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Grid-Connected PV + Battery AC Nanogrid with EV Integration for Increased Resilience

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Abstract. This work concerns a three-phase grid-connected AC nanogrid with PV generation and battery storage. The system is based on SMA Sunny Boy (SB) and Sunny Island (SI) inverters with a Data Manager for monitoring and control. It also includes an EV that can be charged through a standard 208V unidirectional charger when the grid is available. A low-cost single-phase unidirectional Vehicle-to-Home (V2H) inverter, that communicates with the BEMS of the EV, is available at the site. It can supply isolated loads but not to operate in parallel with the PV + battery three-phase system. To allow the EV to support the nano-grid, the V2H is connected through a fourth SI (SI4) to charge the stationary battery. An energy management scheme is proposed for extending load supply following a transition from grid connected mode to islanded mode. It includes not only EV battery support but also load shedding scheme to manage the SOC of the battery. Experimental results are presented.

Key words. PV-battery AC nanogrid, electric vehicle (EV), vehicle-to-home (V2H), DC coupling, energy management,

1. Introduction

Environmental concerns regarding carbon emission have led to vast research works to minimise the use of fossil fuel and increase the penetration of renewable and eco-friendly energy sources (RES). In order to avoid the devastating effects of climate change, a meaningful decarbonisation of the global economy should be implemented by 2050[1]. This includes transportation electrification, ideally charged with RES, and netzero energy homes and buildings. For increased resilience, electric vehicles (EVs) should be able to support homes and buildings during power outages caused by technical faults and extreme weather conditions.

Microgrids and nanogrids are small-scale power grids with controllable sources and storage units that can operate connected to the utility grid or isolated. They offer a promising solution for enhancing reliability and resiliency in the power sector. Besides, by incorporating Distributed Energy Resources (DER), these systems can supply active power to local loads, thereby reducing power losses in transmission and distribution networks. Additionally, they can improve local power quality by providing ancillary services, such as voltage support through reactive power injection, assisting in fault restoration with intelligent devices, and maintaining local control of voltage and frequency [2]. A nanogrid acts as a fundamental unit within a microgrid, which is controlled with smart grid technologies. It must function reliably both in a cluster of nanogrids, a microgrid, and independently, either in islanded (stand-alone) mode or connected to the utility. Its operational independence enhances the reliability, efficiency, health, and fault tolerance of the smart grid [2].

To increase the economic justification of EVs while improving resilience and power quality schemes such as vehicle-to-grid (V2G), vehicle-to-home (V2H), and vehicle-to building (V2B) are considered [3]. There, an EV is considered as an electric energy storage element, absorbing and supplying active power according to a home or building energy management algorithm. The EV is charged (G2V or H2V) at low demand hours (midnight) and helps shaving the peak demand by delivering electricity power to grid (V2G), home (V2H), or building (V2B) in peak hours [3-5]. The connection of EV to an off-grid home is investigated in [4]. There, the EV is exploited as a means to support the home nanogrid and considered as a bidirectional storage, charging mainly at night with wind energy or when renewable energy (RE) production exceeds the consumption and discharging when Hybrid Renewable Energy System (HRES) does not guarantee the load demand. A few methods are used as interface between EV and home. Reference [6] used a bidirectional half-bridge DC-DC converter as an interface between EV and DC nanogrid with a PV system. This paper introduced a 3-phase inverter as an interface between DC nanogrid and AC grid to add the ancillary service of exchanging active and reactive power with the AC grid. On the other hand, reference [7] uses an AC-DC converter as an interface between EV and Home/Grid. In this scheme, EV and home are charged/fed by the utility grid and in case of power outage, the home can be fed from the EV battery and proposed converter. Some research works such as [8] introduced an integrated onboard power converter with G2V/V2G/ and V2H capabilities. There are some commercial bidirectional EV chargers recently introduced and capable of performing V2X along with EV charging as main task. Some of which cannot be installed in North America as they are not certified to be used in this region [9].

In this work the focus is on integrating an EV to a three-phase PV + battery SMA system using a low-cost single-phase V2H inverter. It communicates with the EV BEMS but is intended to supply an isolated load by itself, unable to operate in parallel with other sources/storage units. The final goal is to increase the system resilience using the EV as a secondary energy storage. Besides, it presents an energy management strategy for operation during utility power outage that includes load shedding as the SOC of the stationary battery decreases. The work is tested at the Future Building Laboratory (FBL) that is employs SMA products. Commercial equipment is usually very reliable but not very flexible to prevent non-expert users from configuring potentially risky systems. Thus, the adopted methodology should be compatible with the commercial equipment features and constraints. It should be noted that SMA has some commercial products such as SMA Home Manager 2, with home management features such as weather forecasting and communication with smart devices, but it is not available in North America.

This paper is divided into 6 sections. Section 2 presents the system configuration. In Section 3, the main system components are described. The proposed energy management strategy is discussed in Section 4. Then, the performance of the system with the proposed hardware and control strategy are provided in Section 5. Finally, a conclusion is presented in Section 6.

2. System Description

The Future Building Laboratory (FBL) nanogrid is connected to the utility grid through a 150 kVA, 600 V: 208 V Δ:Y transformer. The overall configuration of the FBL is shown in Figu. 1. The conventional three-phase PV + battery system based on Sunny Boy (SB) and Sunny Island (SI) single-phase inverters is connected to the main service panel. The "priority" and "high priority" loads are connected to the SB's side of the SI inverters. In case of a power outage, the PV + 48 V battery system will supply initially all priority loads. As the SOC of the battery decreases and reaches 50%, the SMA Data Manager (DM), opens a relay through the ioLogik interface and the PV + battery system supplies only the high-priority load. The battery is also connected to the EV's 400 V battery through a single-phase unidirectional grid-forming V2H inverter in series with a relay and another SI (SI4). This concerns the main novelty of the system. It's hardware and control logic are discussed in detail in the following Sections. The EV is charged with a conventional unidirectional charger from the main service panel. The EV should not be charged during islanded condition or discharged when the grid is available.

Fig. 2 illustrates the conventional PV + battery modules arrangement. The three single-phase SI battery inverters are connected in star. In this system SI1 is the master while SI2 and SI3 are slave 1 and slave 2, respectively. SI4, shown in Figure 1 but not in Figure 2, operates independently of the other SIs. The three single-phase SB PV inverters can form delta or star configuration as they can support 120 or 208V. At the FBL, they are connected in star. Thus, each SB corresponds to a SI. On the other hand, each SB works independently from each other. All four SIs are connected to the same stationary battery bank through a splitter box. The master SI communicates with the battery management system (BMS) of the battery bank through a data (CAN) cable. It should be noted that the BEMS has only one CAN communication terminal, meaning that SI4 will not be able to connect to the BEMS to obtain SOC information. A Data Manager (DM) working based on ennexOS IoT platform is used for commissioning, monitoring, and control of the proposed nanogrid. The DM is connected to the master SI (SI1) through a RS485 serial interface. The SBs are connected to the DM through one of the DM ethernet ports. The other port is connected to the Internet.

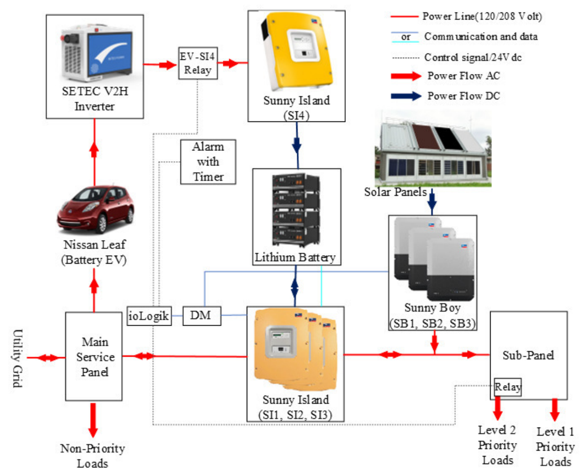


Fig. 1. Schematic diagram of the PV + battery + EV AC nanogrid at Concordia's Future Building Laboratory (FBL).

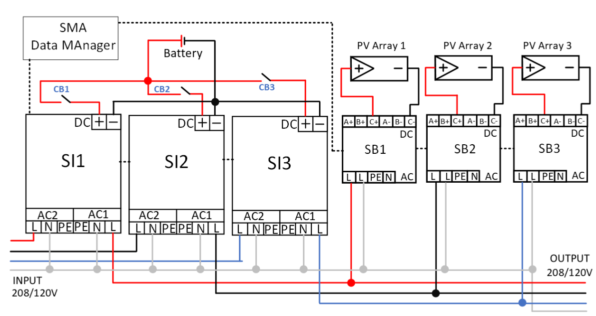


Fig. 2. Schematic diagram of the PV and battery system connections.

3. Main System Components

A. *PV arrays and inverters*

As Fig. 3 illustrates, 12 solar terra Copper 210Wp, 12 Grey 210Wp and 12 Black 230Wp arrays are in the process of being installed on the rooftop of FBL. The array's rated powers are of 2520, 2520 and 2760 Wp, respectively. The last one will be used as BIPV/T for electricity generation and heat recovery.

Three SMA SBs (Sunny Boy 7.0-US) convert the DC power produced by the rooftop PV arrays into AC and deliver it to the nanogrid. This model, in single-phase/split-phase mode is capable of supporting 120V, 120/208V, 208V, or 240V and in three-phase mode, 208 or 240 VLL. Its maximum DC input voltage is 600V. Its Maximum Power Point Tracking (MPPT) voltage range is 100-550V with initial voltage of 125V. Its rated power at 240V AC is 7 kw and at 208V AC it is 6650W. It has a maximum efficiency of 97.9% at 240V. It has 3 MPPT inputs and, as shown in Fig. 2, the inputs C of each SB are used in this system [9].

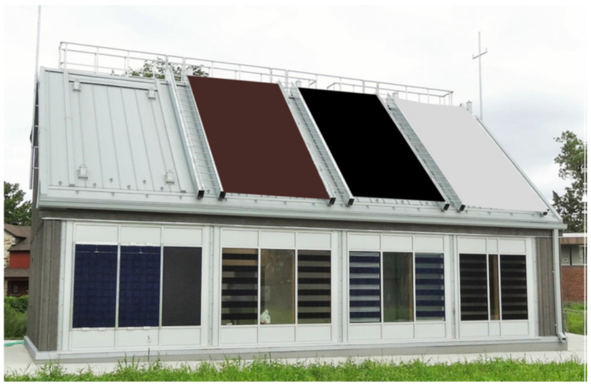


Fig. 3. Solar arrays on the roof of the FBL.

B. PV arrays and inverters

Three SMA SIs (Sunny Island 6048-US) are used in the FBL system. Their nominal battery voltage is 48 V (41 V-63 V), the rated power is 5750W, and the maximum efficiency is 94 %. The nominal AC voltage is 120 V (80 V-150 V) and they are connected in star. The nominal battery charging current is 110 A with a maximum of 130 A. This charging current is adjustable. The AC side current is also adjustable: 0 A-56 A. It accepts Lead-Acid, NiCd and Li-ion batteries from 100 Ah to 10000 Ah [9].

Fig. 4 shows the three internal connections of an SI. The battery bank is interfaced to load/SB through a "bidirectional inverter" which balances PV generation and load demand when forming the grid in the islanded mode. The utility grid/generator terminal is connected to the load/SB terminal through an isolating relay. In case of power outage or deviation of utility grid/Generator voltage and/or frequency out of predefined range, the SI opens the internal isolation relay. When the grid/generator resumes with the required parameters, the "bidirectional" inverter resynchronizes to the grid/generator, the SI closes the internal isolation relay, and the "bidirectional inverter" returns to the grid-following mode.

The battery bank of this system consists of 6 units of Pylontech - US3000C, forming a 21.3 kWh bank with nominal voltage of 48V. This battery is of the LiFePO4 type, and each unit has the nominal capacity of 3.55 kWh with 3.37 kWh of it being usable. The lifetime of this battery would be 6000 cycles in Depth of Discharge (DOD) of 95%. The top battery unit is the master, and the five others are slaves. The slave battery units communicate with the master one through link port terminals and wired in chain configuration. The master SI unit communicates with the master battery unit through a CAN cable and transfers battery information to the DM through RS485.

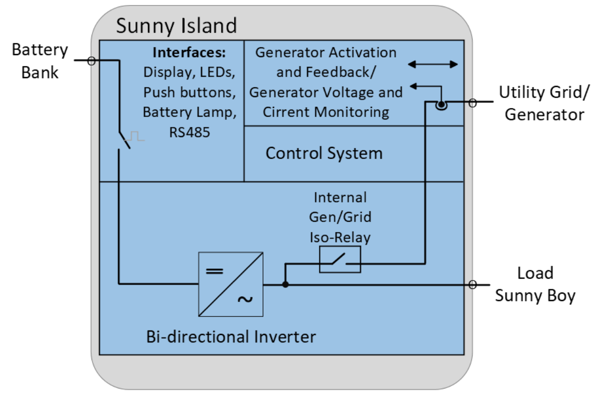


Fig. 4. SI internal connections.

In this research work, two independent SIs (SI1 and SI4) are connected to the stationary battery bank. According to SMA recommendations, only one SI should be connected to the communication port of the master battery unit. Thus, SI4 cannot receive battery information, what is indispensable for configuring the battery as lithium-type. To solve this problem, the type of battery in SI4 is defined as lead-acid. One issue with this solution is that the SI4 becomes unable to measure the SoC of the battery correctly, what might lead to the overcharging of the battery. To solve this problem, an external relay, placed between the V2H inverter and SI4, is employed as shown in Fig. 1. It is controlled by an I/O interface that received the actual SoC of the battery, provided by SI1 through the DM. This relay will stop the stationary battery charging process (protecting the battery from overcharging) by stopping the flow of power from EV to the battery when the SoC reaches a certain level.

C. SMA Data manager and auxiliary circuitry.

The Data Manager M, in combination with the Sunny Portal powered by ennexOS, enables effective monitoring, management, and grid-compliant power control for decentralized PV systems. It supports up to 50 devices with an inverter capacity of 2.5 MVA in closed-loop control mode, or up to 7.5 MVA in open-loop control or monitoring mode. With the help of the user interface of ennexOS, it is possible to monitor the instantaneous and accumulated values of system variables such as PV generated power or battery SoC. It is also possible to perform grid and energy management strategies ranging from load shedding to active and reactive power control of the system [9].

The I/O device used in this project is the ioLogik E1242. It is equipped with 4 analog inputs, 4 digital inputs, and 4 digital configurable digital input/outputs. It also has a 2-

port Ethernet switch for daisy-chain connections. Fig. 5 shows the electrical connection of the ioLogik E1242. The 4 digital outputs are configured and used for load shedding, alarm to connect the V2H to the EV and control the relay between the V2H inverter and SI4. They can be programmed by following the path of "Configuration>Grid management service> Assign digital outputs" in ennexOS. Their status is based on the "Current Battery State of Charge" as the variable, provided by the DM, and each has a different threshold value of SoC.

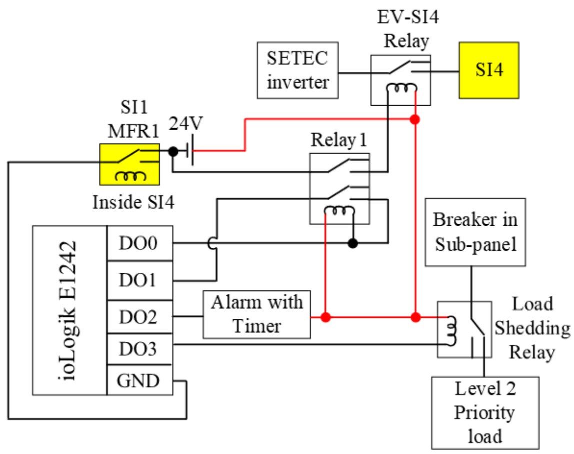


Fig. 5. ioLogik E1242 digital outputs wiring connection.

D. *EV and unidirectional interfaces*

A Nissan leaf model 2015 with a 400 V, 24 kWh Lithiumion battery bank is included in the FBL system. Its original portable charging cable works with 100-120 V/15 A or 200-250 V/ 20 A. The charger used at the FBL is a 208V Grizzl-E mini level 1-2 EV charger, delivering up to 40 A.

For using the EV to support critical loads of the FBL a single-phase Vehicle-to-Home (V2H) SETEC Power inverter shown in Fig. 4, was employed. It is rated at 6 kVA, 110 V/ 60 Hz. It is intended to supply isolated loads with regulated voltage and frequency. It communicates with the BMS of the EV and keeps supplying the load as long as the SoC of the battery is above 30%. It is also protected against overload and short circuit in the AC side. However, it is unable to operate in parallel with other power units, grid or inverters. One option to benefit from the energy stored in the EV to support the three-phase system, is to connect the EV to the stationary battery. For that, one can employ a simple 48 V battery charger in series with the single-phase SETEC V2H inverter. The problem is that these usually do not provide much flexibility to control the power flow from the EV, V2H inverter, to the stationary battery, which should only occur when the latter is at critical SOC. That is why a fourth SI is used in this work, as discussed in Section 2.B.

4. Energy Management Strategy

The proposed procedure for having the EV battery supporting the AC nanogrid under critical utility outage conditions is divided into 7 stages. It should be noted that according to the duration of the power outage, PV generation and load consumption, the system may witness only a few of the 7 stages. Herein, the stages are described in more details.

Fig. 6. 6kVA SETEC Power Vehicle-to-Home (V2H) Inverter.

Stage 1: In this stage the utility grid is "normal", regulating voltage and frequency. All loads including the priority ones, are fed from utility grid and power provide by the PV panels, during daytime. The internal isolation relays of SI1, SI2 and SI3 are on. They follow the utility grid and, if needed, charge the battery.

Stage 2: It starts following a power outage. The internal isolation relays of SI1, SI2 and SI3 open and they start forming the grid, absorbing or supplying the balance between the power produced by the SBs and consumed by the three-phase priority loads. This can cause the SoC of the battery to increase or decrease.

Stage 3: If the SoC of the battery drops below 50%, stage 3 starts. Load shedding is implemented to save battery energy and support higher priority loads for extended periods. The SoC of the battery is continuously informed to the ioLogik by the DM. As the SoC drops below 50%, the Digital Output (DO3) of the ioLogik is activated and energizes the control coil of the "load shedding relay" as indicated in Fig. 5. This is a normal close relay that disconnects the Level 2 priority load when energized. It should be noted that during normal utility grid condition, all outputs of the ioLogik are deactivated. Besides, the ground terminal of the 24 V source, that energizes the control coils of the relays is not connected to the output ground terminal of the ioLogik because relay SI1-MFR1 (Multi-Function Relay 1) inside SI4 is programmed to be open during normal utility grid operation. It is closed following a grid fault. Fig. 5 shows SI1-MFR1 during grid fault condition. The means for programming the ioLogik is described in Section 2.D.

Stage 4: If the SoC of the battery keeps decreasing, dropping below 45%, stage 4 starts. This is the time that the EV should be prepared for connection to the islanded grid to extend the time the Level 1 priority loads are fed. At this SoC, an alarm connected to DO2 of the ioLogik is activated to warn the operator/ homeowner to connect the EV to the V2H inverter. A 1-minute timer was selected for this function.

Stage 5: Since the SIs turn off at a battery SOC of 30%, the power transfer, from the EV to the stationary battery is chosen to start at an SoC of 40% when relay EV-SI4 is energized and closed. Recall that the V2H inverter was energized in the previous stage, while SI4 is always kept on. Chattering, as the SoC of the battery varies, should be avoided. Unfortunately, it is not possible to program the ioLogik or DM to do so. However, a suitable control scheme with MFR1 of SI1, a low current relay (Relay 1) and 2 ioLogik outputs (DO1 and DO0) as shown in Fig. 5 can be used. SI1-MFR1 is closed under power outage conditions and feeds the GND port of the ioLogik. DO0 carries GND when the SOC is below 80%, and Relay 1, controlled by DO1, remains closed while the SOC is below 40%. When Relay 1 is activated (SOC ≤ 40%), relay 1 connects DO0 to DO1. This means, after first activation, even if the battery SOC increases above 40%, DO0 holds Relay 1 active until 80% of SOC as a latching mechanism. The other contact of Relay1 controls the relay V2H-SI4.

With the V2H inverter connected to the AC/Gen side of SI4, it takes a few minutes for the SI4 to close its internal isolation relay and start charging the stationary battery. The power flow from the EV to the battery can be controlled either by setting the AC side or the DC side currents of SI4. If either the SoC exceeds 80% or the power outage ends, the flow of power from the EV to the battery ends as relay 1 opens.

Stage 6: If the SoC of EV battery falls below 30%, the V2H inverter, that communicates with the EV battery, shuts down to protect the EV battery. If this happens while the SoC of the stationary battery is bigger than 30%, one returns to stage 2. If the SoC of the stationary battery falls below 30% prior to that of the EV battery, SI1 the master SI, shuts the system down.

Stage 7: Assuming that the SOC of the stationary battery is above 30%, this stage starts when the utility grid returns to normal condition. The flow of power between the EV and the stationary battery, if any, stops. After grid resynchronization, the internal isolation relays of SI1, SI2 and SI3 close and they return to the grid following mode, recharging the battery. This is followed by a return to Stage 1. It should be noted that whenever the grid returns to normal condition, relay SI1-MFR1 opens, ending load shedding and power transfer from the EV to the stationary battery.

5. Test Cases and Results

The proposed configuration, control strategy and system implementation for allowing an EV with a single-phase V2H inverter to support a three-phase hybrid Photovoltaic plus battery nanogrid was tested experimentally at Concordia's Future Buildings Laboratory (FBL.) The goal was to verify its performance and accuracy following a power outage. As a measurement tool, the DM ennexOS webpage and the display of the Sunny Island inverter (SI4), employed for charging the stationary battery from the EV, were used. Table 1 shows the values of system parameters used in this test.

At the moment of writing the paper, the rooftop PV panels were not yet available for testing. As a result, a scheme with only two PV emulators, one of 2 kW and another of 1 kW was used for testing. The first and larger one was connected to phases AB while the second to phase C and neutral. Since the SBs operate inherently independently, there were no problems, and the SIs of each phase managed the unbalanced power injections.

To decrease the overall time of this test, the SoC levels mentioned in Section IV were modified as follows. Load shedding was activated at 95% of SOC, instead of 50%. The enabling of power flow from the EV to the stationary battery, via V2H inverter and SI4, occurs at 94% of SOC instead of 40% while its disconnection takes place for an SoC of 98% instead of 80% of SoC. In this test, the alarm is also activated at SoC = 95% to have time to connect EV to SETEC inverter.

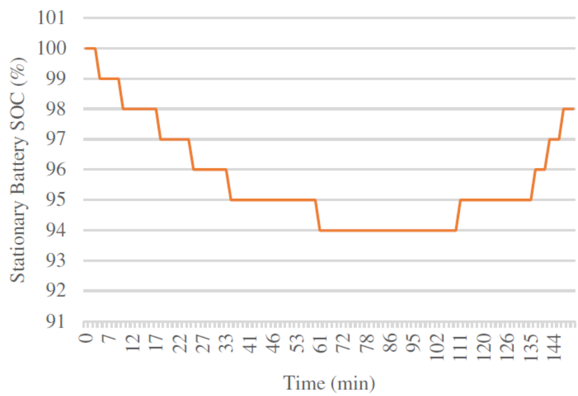
Fig. 8 shows the following quantities of the system under consideration: SoC of the stationary battery, load demand, PV generated power, SIs injected power, and EV-SI4 delivered power. These are measured every minute. The small fluctuations observed in Fig. 8.b) are due to the MPPT feature of the SBs.

Following the grid fault at t = 0 minute, since the load demand (4.8 kW) exceeds the PV power generation (3 kW), the battery inverters supplement the PV inverters and the SoC of the battery decreases. At t = 34 minutes, it reaches 95% and the ioLogik opens the level 2 priority load (1.3 kW) relay. Nonetheless, the load demand still exceeds PV supply but with a lower power shortage (500 W), the SoC of the battery decreases more slowly. Besides, the alarm is activated and warn the operator for one minute to connect SETEC V2H inverter to the EV.

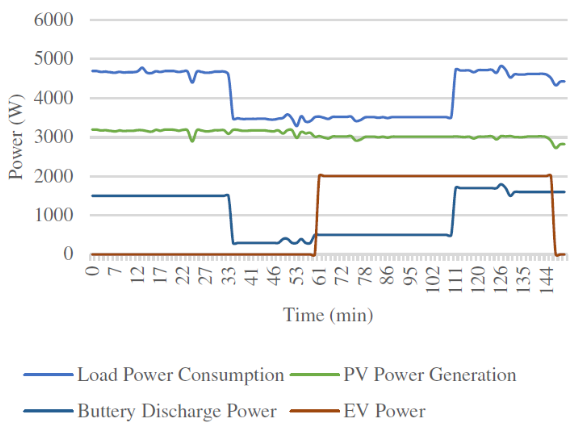
Table I. – System parameters

Parameter	Value
Level 1 priority loads	3480W~3.5kW
Level 2 priority loads	1270W~1.3kW
PV generation	3035W~3kW
EV-SI4 charging power	2010W~2kW
Stationary battery capacity	21kWh
EV battery capacity	24kWh

Then, it takes 17 minutes for the SOC to reach 94%, when the ioLogik and the proposed circuitry closes the EV-SI4 relay, and 2 kW starts to flow from the EV to the stationary battery. Since the load demand and PV generation remain virtually unchanged, there is a net positive power flow into the stationary battery of about 1.5 kW and its SOC increases. As it reaches 95% at t =111minutes, load shedding ends. One can see that this leads to the increase of the load demand and of the power injected by the SIs into the AC bus. Still, due to the 2 kW drawn from the EV, the SOC of the stationary battery keeps increasing until t = 146 minutes when it reaches 98%, prompting the ioLogik to deactivate the EV-SI4 relay and stopping the power flow from the EV to the stationary battery.



(a)



(b)

Fig. 8. Measurements. a. Stationary battery SOC b. Power values.

Fig. 9. Devices used in the proposed test bench: 1. Sunny Islands, 2. Sunny Boys, 3. Nissan Leaf, 4. Sub-Panel and Loadshedding Relays, 5. Pylontech Battery, 5. SETEC V2H Inverter, 7. Sunny Island 4, 8. EV to SI4 Relay, 9. ioLogik, 10. Interface relays, 11. Programmable Load, 12. PV Emulator.

6. Conclusions

A methodology for connecting a single-phase V2H inverter to a 3-phase nanogrid with PV generation and battery storage is presented. The original system is based on SMA technology with three Sunny Boys (SBs) and three Sunny Islands (SIs) controlled through a Data Manager (DM). Since the V2H inverter was unable to be connected to the three-phase system, a scheme employing a spare SI, an ioLogik, relays and an alarm was devised. It allowed the combination of load shedding and supplementing the stationary battery with energy from the EV, so as to extend the supply time of the level 1 priority load under island, grid fault, condition. The logic is based on the SoC of the stationary battery which is shared among all system components by the DM. In this way, one can find a good trade-off between supplying level 1 and possibly level 2 priority loads while resorting to the energy stored in the EV only in critical conditions. Experimental results are provided to demonstrate the feasibility of the algorithm and implementation of the proposed scheme. As future work, one can compare this approach with others concerning cost-effectiveness and performance.

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