

Hard- and software implementation and verification of an Islanded House prototype^{*}

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Abstract: Rising energy prices and the greenhouse effect gave a boost to the innovation of energy saving technologies. One of these technologies is microCHP, a replacement of a boiler producing heat and electricity. We investigated whether it is possible to use a microCHP to decrease discomfort during a power cut by supplying the most important appliances, creating a so called Islanded House. Simulations showed that the discomfort can be decreased when also a battery is added. A prototype is used to justify the assumptions made for the simulation. Finally, one of the control algorithms used in the simulations is implemented as controller for the prototype. Based on these results we conclude that it is possible to create an Islanded House and to decrease the discomfort significantly.

Keywords: Islanded House, energy efficiency, microCHP, control algorithms, system engineering

1. INTRODUCTION

Due to increasing energy prices and the greenhouse effect more efficient electricity production is desirable, preferably based on renewable sources. In recent years, a lot of technologies have been developed to improve the efficiency of the electricity production and consumption. One of the efficiency increasing facilities is Distributed Generation (DG).

Nowadays most residential used electricity is generated in central power plants. However, the efficiency of central generation is at most 55% due to inefficient generation [de Jong et al. (2006)] (transport losses not taken into account). The low efficiency is mainly caused by dumping heat —produced as byproduct— and high fluctuations in demand [de Jong et al. (2006); Peacock and Newborough (2007)]. A growing share of the total electricity production is produced with smaller, geographically distributed generators. These generators often have a higher efficiency or are based on renewable sources [de Jong et al. (2006); United States Department of Energy (2003)]. Two types of DG can be distinguished, (1) small generation sites on a megawatt level (e.g. wind turbine parks) and (2) domestic micro-generators [de Jong et al. (2006)]. Domestic micro-generators generate electricity at kilowatt level in or nearby houses resulting in higher generation efficiency and less transport losses due to production on site. In this paper we focus on this second type of DG.

DG can have more benefits than just increasing generation efficiency and less transport losses. A house or group of houses can become self-supporting, in other words, all

used electricity is generated on site. This is called *islanded operation*. An advantage of islanded operation is being self-supporting in case of a power outage. The disadvantages of a power outage can be diminished by supplying the most important appliances like central heating, lighting and security/safety equipment.

A lot of different micro-generators are available, e.g. solar cells, micro-windgenerators, micro-gasturbines and microCHP devices. The optimization potential depends on the type of micro-generator, in particular on the scheduling freedom determined by the specific type. The use of a micro-gasturbine can be controlled in detail regarding timing and length of runs, whereas solar cells and micro-windgenerators have no freedom at all.

It is foreseen that in the coming years microCHP devices will replace the conventional gas-fired high-efficiency boilers producing next to heat also electricity [United States Department of Energy (2003)]. The advantage of this type of micro-generator is that the produced heat is used for central heating and hot-water taps and that the electricity is used in house or exported to the grid. This results in an efficiency of up to 95%, although it still consumes conventional fuel. The appliance is heat driven, i.e. in the microCHP concept electricity is seen as byproduct (electricity can be imported and exported, while heat cannot). The ratio between heat and electricity production is fixed, for current available microCHP devices the heat-electricity ratio is around 8:1.

Just replacing a conventional boiler with a microCHP device already results in a significant improvement in energy efficiency [Molderink et al. (2008)]. But a microCHP device has even more potential when the runtime is controlled, for example for islanded operation. If -next to

^{*} This research is conducted within the Islanded House project supported by E.ON UK.

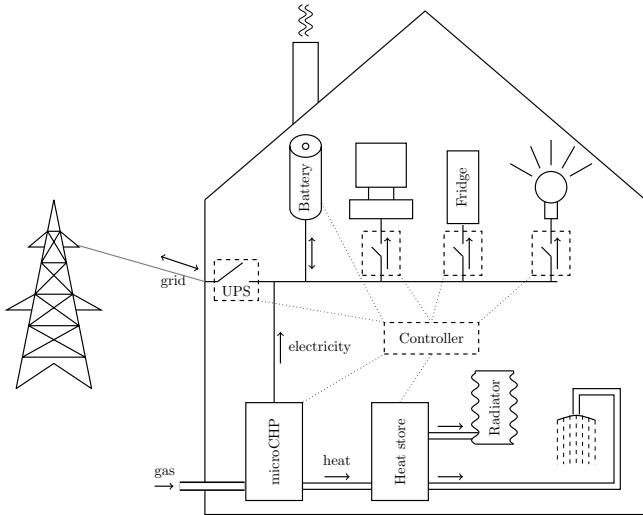


Fig. 1. Proposed house

a microCHP device- also a hot-water tank is installed, the heat and electricity production are decoupled, since heat can be produced before it is used. The total runtime of the microCHP device is determined by the total heat consumption, subject to the enlarged constraint that the heat must be produced before or at the moment it is consumed. In this way a microCHP has a (limited) amount of scheduling freedom.

For our research we focus on islanded operation of a single house in case of a power outage using a microCHP device as micro-generation, but the algorithms are designed such that they are also applicable to other micro-generators. This paper describes the feasibility study that investigates whether it is possible to (1) create an Islanded House and (2) decrease discomfort by supplying at least the most important appliances.

The rest of this paper is structured as follows. The next section describes the approach. Section 3 describes the tests we did and in Section 4 the results are presented. Finally, Section 5 ends up with the conclusions.

2. APPROACH

The proposed house for islanded operation has a microCHP and a heat buffer. Furthermore, we assume that (groups of) appliances can be switched off. A (small) battery is added and a control system that can switch on/off the appliances and microCHP. A schematic of the proposed house is given in Figure 1. The verification whether it is possible to create an Islanded House is split up in three steps.

Control algorithm The first step is to develop a control algorithm for the islanded situation that decides when to start/stop the microCHP and which appliances to supply. With simulation of this algorithm it can be verified whether it is possible to supply (a part of) the appliances and decrease the discomfort during a power cut.

Prototype The second step is to develop a prototype. With this prototype can be verified whether it is possible to start and run a microCHP in an islanded situation and can be investigated what the tolerances concerning

voltage and frequency shift are. A microCHP switches off when the voltage and frequency are not exactly 230V/50Hz ($\pm 10V$ and 1 Hz). First we tried to balance (both real and reactive) load and generation; next a battery is included to start the microCHP, to allow balancing mismatches and to buffer electricity (so the microCHP can be switched off when there is a low electricity demand).

Integration The third step is to combine the first two steps: integrate the control algorithm within the prototype (Islanding tests).

The following three subsections discuss these three steps.

2.1 Control Algorithm

Based on the schematic of the proposed house a model for the energy streams within the house is derived. This model incorporates both heat and electricity. Furthermore, models of the microCHP, the buffers and the appliances are formulated. These models are combined in a simulator together with optimization algorithms to study the effect of the introduction of new technologies and verify the efficiency of the algorithms. More information about this simulator can be found in Molderink et al. (2009b).

Next, a control algorithm for the Islanded House is developed. Simulations of this algorithm show that it is possible to supply critical systems and decrease discomfort of a power outage with electricity generated by a microCHP and buffered by a 1kWh battery. Furthermore, it is possible to develop an algorithm that manages the energy streams by switching on/off the microCHP and appliances. However, this algorithm is very tailored to this particular configuration (e.g. buffer size) and scenario (islanded). Therefore, a more generic algorithm is developed. The main advantage of this algorithm is that changes in the configuration only require changes in the parameters of the particular part that is being changed. Furthermore, also other scenarios are covered. The results of this algorithm in the Islanded House scenario are similar to the results of the dedicated algorithm. A detailed description of these algorithms and the results can be found in Molderink et al. (2008) and Molderink et al. (2009a).

2.2 Hardware prototype

The proposed configuration for our tests imitates a normal house (except for the electrical equipment for balancing tests and measurements).

Basic setup The basis of the testbed is Whispergen microCHP and Gledhill heatstore combination as would be installed in a normal house. The exact types of the used machines are:

- Whispergen Mark 5A ¹
- Gledhill BoilerMate BMA-225-mCHP ²

The Whispergen is connected to the Gledhill. The Gledhill supplies all heat demand, both for central heating and hot water taps. In the test configuration the Gledhill is connected to one radiator and a hot water tap. The

¹ www.whispergen.com

² www.gledhill.com

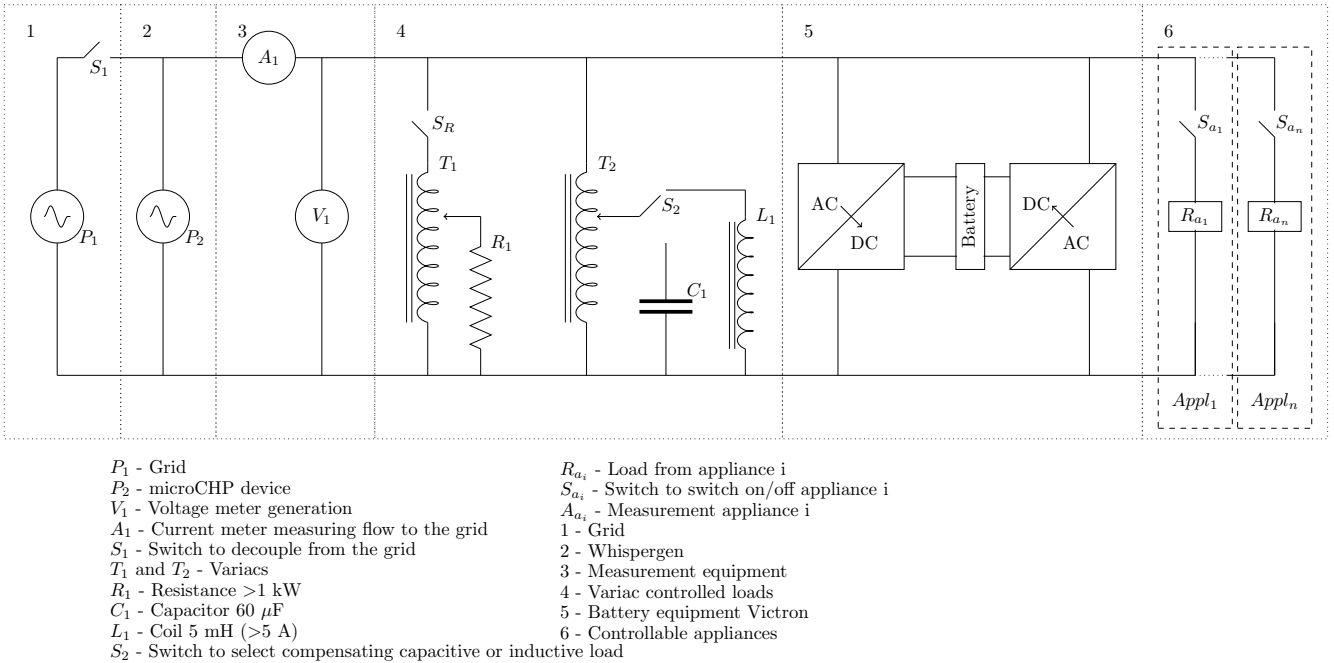


Fig. 2. Electrical equipment configuration

radiator is represented by a forced heat-exchanger on the roof of the test building.

For a Whispergen/heat store combination an extra controller is required. Such a controller is built in the Gledhill. The normal thermostat is connected to this controller and this controller 1) starts the pump to pump water to the radiator(s) based on the thermostat signal and 2) decides when the Whispergen has to be switched on and off based on the level in the hot water tank and the heat demand.

HOMA Software B.V. developed software that communicates with this controller and with the Whispergen to gather information about the Whispergen and Gledhill. Furthermore, the software can send a request to switch on or off the Whispergen to the controller. The controller decides whether the request can be honored or not. Adding HOMA software to the installation is not necessary in normal situations, although it enables global optimization algorithms and it is useful to monitor the installation.

Additional hardware For the tests extra hardware is added to be able to perform the tests. Furthermore, a controller is implemented on the PC (next to HOMA software) for the islanded control.

For the balancing tests adjustable real and reactive loads are required. This is solved with (hand-controlled) variacs, a resistance (heater), a coil and a capacitor. A computer controlled relay card with eight relays is used to switch on/off appliances and to generate the thermostat signal. Six relays are connected with outlets and switch the supply to the outlets on or off. The seventh relay is used to open and close the hot water tap valve and the last relay is used for the thermostat signal. Thus, whether heat is exchanged on the roof or not does not depend on the temperature, but is managed by the control software. The coil, capacitor and relays card are incorporated into one box. The outlets

are built on the outside of the box. Furthermore, battery equipment is added (see next paragraph).

To measure the actual amount of generated electricity and to study the start up characteristics a current meter is added. Because both the resistive and the reactive load must be balanced this measurement equipment must be able to measure both real and reactive load. We used a power analyzer to measure voltage, current, real and reactive load at once. This power analyzer can be connected to the PC via RS-232, so the measurement values can be logged.

All parts of the testbed can be connected with each other with normal 230V plugs and outlets; a normal multiple socket connects all parts together.

The schematic of the electricity setup is given in Figure 2. The setup is divided in six parts numbered from 1 to 6 (from left to right):

- (1) Grid
- (2) Whispergen
- (3) Measurement equipment - HAMEG HM8115
- (4) Balancing equipment
- (5) Battery equipment (see next paragraph for details)
- (6) Equipment to switch on/off appliances

Battery equipment There are two important requirements for the battery equipment:

- **Charge and discharge the battery** - the battery must be charged in case of surplus and discharged to supply shortage
- **Stabilize the 230V/50Hz**

Battery solutions exist for both separate requirements, but as far as we know there is no battery solution commercially available that can stabilize the 230V/50Hz while it is charging the battery. However, it should be possible to

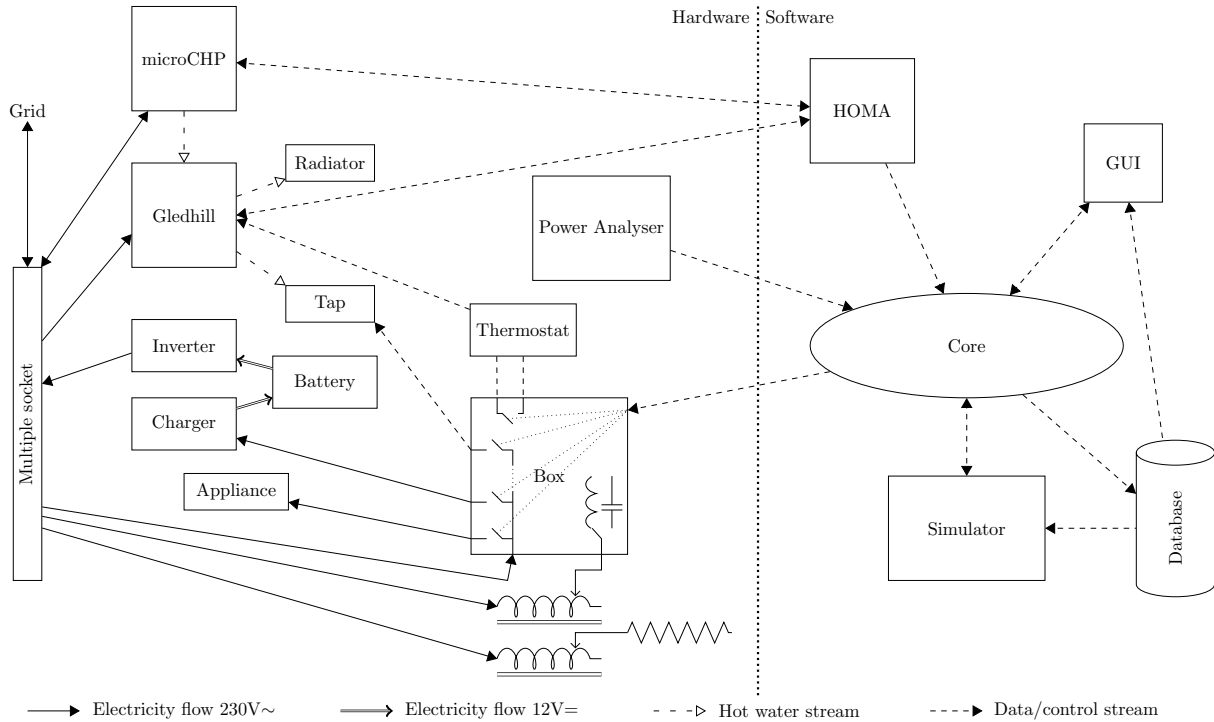


Fig. 3. Schematic of the software

develop such a device. At the moment we are working together with a Dutch company that has experience with battery solutions on the development of such a battery solution. Until this solution is finished we use an alternative battery equipment.

Therefore, two different battery equipments are used for the test: a normal Uninterruptible Power Supply (UPS) and a battery/inverter/converter combination. First it is verified whether the UPS is capable of maintaining the 230V/50Hz well enough to keep the Whispergen running. This worked fine, so we started to work on a full prototype. This equipment consists of a battery, an inverter and a charger. The inverter inverts the 12V= from the battery to the 230V/50Hz, supplies the shortage and stabilizes the 230V/50Hz. The converter charges the battery with the surplus. With this solution the stabilization requirement is met and the battery can be charged. However, the battery is continuously charged, even when there is no electricity surplus. So, the battery is then charged with electricity supplied by the inverter, electricity drawn from the battery. To overcome this, the converter is connected to one of the controlled outlets. Disadvantage of this setup is that it is only possible to charge 360W or nothing at all. The controller solves this with the flexibility of the inverter, it can produce everything between 0VA and 1200VA. Simulations of this situation showed that it is possible to supply most critical loads in this situation as well. However, an electricity surplus can occur when the microCHP is running and there is a low demand.

To test the control algorithm (integration step), the islanded situation can also be emulated by connecting the prototype to the electricity grid. The amount of electricity flowing from or into the grid is the amount that should flow from or into the battery during islanded operation. In

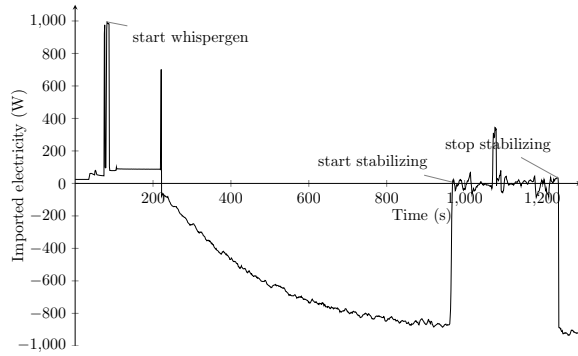
software a battery is simulated with as input this measured electricity flow, using the KiBaM battery model [Manwell and McGowan (1993)].

2.3 Software prototype - Integration

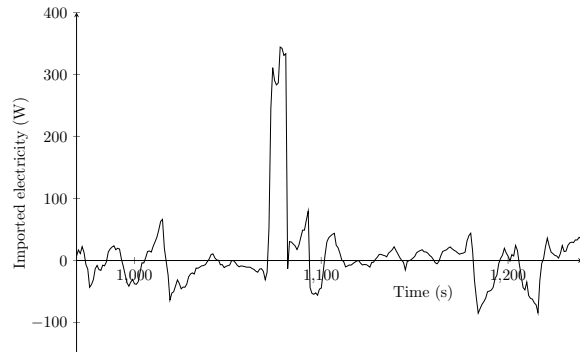
The hardware prototype is controlled via software. This software consists of two parts, one is the interface to all appliances (core) and the other part is for the simulations (simulation). These two parts are connected via TCP/IP to allow them to run on different computers. Furthermore, a Python GUI is built that can connect to the core to monitor the current situation and give commands by 'hand' (switch on/off appliances, the whispergen and the heat demand). A schematic representation of the software is given in Figure 3.

The core part of the software delivers an interface to the hardware for other programs. It can open/close the relays and can therefore manage appliances, the hot water tap valve, the central heating demand and the thermostat signal. Furthermore, it reads the values of the power analyzer every second. Finally, it connects to HOMA software, determines the status of the Gledhill/Whispergen every minute and can send requests to start/stop the Whispergen. All read information is stored into a database.

The simulation part of the software simulates the on/off switch patterns of the electricity/heat demand and contains the controller. Since all loads are managed by the relays, the on/off patterns of these loads are based on switching on/off relays. These requests to open/close a relay are sent to the controller. The controller decides whether a relay is actually opened/closed. The demand can not be measured in the testbed, but since the demand of the connected appliances is known this demand is hard coded in the controller.



(a) Import from grid



(b) Import from grid during stabilization

Fig. 4. Stabilizing the import from the grid

3. TESTS

A sequence of six tests is defined to study the tolerance of the Whispergen and to see whether it is possible to run the microCHP in an islanded situation. The first test verifies the setup and the software and test 2 and 3 verify whether it is possible to create an islanded situation. Test 4 and 5 investigate the tolerances and the last test is the integration step.

- (1) **Run the Whispergen in normal operation** Get the setup running and verify whether the hardware and the core part of the software functions correctly (using the GUI).
- (2) **Start and run a microCHP in an islanded situation using a battery** Verify whether it is possible to start and run the microCHP in an islanded situation. Both the UPS and the inverter/converter are tested.

For the UPS and for the inverter it must be assured that there is always a flow out of the battery since they cannot consume electricity. This is done by using an active load (resistance, a heater) and a variac.
- (3) **Verify islanded operation aspects** The Whispergen is started while the grid is disconnected, the start up electricity is supplied by the battery. Next, switching on/off appliances is emulated using the real and reactive loads and the converter is switched on/off. Goal of this test is to verify whether it is possible to start and run the microCHP in a islanded situation and whether it is possible to charge the battery.
- (4) **Balance the load/generation without battery with grid connected** Try to get a balance with T_1 and T_2 (see Figure 2) with the grid connected, i.e. no load flowing to and from the grid.
- (5) **Find tolerances without battery without the grid connected** When some knowledge about the balance and reactions of the Whispergen is collected it should be possible to maintain this balance without a connection to the grid. The machine is started and when it is running the load and generation are balanced. When there is a balance, the grid will be disconnected.
- (6) **Islanded operation** In this islanded operation test the dedicated algorithm is implemented in the controller and an islanded scenario is imitated. In first instance the battery is emulated while the microCHP

is connected to the grid. If this works correctly the inverter and charger are used without connection to the grid.

4. RESULTS

Every subsection of this section describes one test, how it is accomplished and what the results are.

- (1) **Run the Whispergen in normal operation** The Whispergen and Gledhill are connected to each other and to the grid.

It is verified whether the heat exchanger, hot water tap, electrical equipment box and core software function correctly. This all works as specified.
- (2) **Start and run a microCHP in an islanded situation using a battery** The goal of this test to verify whether the battery equipments can create a stable enough 230V/50Hz for the Whispergen.

First, the Whispergen is started with the grid connected to the UPS. When the Whispergen is running the UPS is disconnected from the grid. However, this disconnection results in a too high fluctuation in frequency so the Whispergen switches off.

For the second UPS test the UPS was disconnected from the grid from the beginning of the test. In this situation it is possible to start and run the Whispergen.

It appeared that it is not possible to start the Whispergen microCHP using the inverter. During the pre-start and starting phase of the Whispergen it works fine, but when the engine starts there is a voltage dip due to the high peak demand of the starter motor causing the Whispergen to switch off.
- (3) **Balance load/generation with appliances in islanded situation** The goal of this test is to verify whether it is possible to switch on/off appliances while the voltage/frequency stays stable enough and whether it is possible to charge the battery with the separate inverter and charger. This could not be tested with the inverter and charger while the Whispergen is running, since it is not (yet) possible to start the Whispergen in that configuration. However, it is possible to switch on and off appliances in an islanded situation without the microCHP being switched off, the UPS was capable of maintaining a stable enough 230V/50Hz. Furthermore, it is possible to charge the battery using electricity out of the

battery with the separate inverter and charger. The voltage stayed stable, so presumably it is possible to charge the battery with electricity produced by the microCHP using the separate inverter and charger (when a solution for the voltage dip during the start up is found).

- (4) **Balance the load/generation without battery with grid connected** For this test the Whispergen is connected to the grid and the electricity flowing from and to the grid is measured (both Watt and VA). The import from the grid during this balancing is given in Figure 4. The first plot shows the electricity import during the complete test, the second shows the import during the stabilization. It appeared that the fluctuations in the output of the Whispergen are too large to compensate with the variac controlled loads manually.
- (5) **Find tolerances without battery without the grid connected** As expected after the previous test, it is not possible to compensate the generation of the Whispergen in such a way that a stable islanded situation can be created. Disconnecting from the grid immediately resulted in the Whispergen switching off.
- (6) **Islanded operation** For islanded operation, the control algorithm has to be converted from a discrete to a continuous algorithm. The inputs of the algorithm are continuous but the outputs are discrete. Therefore, the algorithm is executed when the inputs changed a certain amount (e.g. when production changes 10W).

The battery is emulated while the prototype is connected to the grid since it is not possible to start the Whispergen using the Victron equipment.

Since the Gledhill only starts the microCHP when the level is low enough, the level in the heat buffer must be monitored. When the level is too high to start the microCHP, heat has to be dumped already before the microCHP has to be switched on. The controller is able to decide when to start/stop the microCHP and actually start/stop it. Furthermore, it can decide which appliances to supply.

5. CONCLUSIONS

The feasibility study described in this paper verified whether it is possible to create an electricity independent Islanded House during a power cut.

Simulations showed that it is theoretically possible to decrease discomfort by supplying a part of the appliances with the proposed configuration of a microCHP and a battery. These simulations showed that, concerning the load/generation balancing, islanded operation with a microCHP device is possible and the comfort level can be increased significantly whereas adding prediction might lead to even better results. In these simulations a control algorithm decides when the microCHP is switched on/off and which appliances are supplied. Two different algorithms are developed and their simulation results are compared; the results are similar.

A prototype is built to verify whether it is possible to create an islanded situation and what the tolerances are. Although it is not possible to start the microCHP using the inverter, we could verify that 1) it is possible to start and

run the Whispergen in an islanded situation using an UPS, 2) it is possible to maintain the islanded situation while the Whispergen is running and appliances are switched on/off and 3) it is possible to charge the battery in an islanded situation. The balancing tests showed that the microCHP is very sensitive for voltage and frequency fluctuations. Therefore, it is not possible to run the microCHP in an islanded situation without using (battery) equipment for voltage and frequency balancing.

Next, the prototype is used to verify whether the control algorithm also works fine in a real scenario. The controller is able to control the microCHP and appliances, at least when the battery is emulated and the usage of the appliance is defined instead of measured. However, this is caused by limitations of the prototype and can be adapted when required equipment becomes available.

Based on the results of these tests we conclude that it is possible to create an Islanded House and to decrease the discomfort significantly when stabilizing (battery) equipment is added to the domestic electrical infrastructure.

5.1 Future work

The work for the near future will be to find or develop the required stabilizing battery equipment. When this works, it is possible to investigate the possibilities of an autonomously controlled islanded situation. Furthermore, the generic algorithm has to be converted to a control algorithm.

The proposed house configuration and algorithms (especially the generic one) can also be used in a non-islanded situation. For example for peak shaving and limited peak import (e.g. max 2,5kW). This is already investigated for the generic algorithm using simulations in Molderink et al. (2009a), it has to be verified whether this also works with the prototype.

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