A RESIDENTIAL SMART GRID FACILITY FOR TESTING AND EVALUATION OF DECENTRALIZED LOAD MANAGEMENT STRATEGIES

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ABSTRACT: We present the S2G-Home, a residential smart grid facility aimed at testing and evaluating several decentralized load management strategies. The control systems we are developing are installed in twenty households in a residential low voltage grid in the southern part of Switzerland. The S2G-Home enabled the validation of the energy management algorithm and the developed hardware solution in a controlled environment prior to the deployment in the pilot households. The test facility was equipped with a PV generator, two battery-to-grid systems, a synthetic load and an electric vehicle supply device.

Keywords: battery storage and control, demand-side, grid management, grid stability, testing

1 INTRODUCTION

The development of a fully decentralized control system poses significant challenges. In the Swiss2Grid pilot project we studied a decentralized energy management strategy for household appliances driven by local electrical measurements [1]. Every appliance of the household is controlled by an independent algorithm reacting solely on local electrical values (voltage and power) without direct communication and coordination between the devices. The feasibility of this approach has been verified in a simulated environment. It is however necessary to validate the behaviour of the algorithm in a hardware environment, to verify the validity of the simplifications implicit in the simulation and to address other unforeseen problems.

The S2G-Home test-bed facility enables to evaluate the decentralized control strategies in a situation as close as possible to an actual residential home. The PV system is installed in a location exposed to shadowing effects, which are common to residential installations. The test facility is connected to a LV grid and the synthetic load profiles are generated based on actual measurements from the Mendrisio pilot neighborhood households [2]. Moreover the facility is equipped with an electric vehicle (EV) used in real conditions by actual users.

The S2G-Home enables to perform tests in a controlled environment. This is also important because we need a high degree of confidence before the deployment in the real pilot households where the criticality of the system we control (e.g., heating system and hot water supply) is very high.

In this paper we describe the components manufactured for the test facility and we present first results showing the control of the battery-to-grid system by the decentralized management algorithm.

2 ELEMENTS

We realized the test facility on our campus in Lugano. The rationale behind this test facility is to allow preliminary testing on the hardware components and the algorithm scenarios prepared by the project partner [2]. The facility is used to reproduce in a controlled environment the situation observed in the Mendrisio pilot neighborhood households [3]. The system is depicted in figure 1.

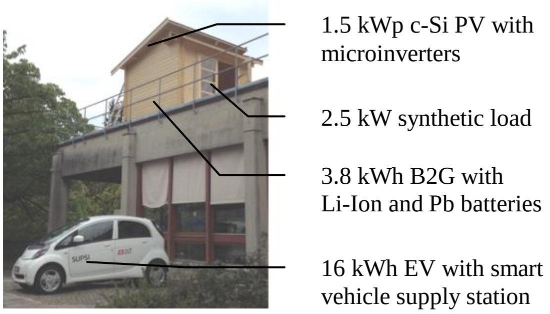

Figure 1: S2G-Home components and features.

The S2G-Home is connected electrically to the SUPSI campus. The exchanged energy between the house and the campus is monitored. The electric car is charged by an electric vehicle supply equipment (EVSE) powered by the S2G-Home.

Every element of the facility is monitored by a Household Appliance Controller (HAC), a hardware developed in-house as part of the Swiss2Grid project [2]. The HAC measures the relevant electrical AC values (voltage, current, frequency) over the three phases and supplies this information to the control algorithm. The HAC has additional communication channels, RS232 and CANbus, for monitoring and controlling the connected appliances. A 230 VAC relay is also included and it is used to power off the connected devices.

Each HAC is connected over a powerline communication (Echelon) to an embedded Linux computer that works as a data concentrator for the test facility.

2.1 PV generator

We installed a 1.5 kWp monocrystalline system. The DC power of each module is converted by a 250 W microinverter. In addition to the HAC measurements we installed a high accuracy AC and DC measurement device, which monitors continuously the PV generation. On the house roof we also mounted a pyranometer and a camera for the evaluation of shadowing effects.

2.2 Battery-to-Grid (B2G).

We designed a B2G system suitable for household installation. The battery technology was selected to ensure a safe behavior in a domestic environment. In the S2G-Home we installed a 24V/200Ah Lithium-Iron-Phosphate (LiFePO4) battery and a 24V/300Ah Sealed-gel Lead-acid battery. The safety is especially critical for the Li-Ion battery pack. The chosen $LiFePO_4$ chemistry is one of the safer options. Moreover the battery pack embeds an industrial grade battery monitoring system (BMS) with an electronic safety switch [4]. A block diagram of the realized B2G system is shown in figure 2.

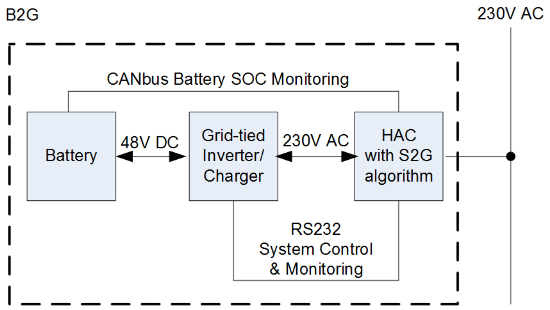

Figure 2: Block diagram of the battery-to-grid system.

The battery is connected to a 2.4kW AC multi-functional grid-tied charger/inverter (Studer XTM 2400-24, Studer Innotec SA, Sion, Switzerland)[5]. We selected this inverter because it has a high level of customization and parameterisation. We used this flexibility to adapt the charge modes and voltage levels to the Li-Ion battery chemistry. Moreover these parameters are externally accessible and modifiable via a RS232 serial line. We used this communication interface to drive the inverter from the HAC with the decentralized control algorithm. The BMS of the battery of the Lithium-Ion battery is also connected to the HAC by a CAN bus line, allowing to monitor the relevant parameters, in particular the state of charge, of the battery. The setup is shown in figure 3.

Figure 3: B2G setup. The grid-connected inverter/charger is shown on the left and the Lithium-Ion batteries on the right.

2.3 Electric Car Supply Equipment

An electric vehicle charging station is connected to the S2G-Home. The car supply equipment is controlled by the algorithm via a RS232 serial line, enabling the modulation of charge power and starting and stopping of the charging process. These functionalities are achieved by using the Mode 3 EV charging [6].

The EV, a Mitsubishi i-MiEV, is used by real users for work related trips. The users can supply additional information to the charge station interface as an input to the control system decisions.

2.4 Programmable load

We developed a programmable active load, which can be used to simulate any appliances of the house. The active load can go up to 2.5 kW power with 20W steps. The load was realized with a resistor bank installed at the exterior of the S2G-Home. We developed a test software which is used to reproduce the load profile monitored in the project pilot households.

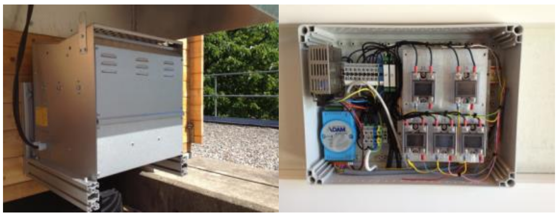

Figure 4: 2.5 kW programmable active load.

2.5 Control software interface

We developed multiple interfacing options in order to maintain a single codebase for the algorithm and allow easy testing in different scenarios (simulation, S2G-Home test site, Mendrisio pilot households). This enables continuous improvements to the algorithm inner workings without affecting the finalized interfaces. The improvements of the algorithm can be simultaneously deployed in the simulation, the test facility and the pilot households.

3 RESULTS

We previously demonstrated in a simulated environment that the local voltage measurements can be used as an input for a control algorithm [1,2]. In particular, the voltage measured at the socket can be used as a predictor of the state of the grid, as it inversely correlates with the power drawn from it. When the measured voltage is higher than average it means that a small amount of power is being drawn from the grid. It would therefore be favorable to turn on shiftable loads, as for example charge a battery or an EV. Conversely, when the voltage is low, it would be beneficial to the grid to turn off shiftable loads and to inject power from B2G systems. Based of the time-history of voltage, the S2G algorithm predicts the future state of the grid and by using a model predictive control strategy it reschedules the activity of the shiftable loads, with the aim of optimizing the electricity costs and the grid stability in lexicographical order.

After the initial development of the algorithm, we performed several tests in the S2G-Home. Difficulties in building robust and reliable interfaces with the hardware devices were manifest, but were solved during the preliminary testing phase.

Figure 5 shows the behaviour of the algorithm controlling the B2G system over a period of three weeks.

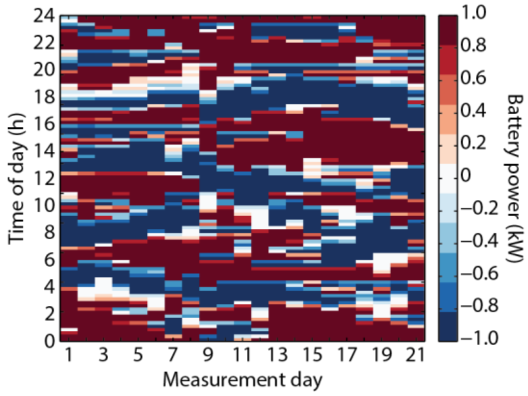

Figure 5: B2G behaviour. Power pattern of the battery measured at different hours of the day (y axis) and measurement days (x axis). 15 min averages of power are shown color coded; red values show charged power, blue values show injected power.

During this test we didn't set cycling constraints, the algorithm freely cycles the battery following the voltage fluctuations induced by the local PV generation and by the synthetic and real loads connected to the same grid.

In figure 6 we show an example of the decisions performed by the algorithm on the battery bank during a 24 hours period. The algorithm used the voltage measured at the plug of the battery-to-grid system and estimated the voltage drop on the line caused by the battery itself using a linear regression on the time history of measured power and voltage changes. It then compensated for this effect and extracted a corrected voltage profile that represents the voltage fluctuations caused by the PV and the other loads in the low voltage grid.

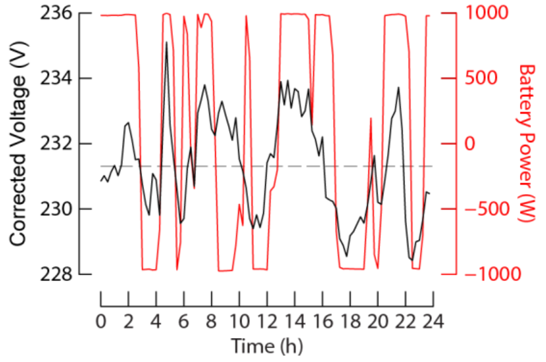

Figure 6: Example of the algorithm controlling the battery system for a 24h period. Black: corrected voltage measured at the battery-to-grid plug. Red: battery AC output power (positive: charging/negative: discharging).

Figure 7 shows the mean B2G power as a function of the corrected voltage for the three weeks of test of Figure 5. The voltage was normalized by dividing it by the mean voltage of the corresponding measurement day, in order to remove long term seasonal voltage fluctuations. As expected, at high voltages the battery gets charged while at low voltages power is injected into the grid. The relationship between the normalized corrected voltage and the mean battery power is highly linear, yielding a correlation coefficient of R=0.945 (red line in Figure 7). The linear fit does not cross the zero power line (dashed line on Figure 7) at normalized voltage equal one, as the efficiency of the B2G system is below 100%. As a consequence, the energy required to charge the battery is higher than the returned one. Over the three weeks of data, we measured an efficiency of 77.6% for the B2G system.

Qualitatively, the algorithm has shown to behave as expected when operating on real hardware. In the example we see that the control algorithm tends to charge the battery when the voltages are high (higher PV generation and/or lower consumption from other loads) and inject back the power when voltages are low (lower PV generation and/or higher consumption).

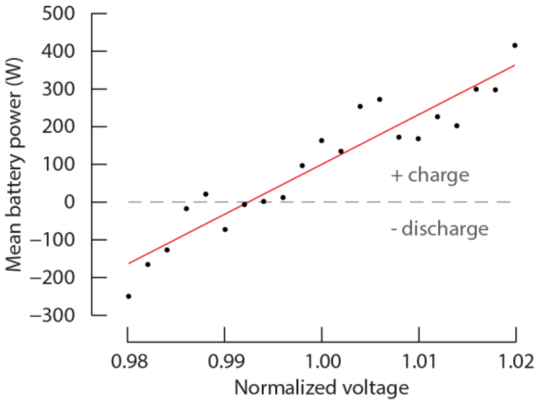

Figure 7: B2G mean power as a function of the normalized corrected voltage. Black dots: mean battery power, red line: linear regression.

4 CONCLUSIONS

The first real testing has shown a qualitatively reasonable behavior of the algorithm, which was able to respond to unpredicted changes in voltage. The testing also confirmed the need to discount voltage-drops induced by the decisions of the algorithm itself in order to guarantee a higher quality inference of the future state of the network and achieve a smooth behavior. The validation of the control system in a test hardware environment enables the deployment of the algorithm in the pilot neighborhood.

5 ACKNOWLEDGMENTS

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