 W ; -6 % / 3600 VAr) because it is assumed to have a bigger battery which allows to control a higher power flow compared to the other two.

The active and reactive power of the loads in this grid configuration depend on the voltage. Moreover, the reactive power is a mixture of capacitive and inductive reactive power with a ratio of 1:2. This considered reactive power results from a power factor of 0.95, which defines each load. The loads consume 1 kW active power at rated voltage.

Two different types of asynchronous motors are connected to the grid. The three asynchronous motors at the busbars ‘SI 1’, ‘SI 2’ and ‘SI 3’ are of the same 1.5 kW type. In contrast, at busbar ‘Remote 4’, a 15 kW asynchronous motor is connected at the time $t = 0$ s.

All these components are connected via low-voltage cables of different length with a cross section of 25 mm^2 and a rated current of 100 A.

4.1 Load flow analysis

Figure 6 shows the analysed grid configuration 2 s after the connection of the asynchronous motor ‘AM 4 15 kW’ to busbar ‘Remote 4’. This figure can be compared with the load flow before the connection event, which shows the difference in active and reactive power flow and positive-sequence voltage caused by the connected asynchronous motor. A transient simulation in the next paragraph shows these changes over the time in more detail. The three battery inverters share the active power supply according to the setting of their droop slopes so that ‘SI 1’ (-12.8 kW) supplies twice the active power of each of the other two (-6.4 kW).

The amplitude of the positive-sequence voltage of busbar ‘Remote 4’ drops from 319.3 V to 284.7 V or by approximately 11 % caused by the increased power flow in ‘Line 800m’, which produces losses of 18.31 kW - 16.47 kW = 1.84 kW. An additional voltage drop occurs due to the increased reactive power supply, which results in a decrease of the voltage at the inverter-controlled busbars because of the applied droop concept (e.g. reduction of the voltage at ‘SI 1’ from 321.5 V to 315.1 V).

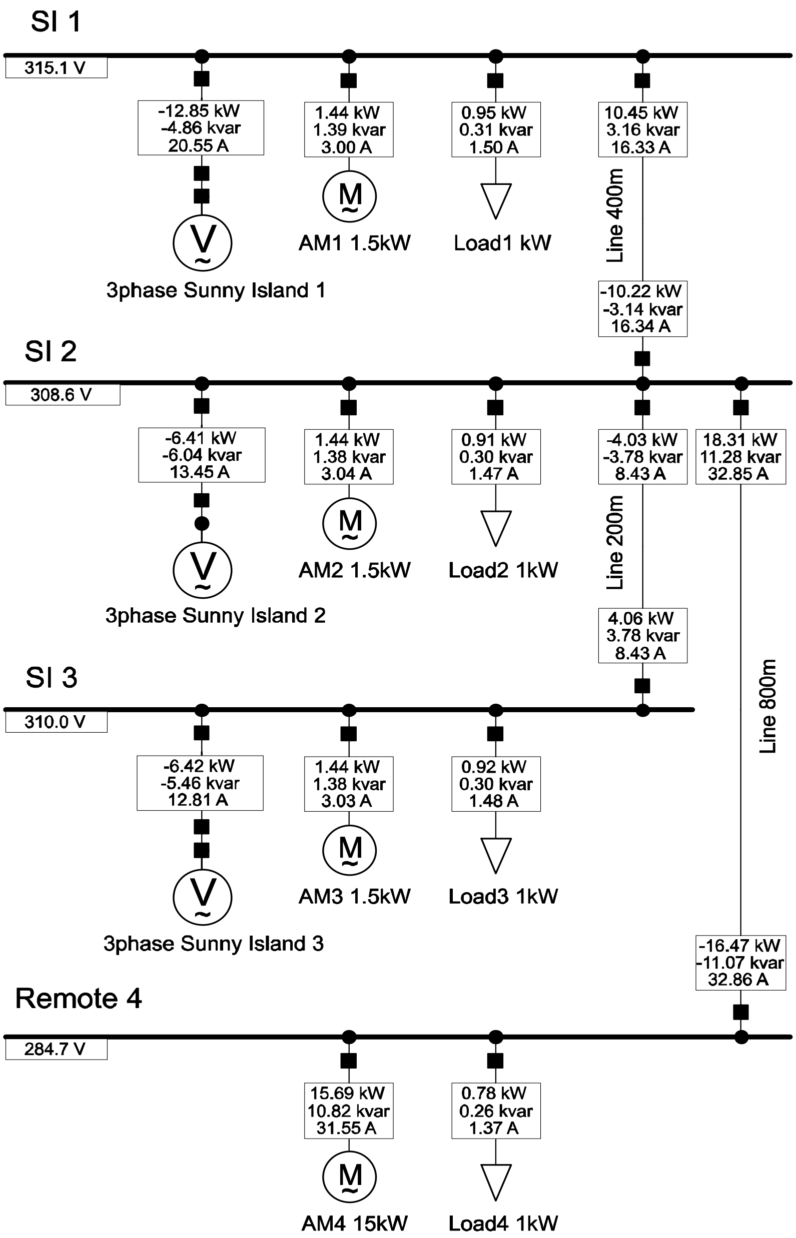

Figure 6: *Load flow in island grid 2 s after the connection of the asynchronous motor 'AM4 15kW' at busbar 'Remote 4'. Each busbar 'SI 1', 'SI 2' and 'SI 3' is controlled by one three-phase Sunny Island battery inverter. These four busbars are connected via low-voltage cables of different length. At each busbar, an asynchronous motor and a load are connected.*

4.2 Transient simulation

Figure 7 shows the transient currents of phase A of the three battery inverters at the time of the asynchronous motor connection. The figures displays higher currents at the beginning followed by a decay until the current reaches its steady state. Due to the parallel operation of the three battery inverters, all three supply a part of the power, which depends on the droop characteristics. However, the distance over cables leads to a damping of their contribution the longer the cable.

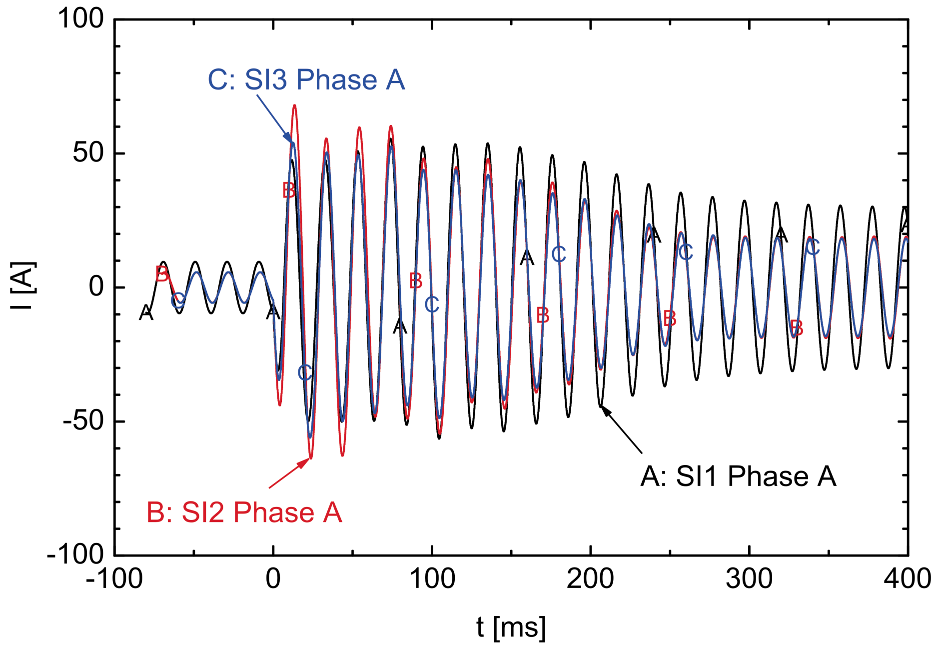

Figure 7: *Comparison of the transient currents I of phase A of the three Sunny Island battery inverters. The connection of the 15 kW asynchronous motor is at the time t = 0 ms.*

This causes battery inverter ‘Sunny Island 2’ to have the highest starting currents, which are four times higher than its steady state values. ‘Sunny Island 1’ with an additional cable distance of 400 m has the lowest starting currents which are only twice its steady state values. Moreover, the figure shows that the amplitudes of ‘Sunny Island 1’ have twice the value of the amplitudes of the other two battery inverters in steady state situation. This results from the described droop slope settings.

Figure 8 shows the droop signals of the three battery inverters at the time of the asynchronous motor connection. The figure on the upper left hand side shows the increase of the active power supply as well as the power sharing between the battery inverters. Due to this increased active power supply the frequency in the figure of the lower left hand side is reduced from 49.8 Hz to 49.4 Hz as defined by the droop characteristic. On the right hand side the upper figure displays the increase of the reactive power supply, which causes a reduction of the voltage in the lower figure as defined by the droop characteristic. Additionally, the figure of the root mean square voltage shows the voltage level at busbar 'Remote 4'.

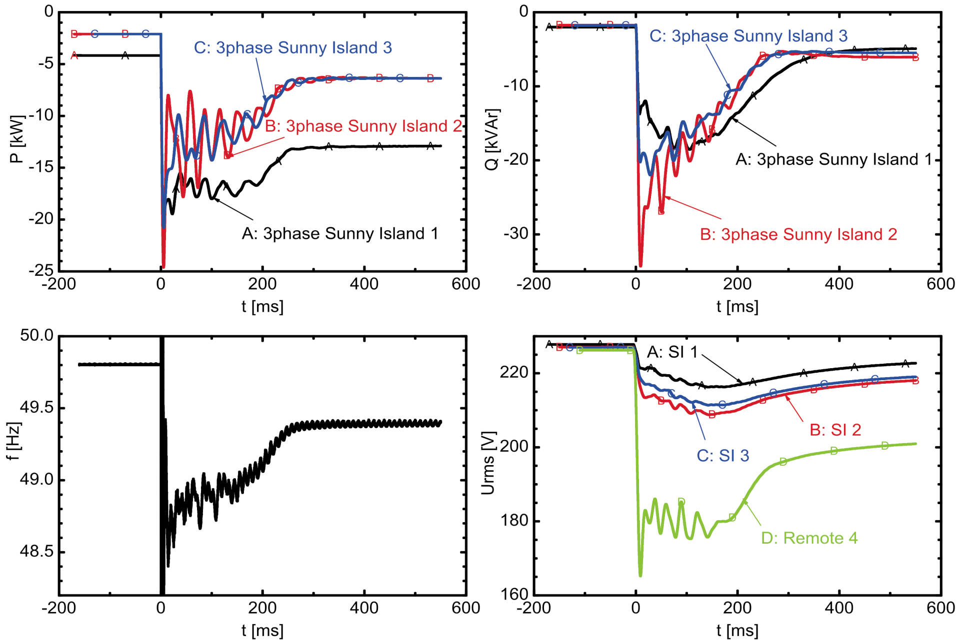

Figure 8: *Comparison of the droop parameters of the three battery inverters. The connection of the 15 kW asynchronous motor is at the time t = 0 ms. On the left hand side are the figures of the active power P and frequency f. On the right hand side are the figures of the reactive power Q and the root mean square voltage Urms.*

5 CONCLUSIONS

This contribution describes the development, implementation, verification and application of a bi-directional battery inverter model in the simulation environment of the power system analysis tool *PowerFactory* from DIgSILENT. The model is used for transient simulations in low-voltage grids with variable frequency and variable voltage.

The comparison between simulated data in *PowerFactory* and measured data in the laboratory shows a good congruence of the short-term transient simulations. The characteristic behaviour of the droop mode of three-phase Sunny Island battery inverters is reproduced well. Also the parallel operation with different droop slopes shows the expected behaviour of power sharing between the battery inverters.

An application of the model describes the connection of an asynchronous motor via a long feeder to a grid configuration with three battery inverters in parallel operation, asynchronous motors, loads and cables. On the one hand, a load flow analysis shows the loading of the components, especially cables. On the other hand, a transient simulation shows the dynamic behaviour of the grid.

The contribution demonstrates successfully the modelling of a battery inverter as well as its simulation with two of the analysis features of *PowerFactory*, which are load flow analysis and transient simulation. In the present model state, short circuit analyses are not possible which are another interesting feature of P*owerFactory*. The results show that *PowerFactory* from DIgSILENT is an appropriate power system analysis tool for micro-grids. However, at present few models of micro-grid components are available.

6 ACKNOWLEDGEMENT

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