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Next generation of AC coupled Hybrid systems -

3 phase parallel operation of grid forming battery inverters

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Summary:
The AC-coupling of components for stand-alone PV-battery-diesel hybrid power systems and the distributed generation in renewable energy micro grids is a challenging task for the control technology. Today's systems mostly run in master/slave operation with one battery inverter or one genset as the grid master. Extendable distributed power supplies can be considerably improved by introducing multi-master control concepts for hybrid systems that were demonstrated by ISET and SMA for the first time world-wide. In experiments and first pilot installations it was shown that a grid compatible parallel operation of inverters and small standard asynchronous and synchronous motor-generator sets is possible. This control technology has been extended from single phase operation to three phase operation.

Multi-Master operation
Implementing a multi-master control concept into battery inverters enables a simple PV-battery-diesel system design. This is characterised by an easy expandability with further battery inverters and/or gensets (s. Figure 1).

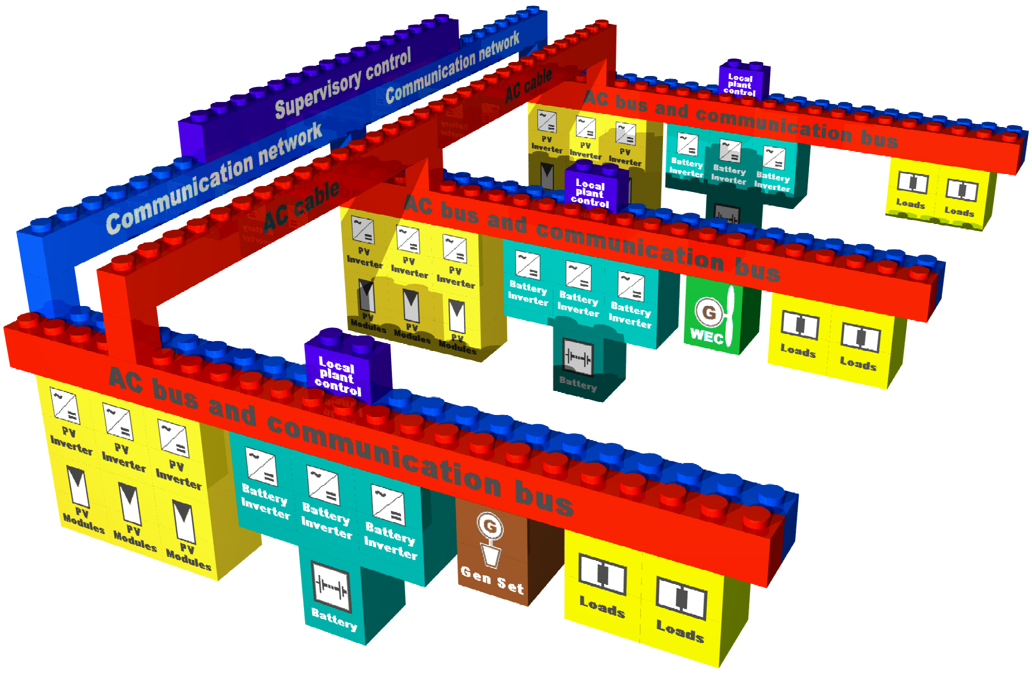

Figure 1: AC-coupled modular hybrid system

Power sharing without communication

Communication and extra cabling can be avoided if the components themselves determine their instantaneous set value for active and reactive power. In [1][2] a concept has been developed using reactive power/voltage and active power/frequency droops (Figure 2) for the control of the inverters. The droops are similar to those in utility grids. The supervisory control just provides parameter settings for each component. Expensive control bus systems are replaced by using the grid voltage and frequency for controlling the components.

Such approach results in the following advantages:

1. simple expansion of the system
2. increased redundancy, as the system does not rely on a vulnerable bus system
3. for optimisation a simple bus system is sufficient
4. a simplified supervisory control

The more complex control tasks require a minimum of computing power, e. g. a digital signal processor (DSP).

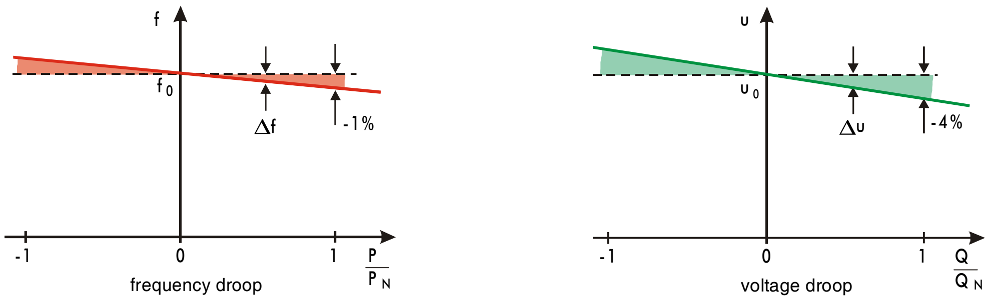

Fig. 2: Grid compatible frequency and voltage droops for synchronisation

Paralleling Voltage Source Inverters

Additional redundancy in hybrid systems can be achieved by using voltage source inverters (VSI) in parallel. This approach avoids the master/slave operation. Thus 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. 3 a).

But the configuration in Fig. 3 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:

$$\boldsymbol{P} = \frac{\boldsymbol{U}_1 \cdot \boldsymbol{U}_2}{\omega \cdot (\boldsymbol{L}_1 + \boldsymbol{L}_2)} \cdot \sin(\delta) \quad (1) \quad \text{and} \quad \boldsymbol{Q} = \frac{\boldsymbol{U}_1^2}{\omega \cdot (\boldsymbol{L}_1 + \boldsymbol{L}_2)} - \frac{\boldsymbol{U}_1 \cdot \boldsymbol{U}_2}{\omega \cdot (\boldsymbol{L}_1 + \boldsymbol{L}_2)} \cdot \cos(\delta) \quad (2).$$

P:	active power	δ:	phase shift between voltage sources
Q:	reactive power	ω:	cycle frequency of the grid
U_1,U_2:	rms-values of the voltage sources	$L_{1,2}$:	coupling inductances

Equation 1 reveals that a phase shift δ between two voltage sources causes active power transmission. Reactive power transmission is due to voltage differences U_1-U_2 (Eqn. 2). Assuming standard values for the inductance

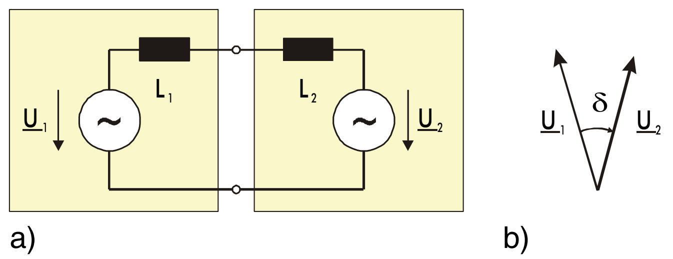

Fig. 3: Voltage sources coupled via inductors (equivalent circuit and phasor diagram)

L_1+L_2 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 [3].

Three phase parallel operation

The described principle has been successfully implemented for single phase application in the commercial battery inverter "Sunny Island®" [4]. As a further step the inverter has been extended for three phase parallel applications by clustering 3 single phase devices to one "three phase cluster inverter". Figure 4 gives an overview on the internal structure of such a cluster. A cluster comprises three single phase inverters connected to one battery. The "droop master" is responsible for the operation control of the cluster. It runs in the above described "droop mode" and thus synchronises to the overall power system respectively other "three phase cluster inverters". The "droop master" communicates with the slaves feeding phase L2 and L3 by a relatively slow RS485 bus. This communication is being used for information exchange such as Start/Stop signals and measurement values (e.g. battery current of the phase slaves, AC power etc.). Furthermore the "Droop master" generates a synchronisation signal at the beginning of every sine wave cycle of its AC-voltage. This signal is being distributed via separate wires to the slave inverters which calculate their AC frequency and control the voltage with respect to the phase shift in three phase systems (+- 120°).

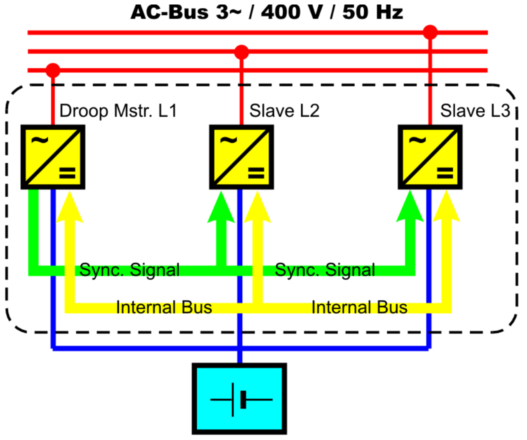

Fig. 4: "three phase cluster inverter"

Application at Demonstration Plant "HYBRIX" (San Agustin, Spain)

The three phase parallel operation is currently being applied at the pilot installation "HYBRIX". The system is part of the "Iberdrola Test and Demonstration Centre". It consists of 3 x 3 Sunny Island battery inverters, 3 lead acid batteries (2x2200 Ah, 1x800 Ah, 60 volts),15 Sunny Boy PV string inverters (27kW), a 10 kW Vergnet wind energy converter (WEC) and a 20 kVA diesel gen set. During the test phase the system is connected to a set of loads allowing the automatic application of a given load profile. As a later step the autonomous supply of the Iberdrola office building is an option.

Fig. 5a: PV and WEC installation

Fig. 5b: Sunny Island inverters

Fig. 5c: 20 kVA diesel gen set

Figure 6 shows monitoring results from the system in three phase parallel operation. The load demand (negative values) of approximately 15 kW peak in this case is covered by 3 Sunny Island clusters (Psi 1-3, Psi 4-6, Psi 7-9). Due to the droop control all clusters immediately respond to load steps.

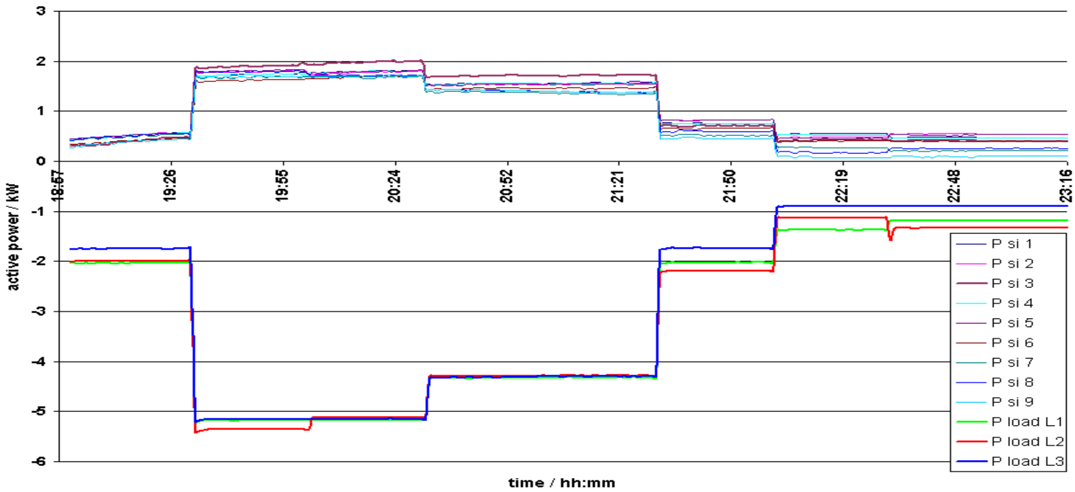

Fig. 6: active power sharing of 3 Sunny Island clusters

Active power sharing between the inverters can be influenced by changing the idle frequency set point of each cluster. The following figure displays monitoring results during a charging procedure. At the time where the battery voltage of cluster 3 reaches the recommended voltage (output of the battery management system), the operation control is influencing the idle frequency set point. This results in lower received power and a controlled battery voltage.

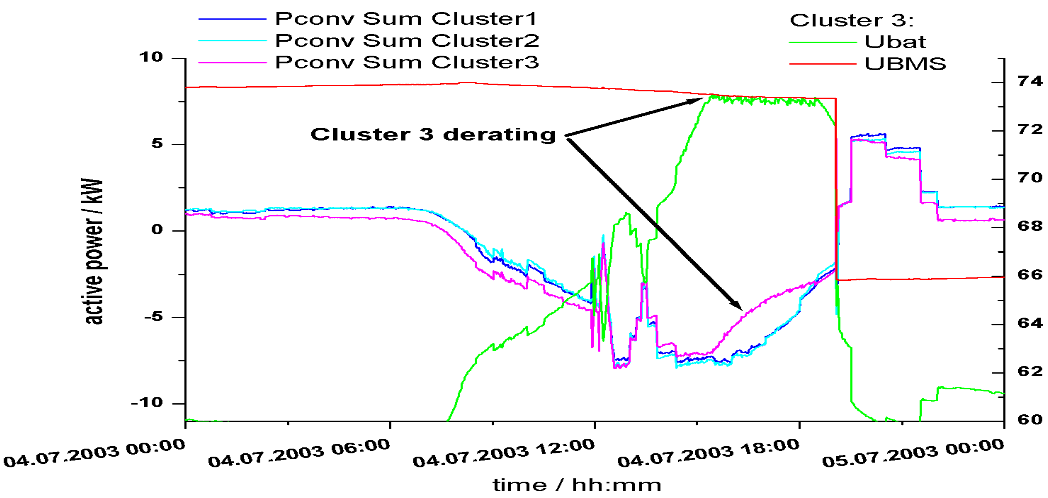

Fig. 7: Active power sharing during charging

Conclusion

The feasibility and advantages of parallel working battery inverters in modular PV and RE hybrid systems have been shown. 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 conventional interconnected grids. 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 therefore will increase the reliability of supply systems and simplify the supervisory control. An innovative system design characterised by an easy expandability will result.

Acknowledgement

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