AC COUPLED PV HYBRID SYSTEMS AND MICRO GRIDS - STATE OF THE ART AND FUTURE TRENDS

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ABSTRACT

The consequent AC-coupling of generators, storage units and loads for setting up hybrid systems or hybrid micro grids is under investigation at ISET since more than ten years. After the development of suitable components like the PV-inverter Sunny Boy® and the battery inverter Sunny Island®[1] and after the implementation of new control concepts for parallel operation, these systems can be easily set up with series produced components.

This paper describes the principals of the Modular Systems Technology and shows some examples of operating hybrid micro grids containing AC-PV, AC-battery power units, wind turbines and diesel gensets. Further developments and aims are described including the distributed generation and energy storage in micro grids as well as the stepwise interconnection of micro grids. A first approach for the control and management of disconnecting houses or grid parts which make use of their distributed energy generators or storage units for emergency power will be outlined.

1. MODULAR AC-HYBRID SYSTEMS

1.1 Modular Systems Technology

The guarantee of a permanent 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.

The Modular Systems Technology (MST) is characterised by a stipulated energy coupling (ac-bus bar with e.g. 230/400 V, 50 Hz), a standardised information exchange and a supervisory control [2]. This approach allows to set up an adaptable and expandable system structure, thus covering almost every supply situation; but mean that the generators integrated into the systems have to be equipped with special control features.

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 generator sets. A battery storage unit with a bi-directional inverter can be applied to balance renewable to match the load demand. For reasons of stable operation and for increasing the short-circuit power the integration of a short-term storage with rotating mass (synchronous generator with increased inertia) might be considered. With this technology standard loads designed for interconnected grids can be supplied. A supervisory control cares for the energy management of the system using a communication bus to acquire information about the system's status and to parameterise the power units. A further task can be the function as a terminal to a remote control unit.

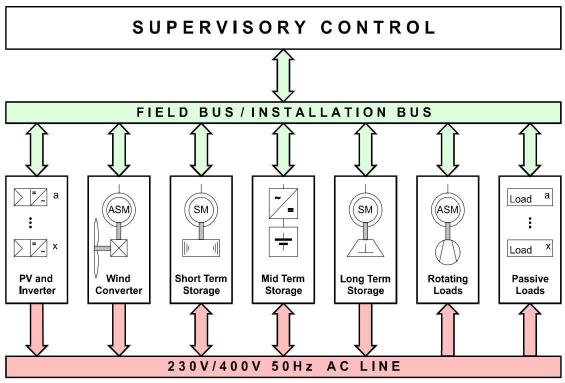

Figure 1: General structure of a modular hybrid system

In small systems the battery unit with its bi-directional inverter can effectively form the grid. In order to keep the system stable the reserve power of the grid forming unit plays a key role (see Chapter 1.2). Therefore the system's properties can be considerably improved if several power components support the grid forming. In the past this was mainly solved with master/slave concepts but here a new control concept is described that allows a multi master operation of several grid forming units without additional communication requirement. A principally unlimited number of inverters and/or electrical machines can contribute to the primary control [1].

1.2 Classes of Power Units

The components of such modular systems 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 as a master which can be a diesel generator set or a battery inverter.

Grid supporting unit: Being similar to traditional electrical supply systems, the grid supporting unit's active and

1 Sunny Boy®and Sunny Island® were both developed in cooperation by ISET and SMA Regelsysteme GmbH, Niestetal, Germany and are produced by SMA.

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.

The size of common grid forming units is determined by the overall maximum apparent demand or supply of power. In case of dominating loads the power of the grid forming units is simply determined by:

$$S_{Formation} = \sum_{i=1}^{n} S_{Load_i} \quad (1)$$

and by:

$$S_{Formation} = \sum_{j=1}^{m} S_{Generator_j} \quad (2)$$

in case of dominating generators with S for apparent power.

1.3 Multi-Master Parallel Operation of Inverters

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 (Fig. 2). 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.

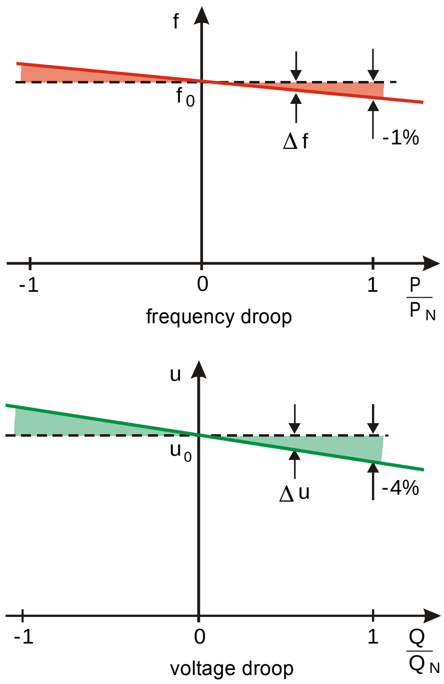

Figure 2: Grid compatible frequency and voltage droops for synchronisation

Such approaches result in the following features:

- simple extension of the system
- increased redundancy, as the system does not rely on a vulnerable bus system
- for optimisation tasks a simple bus system is sufficient
- a simplified supervisory control

Additional redundancy in hybrid systems can be achieved by using voltage source inverters (VSI) in parallel. This approach avoids the master/slave operation [5]. 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).

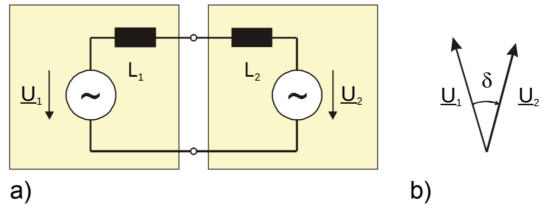

Figure 3: Voltage sources coupled via inductors
a) equivalent circuit b) phasor diagram

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:

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

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
δ:	phase shift between voltage sources
ω:	cycle frequency of the grid
$L_{1,2}$:	coupling inductances

Equation 3 reveals that a phase shift δ between two voltage sources causes active power transmission. Reactive power transmission is due to voltage differences V_1-V_2 (Equation 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].

1.4 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 4b shows the start of a compressor which is connected to two inverters. The voltage of the two inverters (Ch1, Ch2) is equal. Though the inverters are overloaded in the beginning, their currents (Ch3, Ch4) equalise within three periods.

Figure 4a: Two battery inverters (*Sunny Island®*) operating in parallel

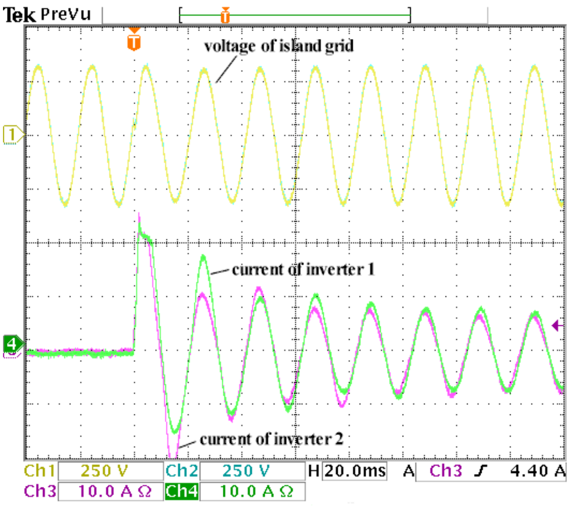

Figure 4b: Performance of transient overloaded parallel operating inverters in an island grid.

2. EXAMPLES OF MST HYBRID MICRO GRIDS

2.1 AC PV-Battery House

For the system depicted in Figure 5 the main supply task is the irrigation of vegetable fields but also standard household loads have to be supplied. A water tank allows an efficient energy management. The water is mainly pumped during sunshine time in order to avoid high cycling rates of the battery. The tank is equipped with two water level switches which indicate 20% and 100% of tank level respectively. The operational control switches the pump on if the level is below 20% or during high irradiation. The second condition for water pumping is depending on the battery state of the battery. Additionally the user is able to control the pump manually. In this case the user is advised to check the battery state of charge in order to avoid too low battery state of charge. Besides this pumping task the system is able to supply machines for honey production and normal household loads.

The control and the power electronics of the battery inverter is designed in a way that a standard 16 Ampere A-Class circuit breaker can be triggered.

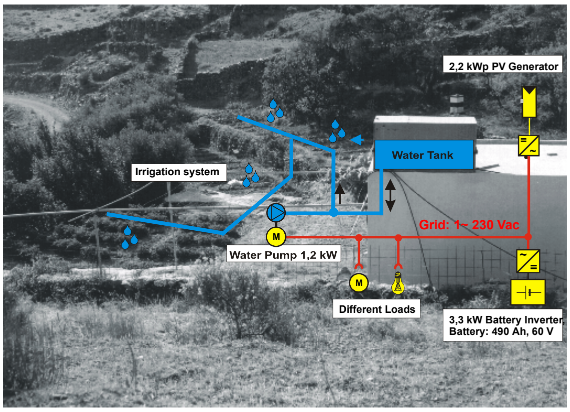

Figure 5: Single-phase AC-PV System for supply of household loads and irrigation system

2.2 AC PV-Battery Micro Grid

Three synchronised single-phase battery inverters are interconnected to form a three-phase system. (Figure 7 right hand side) The battery inverter on Phase 1 is the master and the others provide an output with the same voltage and frequency but with a phase difference of 120° and 240° respectively. The nominal power output of this system is 11 kW. Unbalanced loads can be supplied if the total load on each single phase does not exceed the limitations given for one battery inverter i.e. 3.6 kW. All three inverters are connected to the same battery bank.

The described three-phase application is a possible extension step for end-users who are already have the single-phase PV-Battery-System described in above. Two additional battery inverters and a software reconfiguration permit a stepwise plant extension with the same standard components. The total energy of the PV-inverters connected to the AC-bus should not exceed the battery inverters nominal power.

In the frame of the PV-MODE project the three-phase PV-Battery System was installed for the electrification of some houses in a remote valley on the Greek Island Kythnos. The houses are interconnected with a micro grid. Due to the system structure it is possible to feed in PV power at any point reached by the grid. This allows the integration of several PV generators at visually or functionally optimal places. All the known PV integration options like e.g. roof integration or shadowing facilities are possible. First discussions with the end-users have shown that a smooth integration of the PV is of great interest.

2.3 PV-Battery-Diesel Micro Grid

The integration of diesel gensets into small AC coupled PV-battery micro grids is investigated in the MORE project (see Figure 6 and Figure 7 left hand side). Here two principle operation modes are possible: in one operation mode the battery inverters form the electrical grid and in the other operation mode the diesel genset is the grid master. The first operation mode is similar to the three phase PV-battery system. In this mode the diesel genset can either be switched off or work as a controlled current source in grid parallel operation. In the second operation mode the diesel is forming the grid and all inverters operate in grid parallel operation.

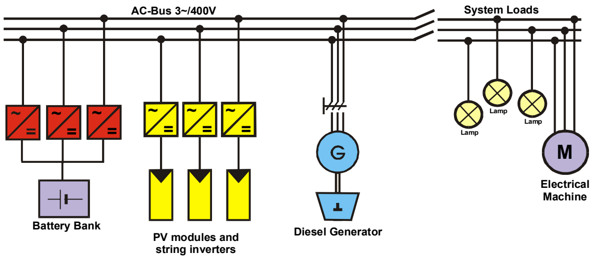

Figure 6: Structure of a three-phase HPS

Several aspects have to be regarded for the integration of small diesel gensets into such automatically controlled systems. According to guidelines of the diesel genset manufacturers the engine should not run under less than 40% partial load. Also frequent start-ups and shut-downs of the diesel engine diminish the generators life expectancy and generally increase the maintenance effort. Furthermore, a minimum surveillance of the gensets is required which can be performed automatically but especially the small gensets normally do not supply the appropriate sensors as a standard.

In the special application of the MORE project, an 11 kW hybrid micro grid was installed for the electrification of about six houses in a small remote valley on Kythnos. The system supplies electricity for about six houses with a three phase 400 V micro grid (see Figure 7).

2.4 Wind-PV Battery Diesel System

In the frame of the European HYBRIX-project a Wind-PV battery diesel system has been set up. This system is an experimental system for testing different configurations of modular hybrid systems. First experiments for the integration of small wind turbines into modular island systems have been performed [8]. A part of the system, as depicted in Figure 8, was used to perform the following experiment.

The asynchronous machine of the wind turbine feeds power in grid parallel operation. The wind power is limited only by means of the original mechanical over speed protection. After setting up the three phase grid with the battery inverters as the grid forming units, the wind turbine was connected with the grid. The wind power output is depicted in Figure 9

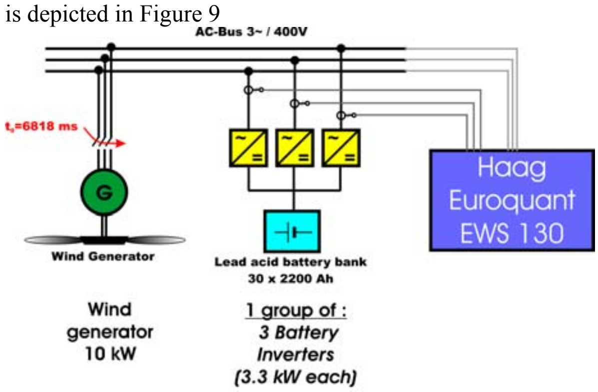

Figure 8: Set-up of the system and measurement equipment [8]; the system part consists of three 3,3 kVA Sunny Island® battery inverters and a 10 kW Vergnet GEV 7/10® wind turbine.

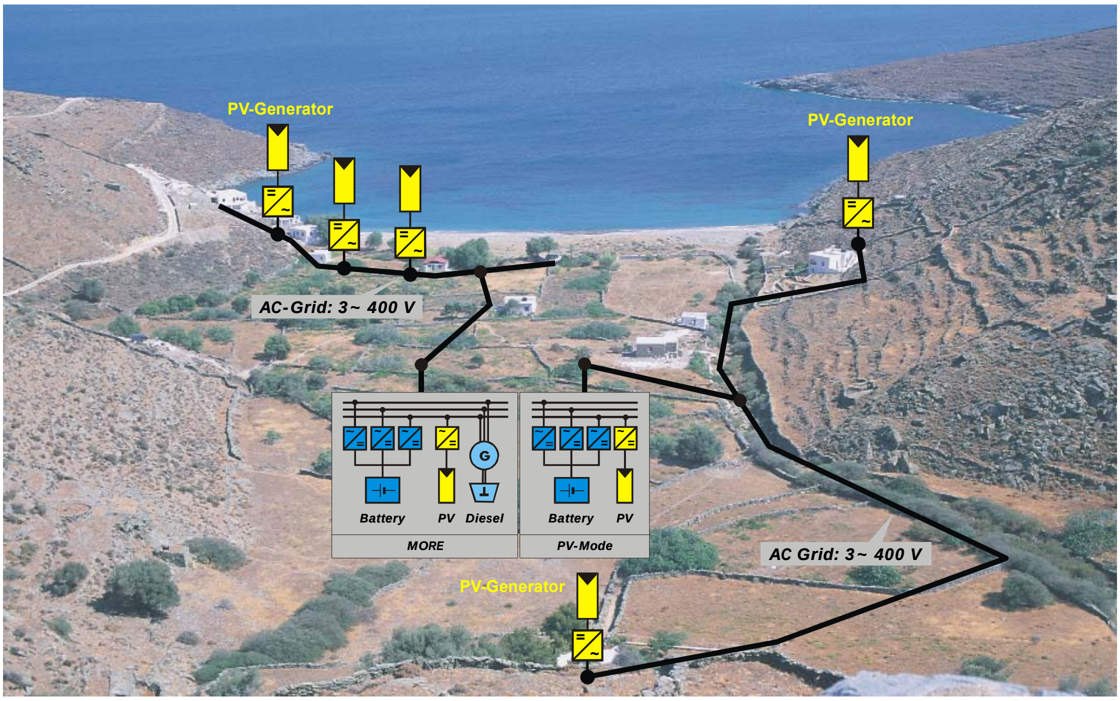

Figure 7: Two three-phase micro grids on the Greek island Kythnos - AC Hybrid System and AC PV System

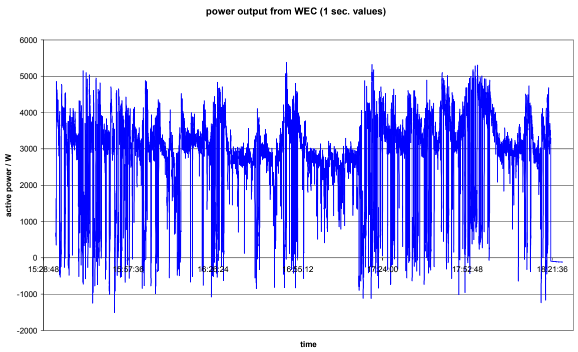

Figure 9: Active power output WEC (1 sec. values, max. power fluctuation from about -1kW to 5 kW) [8]

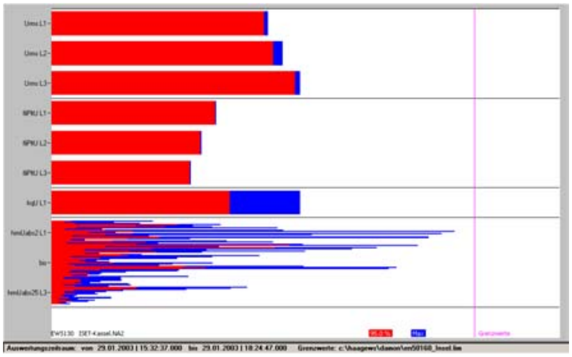

Figure 10: Grid quality evaluation (from top to bottom: Voltages L1, L2, L3, flicker of L1, L2, L3, grid frequency, harmonics; Vertical line: limits of grid standard EN50160) [8]

The grid quality was measured and limits according to the European standard EN50160 for interconnected grids were kept (Figure 10). This experiment shows that MST low voltage micro grids can be set up including typical wind turbines and complies with existing standards.

3. DISTRIBUTED GENERATION IN MICRO-GRIDS

Today's small micro grids usually have centralised power supply stations which use an ac grid for power distribution. The new approach is to use the grid for bi-directional power exchange rather than only for distribution.

3.1 Level of Distributed Generation

It can be seen in some examples above that the micro grids can be supplied by distributed generators (DG) like PV generators or wind energy converters. Depending on the degree of decentralised renewable energy converters the control and management of such micro grids have to cope with different tasks:

1. Only one central power supply of the grid: the grid has the task of power distribution only
2. Low share of DG; DG Power below minimum load; negligible influence of DG on grid stability: safety issues concerning unintended islanding have to be taken into account
3. High share of DG; DG power above minimum load: requires control mechanisms for limiting of decentralised power during power surplus
4. Storage which is necessary to guarantee the grid stability is partially or fully distributed in the grid: energy management has to organise decentralised energy reserves.

3.2 Distributed integration of PV Generators

Conventional PV-micro grid systems usually contain PV generators connected at a central power station. The new approach is to allow PV integration also at any other connection point in the grid. This kind of distributed generation has shown its feasibility in interconnected grids but with a very limited share of PV power. For small island systems additional aspects have to be considered that mainly result from the weakness of the island grids and the higher proportion of PV power:

1. Small island systems often have a load profile that requires the *limitation of PV power* at times of low load and full batteries;
2. PV inverters have to adapted concerning *frequency and voltage limits* as island grids mostly have wider voltage and frequency bands;
3. *Safety aspects* have to be solved, concerning unintended islanding. Enough short circuit power has to be provided also with high shares of inverter power
4. Especially multi customer systems have to be well organised concerning *contractual issues* (e.g. resulting from power limitations)

3.3 Contractual issues in future DG micro grids

The new technical solutions give certain degrees of freedom for organising “liberalised energy markets” also for micro grids. Similar to the recent developments in the liberalisation of the energy market in the interconnected grids power generation and distribution can be organised by different legal bodies. A lot of the questions that arise also for bigger interconnected systems are even more crucial for the small ones.

One hypothetical scenario is described in the following. We can imagine a micro grid with a very high share of DG power, with a high number of power producing participants and no central power supply (Level 4 as described in Chapter 3.1). In this scenario the contracts between the participants have to consider all aspects regarding the reliable, safe and efficient operation of the grid. All these tasks have to be shared between the contractors.

In order to make such an approach feasible it is necessary to enable the DG units to fulfil their tasks in the frame of the contracts automatically. Preferably they should be parameterised accordingly, which is principally possible especially for inverters with control properties described above. But in order to guarantee an overall stable system design tools are required that consider also these contractual issues.

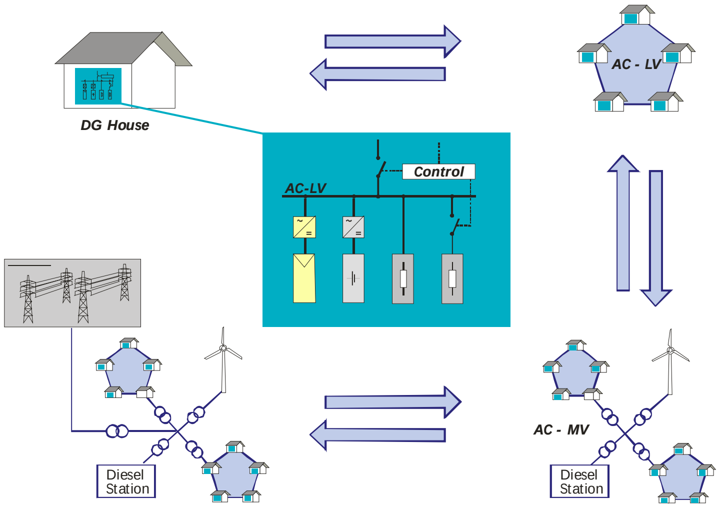

Figure 11: Interconnection and island grid forming of DG Houses

4. INTERCONNECTION OF SYSTEMS

4.1 Interconnection of Modular Island Systems

It was shown above that AC-low voltage systems can be set up according to the Modular Systems Technology. These systems can supply single households, farms, hospitals etc., but can also be interconnected to form low voltage (LV) islands grids. The next step is the interconnection of the LV-island grids with other LV-island grids or power generators on the medium voltage (MV) level as depicted in Figure 11. In a German project dealing about the interconnection of modular power supply systems ("Vernetzung Modularer Systeme") this issue is being investigated. One aim of the project is to show that, with the help of available communication technology, grids of this structure can be managed and can be even integrated in interconnected grids. LV and MV laboratory hardware grid simulators including typical MV transformers will be set up in order to test newly developed DG power units in the appropriate system environment and a grid management system will be set up in order to test the concept. If these developments succeed the results can considerably contribute to a compatible distributed generation technology for island and interconnected grids.

4.2 Intended Islanding

Further Investigations[2] concern the possibility of disconnecting grid parts or even single houses that contain DG units. This can help in case of emergency, power shortages or power interruptions in the main grid. These grid parts or houses have to be enabled to operate in disconnected mode. For this purpose this concept would need decentralised controllers that care for a safe disconnection and reconnection of the relevant system part. If the power or energy reserve is too small it is necessary to organise an appropriate load management

[2] some of these aspects are investigated in the European project Microgrids, ENK5-CT-2002-00610

5. ACKNOWLEDGEMENT

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