CONTROL OF PARALLEL OPERATING BATTERY INVERTERS
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ABSTRACT: The approach of modular systems technology has now become generally accepted for the design of island grids with different renewable energy converters. This technology is characterised by a stipulated energy coupling (ac-bus bar 230/400 V, 50 Hz), a standardised information exchange and a supervisory control. These preconditions allow an adaptable and expandable system structure to be set up, thus covering almost every supply situation; but mean that the generators integrated into the systems have to be equipped with special control features. The core of a modular designed island grid is the grid forming unit. Because of its control and storage properties a battery storage unit should be chosen. The systems mostly run in master/slave operation with one battery inverter as the master. Such energy supply systems are only expandable as long as the original battery inverter has been oversized or is replaced. It would be preferable to install further inverters, i.e. parallel operation. It will be shown that voltage source inverters are preferable for distributed renewable energy systems. The synchronisation of the inverters can be handled by introducing static properties (droops) according to the conventional approach of the utilities. This way only slow communication for system optimisation is necessary. Some simulation and experimental results will be presented proving the feasibility.

1 MODULAR AC-HYBRID SYSTEMS

1.1 Systems technology
Most promising opportunities for renewable energies are stand-alone power ac-supply systems for decentralised electrification.

Figure 1 shows a general diagram of an isolated grid supplied mainly with renewable energy sources like PV generators and wind energy converters but also with fossil fuel and biomass-fueled aggregates. The central component of the system is a battery storage unit with a bi-directional inverter, capable of forming the island grid. For reasons of stable operation the integration of a short-term storage with rotating mass (synchronous generator with increased inertia) might be considered. Standard loads like ohmic loads and induction machines, e.g. pumps can be supplied. In order to achieve modularly expandable grids which are suitable for hybrid systems, the energy coupling and communication of the components have to be standardised. Field and installation busses are suitable for the communication purposes. The standard AC bus (230V / 400V; 50Hz) is the obvious choice for energy coupling and allows the direct supply of standard loads.

The guarantee of a constant power supply in systems with renewable energy sources is aggravated by the fluctuations of wind and solar radiation. In order to maximise the use of renewable energies and to increase the systems’ performance, adequate storage units (battery, rotating mass) and an intelligent supervisory control are required.

1.2 Categories of power units
The components of such a modular system can be distinguished by their function as either a grid forming unit, a grid supporting unit (controllable generators) or a grid parallel unit (uncontrollable generators and loads).

**Grid forming unit:** The grid forming unit controls grid voltage and frequency by balancing the power of generators and loads. Standard systems contain just one grid forming unit (master) which can be a diesel aggregate or a battery inverter.

**Grid supporting unit:** Being similar to traditional electrical supply systems, the grid supporting unit’s active and reactive power is determined by voltage and frequency characteristics which allow primary control and power distribution.

**Grid parallel unit:** These units comprise loads and uncontrollable generators. Uncontrollable generators are e.g. wind energy converters without control or PV-inverters for grid connection. Both devices are designed to feed as much power into the grid (island grid) as possible.

1.3 Sizing of power units
The size of common grid forming units is determined by the overall maximum apparent demand or supply of power. These systems mostly contain one grid forming unit (master), loads and several uncontrollable generators designed as current sources (slaves). In case of dominating loads the power of the grid forming unit is simply determined by:

\[ S_{\text{Formation}} = \sum_{i=1}^{n} S_{\text{Load},i} \]  \hspace{1cm} (1)

and by:
\[ S_{\text{Formation}} = \sum_{j=1}^{m} S_{\text{Generator}_j} \quad (2) \]

in case of dominating generators with \( S \) for apparent power.

Such energy supply systems are only slightly expandable if the original grid forming unit has been oversized. However, it would be desirable to introduce further grid supporting units and thus expand the systems without restrictions.

2 PARALLEL OPERATION OF INVERTERS

An important aspect for island supply systems is the ease with which they can be expanded with additional generators. This can be achieved in different ways. A system with a voltage source as master and additional controllable current sources (grid supporting units) is suggested in [5] (s. Figure 2). The supervisory control is responsible for the power distribution.

![Figure 2: System with parallel units controlled via bus](image)

The features of this approach can be summarised as follows:
- simple control algorithm in components
- high expenditure for busses and their cabling
- difficult expansion of the system
- supervisory control required.

This approach is not suitable for decentralised electrification because the communication requirements are high and a supervisory control and extra cabling is even necessary for small systems.

In [8] another method for master/slave operation has been suggested, which avoids communication but still requires extra cabling for current sensors. In Fig. 3 each slave (current source) measures the current of the master (voltage source) and impresses the same or a weighted current into the island grid. This way active and reactive power and even harmonics are distributed. Due to the cabling for the current sensors this approach is also not suited for decentralised applications.

Communication and/or extra cabling can be overcome if the components themselves set their instantaneous active and reactive power.

![Figure 3: System with parallel units controlled via current sensors](image)

In [7] a concept has been developed using reactive power/voltage and active power/frequency droops for the power control of the inverters. The droops are similar to those in utility grids. The supervisory control just provides parameter settings for each component. This way expensive control bus systems are replaced by using the grid quantities voltage and frequency for co-ordination of the components.

Such approaches result in the following features:
- simple expansion of the system
- increased redundancy, as the system does not rely on a vulnerable bus system
- for optimisation a simple bus system is sufficient
- a simplified supervisory control
- more complex control tasks in the components.

These have led to the decision to integrate the droops in the components.

Additional redundancy in hybrid systems can be achieved by using voltage source inverters (VSI) in parallel. This approach avoids the master/slave operation. Thus

![Figure 4: Grid compatible frequency and voltage droops for synchronisation](image)
Figure 5: Voltage sources coupled via inductors
a) equivalent circuit b) phasor diagram

it is not possible to distinguish between grid forming and grid supporting units. In fact all VSIs form the grid.

The inverters are coupled via the inductances resulting from cabling and filters for the pulse suppression of the inverters (s. Fig. 5 a).

But the configuration in Fig. 5 a is difficult to handle as will be shown. The active power $P$ and the reactive power $Q$ of voltage sources coupled with inductors can be calculated as follows:

$$P = \frac{U_1 \cdot U_2}{\omega \cdot (L_1 + L_2)} \cdot \sin(\delta) \quad (3)$$

and

$$Q = \frac{U_1^2}{\omega \cdot (L_1 + L_2)} - \frac{U_1 \cdot U_2}{\omega \cdot (L_1 + L_2)} \cdot \cos(\delta) \quad (4).$$

$P$: active power

$Q$: reactive power

$U_1, U_2$: rms-values of the voltage sources

$\delta$: phase shift between voltage sources

$\omega$: cycle frequency of the grid

$L_{1,2}$: coupling inductances

Equation 3 reveals that a phase shift $\delta$ between two voltage sources causes active power transmission. Reactive power transmission is due to voltage differences $V_1 - V_2$ (Eqn. 4). Assuming standard values for the inductance $L_f$ results in very sensitive systems, where even smallest deviations of the phase and the magnitude cause high currents between the inverters. Therefore a precise control with complex algorithms is required for the parallel operation of voltage source inverters [9].

3 SIMULATION RESULTS

Due to its high redundancy the most promising approach for paralleling inverters in modular AC-hybrid systems is the usage of VSIs with voltage and frequency droops for their co-ordination. Respectively a control algorithm for paralleling VSIs has been developed.

A prerequisite for the implementation of P/Q-droops of course is the knowledge of the instantaneous active and reactive power. The measurement of these values is especially difficult in single-phase systems. ISET successfully developed a fast P/Q-acquisition for single-phase systems which is the base for the control algorithm.

Beneath some simulation results are presented. In Fig. 6 a synchronisation process is depicted. Two mismatched inverters with a cycle frequency difference of 1 rad/s and a voltage difference of approx. 3 Vrms are connected to an ohmic load at $t = 0$ sec.
The voltage difference is about 1% of the rated output voltage and thus a typical value. It is due to tolerances and the drift of the voltage sensors and their signal conditioning. For demonstration purposes the frequency difference is chosen ten times higher than it could occur with standard crystals (max. tolerance approx. 100ppm).

With the developed control a smooth waveform of the grid voltage even during the synchronisation process is achieved. The high starting currents $i_1$ and $i_2$ fade away.

The phase and frequency of the inverters are adjusted by the active power $P_1$ and $P_2$ of the inverter. As the frequency of the inverters at zero power is different (1 rad/s) the frequency droops of the two inverters are not equal. This results in a difference of the output power at the same frequency. This is the main reason for the difference of the currents $i_1$ and $i_2$ in the simulation example. With the standard tolerance of crystals this power difference becomes negligible.

Here the frequency is equalised within two periods. The steps in the plot of the frequency difference are due to the discretisation of the oscillator’s resolution with 1/100 Hz.

The voltage is adjusted with the reactive power. As there is no reactive load both inverters feed the same reactive power $Q_1$, $Q_2$ with a different sign (one inverter capacitive and one inductive) into the island grid. The rms-voltage difference $u$-diff becomes smaller, i. e. virtual inductors are added in series to the grid.

4 EXPERIMENTAL RESULTS

The above described approach has been successfully implemented. Various experiments with active, reactive and transient loads were carried out. A very precise load sharing (<1% error for active load) between the inverters was achieved.

Figure 7 shows the start of a compressor which is connected to two inverters. The voltage of the two inverters ($Ch_1$, $Ch_2$) is equal. Though the inverters are overloaded in the beginning their currents ($Ch_3$, $Ch_4$) equalise within 3 periods.

![Image of voltage and current waveforms]

**Figure 7**: Performance of transient overloaded parallel operating inverters in an island grid

5 CONCLUSIONS

The feasibility and effectiveness of parallel working battery inverters in modular PV and RE hybrid systems have been shown. In order to distribute power between several generating units the performance and expandability of hybrid systems is improved by introducing control algorithms applying active power/frequency and reactive power/voltage characteristics. These are compatible with the conventional power supply. Hybrid systems with such features for power distribution are most suitable for decentralised electrification purposes and thus for the dissemination of PV and RE technologies.

The development of battery inverters synchronised with droops will increase the reliability of supply systems and simplify the supervisory control. Thus an innovative system design characterised by an easy expandability will result.

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