Energy Management in a Prosumer Installation Using Hybrid Systems Combining EV and Stationary Storages and Renewable Power Sources

Pawel Kelm *, Rozmyslaw Mieniński and Irena Wasiak

Institute of Electrical Power Engineering, Lodz University of Technology, 90-924 Lodz, Poland; rozmyslaw.mieniski@p.lodz.pl (R.M.); irena.wasiak@p.lodz.pl (I.W.)
* Correspondence: pawel.kelm@p.lodz.pl

Abstract: Modern consumer installations can be equipped with renewable power sources (RESs) and stationary energy storage systems (ESSs). In addition, electric vehicles (EVs) are expected to become part of such installations in the not-too-distant future. The paper presents the control strategy that allows for efficient energy management and the option of EV “fast-home” charging. The novelty of this approach includes the use of the “time-dependent energy storage” (EV battery) together with ESS and PV sources with the focus on prosumer benefits. All goals can be achieved without the need for extensive expenses in the home electric infrastructure. To enable the synergy effect, it was necessary to develop a controller algorithm that uses the operating status of the prosumer infrastructure (current power generation and consumption), the state of charge of both the stationary storage and the EV battery, and the possibility to control the EV drive inverter during the parking state. The paper presents a developed simulator built in the PSCAD environment and the simulation results.

Keywords: vehicle-to-home; EV drive inverter; hybrid storage system; ancillary services; electrical installation; on-board charger

1. Introduction

In the prosumers’ installations connected to low-voltage (LV) distribution networks, photovoltaic sources (PVs) are used most often.

The PV power generation profile usually differs from the profile of power demand [1–3]. As a result, during times of high PV generation and low-power consumption, the power is fed to the supplying network [4,5]. The impact on the network operation of randomly varying and non-dispatchable PV power is widely discussed in literature [6–8]. It may result in voltage variations, a reversed power flow, and an unacceptable voltage rise in the network nodes. These phenomena cause the deterioration of power quality in the network and may lead to the disconnection of PV inverters when the voltage limit at the point of common coupling (PCC) is exceeded.

The mismatch between power generation and consumption is a challenge for both the distribution network operator (DSO) and a prosumer who must accept that some part of the generated energy might be lost if it is not immediately consumed. For example, there are law solutions where the prosumer can use the supplying network as a storage of 80% or 70% efficiency [9], depending on the rated power of the PV installation (80% in micro-installations up to 10 kWp, and 70% in small installations up to 50 kWp). Thus, the prosumer may recover only 70–80% energy transferred to the supplying network within one year. Stationary energy storage systems (ESSs), designed for residential applications, can help in more efficient energy management [3,10]. However, due to relatively high
prices, the ESS in the prosumer installation usually has a low capacity, rarely exceeding 10 kWh. Hence, its functionalities are limited.

In recent years, a fast development of electromobility has been observed. Due to the decreasing prices of electric vehicles (EVs) and a constantly expanding number of available models, it can be anticipated that an EV will become a standard element of the prosumer installation in the near future. The EV considered as a large mobile storage system (between 50 kWh to 100 kWh) can be used for energy management during parking if it is connected to the prosumer installation. Thus, the prosumer gets a new tool for better use of their electrical energy resources.

This is an interesting research topic, which raises the question of how to integrate three types of devices (PVs, ESSs, and EVs), not only to mitigate the potential problems of their impact on the supplying grid but also to obtain a synergy effect for the prosumer.

In the most straightforward approach, one can assume that for the effective use of renewable energy generated in the prosumer installation, the EVs should be charged whenever there is excessive power available from renewables. Additionally, the local power consumption could be supported with the smart charging [11] functionality. This should eliminate or postpone the need for investment in the supplying network reinforcement required due to the increased power demand. This approach, although reasonable, rather concentrates on the mitigation of the negative effect of the high deployment of EVs and is mainly beneficial for the network operators. However, in the authors’ opinion, the potential of electromobility could be better explored if EVs were used for ancillary services focused on the prosumer’s benefits, assuming that these are equipped with bi-directional drive inverters that can also be used for charging and discharging the EV battery.

There are numerous publications dedicated to the problem of self-consumption of locally generated power with the use of Vehicle-to-Building (V2B) or Vehicle-to-Home (V2H) services. In most cases, the authors assume high aggregation of EVs (a large number of EVs available for management). Other studies consider EV fleets at a city or region level. In a previous study [8], the V2B service is discussed as an element of the Internet of Energy [9–11]. EVs are used as a temporary storage for the surplus PV generation in the building installations. The issue of the storage availability is solved assuming a large number of vehicles at the building parking lot. The authors used real data from different regions of the USA and the achieved electricity cost reduction from 5% to 16%.

In previous research [12], the authors propose a communication energy management framework for an office building with RESs (Renewable Energy Sources), stationary storage and a fleet of EVs. The authors conclude that the communication with the DSO can be achieved through aggregators using advanced metering infrastructure. The energy produced by prosumers can be sent to the grid and/or it can be stored for future utilization.

In another study [13], a price-incentive model is used to coordinate the charging of EVs and battery-swapping stations to optimize energy management and to eliminate the uncoordinated charging. Grid-connected and islanded-mode operation are discussed.

The charging optimization problem in real time pricing (RTM) electricity market is discussed in [14]. The authors presented the optimal EV charging algorithm, which considers battery charging in a spot or real-time electricity market. The strategy is to automatically manage the charging time once the vehicle is plugged in to provide a full charge when required but at the lowest cost. The numerical simulations were used to present the possible benefits based on the example of the Illinois RTP tariffs.

The concept of increasing the PV power self-consumption by smart charging EVs and the use of “Vehicle to Grid” (V2G) technology/service is studied in [15]. The authors focused on a microgrid in Lombok, the Netherlands, and presented a model developed to study different optimization strategies.
An agent-based simulation model is presented in [16]. It is used to evaluate various demand-response programs designed for a household with controllable loads, PHEV, PV generation, and storage.

The issue of high power demand in the case of fast charging stations is discussed in [17]. The study proposed a charging station system including a medium voltage DC network, PV system, ESS battery, and a grid connection. The decentralized control system uses the DC bus voltage as a key parameter for controlling the energy sources. With the use of the proposed distributed model predictive controller (MPC) the authors proved high system performance. The review of the EV charging requirements, specifications, and design criteria for high power applications is in [18]. Authors presented converter topologies of solid state transformers that can be used in super-fast charging applications.

The potential problem of overloading of the utility grid and ineffective utilization of renewable energy sources connected to the multiport charging station is discussed in [19]. Authors introduced a new energy management system maintaining the DC bus power in an analyzed hybrid installation.

Technical issues related to the power quality (in particular a voltage harmonic distortion) in distribution networks are studied in [20]. Large EV centralized charging stations connected directly to the medium voltage and distributed charging stations connected to low-voltage networks were distinguished to investigate the level and impact of harmonic distortion.

A review of different analyses and studies performed to evaluate the impact of increasing EV charging station penetration on the power quality in supplying network is in [21]. The paper presents a strategies proposed to improve the grid performance.

In automotive applications, hundreds of battery cells must be connected in a series to provide high enough operating voltage, which requires a suitable charging strategy to ensure that all cells are charged within the reliable conditions. Charging strategies are implemented in advanced battery management systems and integrated in vehicle battery packs. Although the development of such systems is a different research area, progress in that respect contributes to the development of EV ancillary services. This subject is addressed in [22], where authors focus on the optimized charging control strategies taking into account the efficiency and safety of the battery cells. Higher efficiency is achieved by the reduction of energy losses. The leader-followers-based approach was proposed to enable optimal charging control.

The challenge related to the battery cells equalizers is addressed in [23]. The authors develop and evaluate new equalizer topologies that offer high speed and efficiency with a compact size. The challenge of the battery thermal management is addressed in [24]. In this paper, a charging control strategy that applies a developed coupled thermoelectric model is proposed.

The battery pack can be effectively used for driving and V2H services only if the drive inverter meets versatile requirements, such as high efficiency and reliability for an affordable price. The study presented in [25] is focused on the development of inverter topology design. Authors proposed an inverter topology that has a lower efficiency compared to other topologies; however, it reduces cost and size by utilizing low rating components at higher-voltage gain operations.

The papers mentioned above provided relevant contributions to the concept of future smart networks with a high deployment of EVs (assuming their large-scale integration into buildings and the supplying network). However, the authors of the cited research either focused on the technical issues or potential effects on the supplying network rather than on the benefits for prosumers.

Since the discussed resources (PVs, ESSs, and EVs) are part of the prosumer installation, this paper focuses on the possible benefits for its owner. Our study aims to show the benefits of using EVs drive inverter, RESs, and stationary storage technology for coordinated energy management, as a small-scale project that can be realized in the prosumer installation without extensive costs. The presented “fast-home” charging
functionality does not offer the charging speed typical for super and extra fast public chargers. However, the introduced system can be used to speed up the charging process at home and be applied for services that require bi-directional power flow. To sum up, the main focus is on the prosumer benefits and other curtailments are not considered.

In the following sections, the elements of generic prosumer installation and a typical EV user’s behavior are presented (Section 2). What follows are the assumptions, the description of the control strategy, and the control algorithm (Section 3). Next, there are the results of the simulations with a description (Section 4) and finally the conclusions (Section 5).

2. Characteristics of the Prosumer Installation

2.1. Description of the Installation

The generic structure of the discussed prosumer installation connected to the low-voltage distribution network is presented in Figure 1. It consists of loads, a PV system, a stationary energy storage system, and an electric vehicle.

![Figure 1. Generic structure of prosumer hybrid installation connected to the LV network.](image)

According to the binding regulations, the prosumer uses an energy source for their own purposes. Therefore, the rated power of a PV system should not be greater than the power contracted with the DSO. The prosumer is billed for electricity according to the 2-zone tariff, in which the higher energy prices are from 6 am to 1 pm and from 3 pm to 10 pm.

The ESS is used to reduce the costs of purchasing energy from the network for the prosumer. It performs a function of a power and energy buffer for the time periods of high energy when load demand is higher than local generation, and its operating charging and discharging schedule is defined according to the energy tariff. If the energy price is high, the ESS is discharged with constant power and thus decreases the energy drawn from the grid. In the rest of the time, the ESS is charged, and the charging power is dependent on the duration of the low-price tariff and the rated power capacity of the inverter of the stationary storage.

The EV exploited by the prosumer is equipped with a bi-directional drive inverter, which is used for driving and, additionally, together with the EV battery, it can be used as an energy storage system during parking. In the second case, in general, the EV drive inverter is expected to charge and discharge EV batteries according to the assumed strategy to support the energy management in the prosumer installation. However, the availability of EV used for ancillary services strongly depends on the user’s behavior. It will be described in the next Section.

2.2. EV User’s Behaviour scenario
The impact of EVs on the supplying networks as well as the possibilities of their use for V2G or V2H ancillary services significantly depend on the EV user's behavior. Some typical behavior can be identified on the basis of the factors describing the way of EV exploitation. These are:

- The distance that a user drives during a day;
- The place where a user charges their car;
- The time when a user charges their EV.

The literature offers some research on the EV user's behavior regarding daily travelling distances. According to [12,13,15,16], EVs are usually used for commuting and short trips, and the 99.9% of the covered urban daily distances is less than 50 km (the commercial use of EVs is not discussed in this paper).

In the scenario of short-distance travelling and parking on private property most of the day, the EV can be connected to the home electric installation not only for charging but to provide V2H energy storage services, too. Such EV use might be particularly advantageous in the case of a family second vehicle. However, as the EV user's behavior is difficult to predict, some amount of energy should remain intact (energy reserve) to let the user drive at any moment for a short distance. If we assume that the energy needed to make a short trip (less than 100 km) is not higher than 16–20 kWh [26], the capacity of the EV battery eligible for V2H service must be larger to provide a comfortable vehicle range and some spare capacity for energy balancing in the prosumer installation. For example, assuming that the EV is equipped with a 100 kWh battery, 20% of its capacity can be reserved for short daily trips and the rest (up to 80%) can be used for V2H services.

3. Proposed Strategy for Energy Management

3.1. Assumptions

The overall goal of the proposed control strategy is to enable the effective interaction of home infrastructure elements consisting of a PV source, stationary ESS, and the EV (in particular EV drive inverter and vehicle batteries). Assuming that the ESS works according to a fixed charging and discharging schedule, the proposed strategy comes down to the control of the EV battery, provided that the car has returned from driving and is connected to the prosumer installation.

The main assumption of the strategy is to include the EV control in the energy management system so that the following objectives can be achieved:

- All energy produced by the PV source should be used locally by loads in the prosumer installation;
- The missing energy should be taken from the network only during the periods of a low-price tariff.

The achievement of these objectives will be possible depending on the parameters of all prosumer devices and the nature of their operation, the parameters of the power network, and the way of EV usage. It is obvious that an EV driving function should not be restricted by any additional V2H functionality. As on the one hand the EV should be ready for a ride whenever the need arises, and on the other hand, the EV user's behavior profile is difficult to define, the strategy must prioritize the EV functions.

The proposed strategy assumes the EV readiness to drive as a priority of the management system. As it has been stated before, short-distance driving should be available at any time (it is the so-called default mode of the EV operation). As for longer distances, the EV is available at a scheduled time (so-called custom mode of the EV operation). Long-distance driving parameters are entered into the management system every time after the EV is connected.

With the above assumptions, a control algorithm was defined. It calculates the charging and discharging power of the EV drive inverter when it is connected to the installation.

3.2. Control Algorithm
The algorithm uses the input data listed below:

- General data uploaded off-line in the form of tables of constant values:
  - Energy tariff for each hour and day of the year;
  - The PV generation profile for maximum solar radiation (maximum generation conditions) for each hour and day of the year;
  - Maximum supplying power of the installation (based on the contract with the DSO);
  - The nominal power of the EV drive inverter.

- Data regarding cloud cover obtained from the weather forecast for the next day.

- Data obtained online from the appropriate meters:
  - Active power consumed by the prosumer loads;
  - Active power generated by the PV;
  - Active power exchanged by the ESS converter;
  - The current energy level of the EV battery.

- Data entered by the prosumer EV user:
  - Introduced off-line: The minimum level of the EV battery charging, required for short distance driving and the maximum energy level, the exceeding of which shortens the battery life. It was assumed that \( \text{SOC}_{\text{min}} = 20\% \) and \( \text{SOC}_{\text{max}} = 80\% \); however, the EV user is able to change this value, if required;
  - Introduced at each connection to the installation: The scheduled time to start the next trip and the distance of this trip.

The control system starts to operate after connecting the EV to the charging circuit (wallbox—compliant with charging mode 3 [27]). First, the current day \((i)\) and hour \((t)\) are identified, and the input data are introduced by the driver. Then, the algorithm checks the current state of charge of the EV battery to examine whether or not the required energy reserve is secured. If not, i.e., the SOC is lower than 20\%, the algorithm forces the battery to charge with all the power available in the installation, taking into account the limitations of the power supply from the supplying network. In this way, the algorithm keeps the battery charge on the level allowing short-distance driving at any time.

The V2H service is provided only when the required energy reserve is secured. When operating in this mode, the algorithm controls the power of the EV inverter by charging or discharging the battery in a way that the supplying power has a zero value, regardless of the power of other devices in the prosumer installation. According to these assumptions, the operating range of the battery SOC is \( 20\% \leq \text{SOC}_{\text{av}} < 80\% \) of the maximum energy level.

Due to the priority of preparing the EV for the next trip, the period of V2H operation may be lower than the period of the EV connection. The algorithm turns on the battery charging at a moment determined on the basis of the trip data introduced by the driver, in order for the EV battery to reach the planned level of SOC before the time of driving commencement. The charging process takes place in the same way as for a short-distance charging, i.e., using the maximum currently available power.

With randomly variable generation and power consumption in the prosumer installation and the need to have the EV battery charged before driving, some amount of energy must always be taken from the supplying network. If due to the poor weather conditions the local generation is low, the energy derived from the network is bigger. From the weather forecast, the algorithm calculates the amount of missing energy, not generated by the PV source, and by appropriately controlling the power of the EV inverter, it may cause the missing energy to be taken from the power network during the low-price energy tariff.

A flow chart for a developed control algorithm is presented in Figure 2 (divided into part A and B).
START

\( t = t + \Delta t \)

\( t < 24 \)

\( i = i + 1 \)

\( t = 0 \)

\( TSOCl1 = TSOCl - 24 \)

\( \text{lowTarif}(t+1,i) \)

\( \text{AND} \)

\( \text{NON lowTarif}(t,i) \)

\( \text{AND} \)

\( t > 20 \)

Read:

\( \text{SOC}_{\text{ev}}, P_{\text{load}}, P_{\text{pv}}, P_{\text{ess}} \)

\( \text{SOC}_{\text{ev}} < 20\% \)

\( \Delta A = \Delta A + \text{profil}_{\text{pv}}(tt,i+1) \times \text{Cloud}(tt,i+1) \times \Delta t \)

\( tt < 24 \)

\( \text{THFCh} = \frac{(SOC - SOC_{\text{ev}})}{(maxP_{\text{net}} - P_{\text{load}} - P_{\text{pv}} - P_{\text{ess}})} \)

\( \text{THFCh} > 0 \)

\( t > t_{\text{HFCh}} \)

\( \text{lowTarif}(t,i) \)

\( P_{\text{net}} = \Delta A / \Delta Ti_{\text{lowTarif}}(i) \)

\( P_{\text{net}} = 0 \)

\( i = \text{current day}; \)

\( t = \text{current hour}; \)

\( \text{SOC}_{\text{in}}; TSOCl_{\text{in}} \)
**Figure 2.** (a) Flow chart of the control algorithm—part A. (b) Flow chart of the control algorithm—part B.
4. Simulation model

Model Structure

To examine the effectiveness of the proposed energy management strategy, a simulation model of the prosumer installation connected to the distribution network was built in the PSCAD program environment [28] (Figure 3).

The model consists of the following modules:

- Distribution network (SUPPLYING NETWORK);
- Feeder breaker (MAIN BREAKER);
- Loads connected to the installation (PROSUMER LOADS);
- PV panels (PROSUMER PV INSTALLATION);
- Stationary energy storage system (ESS);
- Electric vehicle (EV);
- The external controller (MAIN CONTROLLER).

![Figure 3. Schematic diagram of EV and home installation simulator model.](image-url)
machine’s angular velocity $\omega$. It is assumed that the resistance to the movement and thus the mechanical torque are proportional to the angular velocity of the car.

The EV DRIVE INVERTER block represents the DC/AC motor inverter. The inverter is built as a 6T bridge of GTO thyristors. In the block of the EV DRIVE INVERTER CONTROLLER, the firing pulses to thyristors are generated using the PWM technique. Hysteresis control is applied, in which the inverter AC current iF reproduces the reference current vector iref determined in the block of EV CONTROLLER. The RLC elements are used to reduce the current harmonics of high frequencies resulting from the thyristor switches operation.

The battery is represented by the DC voltage source complete with the elements used to model charging and discharging efficiency and the battery state of charge.

The details and the potential applications of the motor inverter were presented in [29].

The prosumer load module is used to reproduce the load profile based on the real power measurements. The measurements were previously recorded and averaged for the group of consumers. The data file used in the simulation includes a one-day profile with 24 active power values.

The PV installation module consists of three main parts: Photovoltaics panel, controllers, and the PV inverter (the 6T bridge of GTO thyristors). The irradiance from real measurements was used as an input for the PV model. The irradiance may change (due to the cloud cover forecast) so different weather conditions can be analyzed.

The ESS design is similar to the EV module. Obviously, it does not include the drive block. Furthermore, the battery capacity and the system power are significantly smaller. Since the ESS is permanently available, it is possible to plan its operation based only on tariff prices: Battery charging is conducted during the low-price tariff and discharging during the high prices.

The details regarding the prosumer installation and the EV parameters are given below:

- Installation rated power at the connection point (limited by feeder fuses): 15 kW, 3 × 400 V;
- PV installation rated power: 15 kWp, 3-phase inverter;
- Maximum (without EV) load power: 12 kW;
- ESS rated power: 10 kW;
- ESS capacity: 10 kWh (safety SOC limits: 20–80%);
- EV motor rated power: 100 kW (e.g., 100 kW in Renault Zoe, 150 kW Volkswagen ID.3);
- EV battery capacity: 100 kWh (e.g., 100 kWh in Tesla model S, 64 kWh in Hyundai Kona);
- Load profile—is based on the real measurements (average values) from the chosen households;
- PV generation profile—is based on the real measurements from the PV.

5. Simulation Scenarios and Results

Three operation scenarios have been discussed. For the reference purposes in each scenario, the assumed load profiles are repeated (the PV profile changes due to the cloud cover forecast). The V2H services are enabled in scenarios 2 and 3. The simulations were performed for a one-week period. To make the figures easier to analyze, the presented time duration is 2 days. The scenarios are described below.

(a) Scenario 1—reference: only the PV and the ESS connected to the prosumer installation

In this scenario, the prosumer installation operates without the EV connected (Figure 4a). Relatively high PV generation ($P_{\text{PV}}$) along with smaller power consumption ($P_{\text{load}}$) result in the reverse power flow ($P_{\text{net}}$—a negative value means that the energy is fed to the grid, a positive value means that the energy is consumed). The simple ESS controller uses
a timer (based on the duration of two contracted tariffs) to conduct charging and discharging at a constant time ($P_{stor}$). This scenario illustrates that the functionality of a typical ESS (e.g., 10 kWh), designed for home installations, is limited because of relatively low power and low capacity. Note that if only part of the energy transferred to the supplying network can be “recovered”, in some periods, the adopted ESS control system can even lead to additional losses (reverse power flow caused by the PV is increased by discharging the ESS). Such a situation can occur during the low-price tariff (green rectangles), high PV generation, and low-energy consumption.

Even if the basic control strategies (based on the timer) were replaced with a more sophisticated one, the efficiency of the ESS used is limited because of its low capacity.

The changes of ESS SOC are presented in Figure 4b. The rate of the SOC change is related to the charge and discharge powers ($P_{stor}$), which are calculated based on the known duration of high- and low-price tariffs.

![Figure 4](image)

**Figure 4.** Results of reference scenario. Green and orange colors represent periods of low and high-price tariffs, respectively. The yellowish rectangle highlights the example of the increased reverse power flow in the feeder ($P_{net}$) due to PV ($P_{pv}$) ESS ($P_{stor}$).

The obtained results show that:

- In case of high PV generation, higher than both the loads and the rated power of ESS charging, the surplus energy has to be transferred to the supplying network.
- If a high generation of the PV takes place at the same time when the ESS is being discharged (periods of the high-price tariff: 6 am–1 pm and 3 pm–10 pm), the reverse power flow might increase.
(b) Scenario 2—the PV, the ESS and the EV connected, V2H services activated, the EV in the default mode

Scenario 2 illustrates the energy management possibilities in the prosumer installation using the EV battery (Figure 5).

The EV is connected to the home charging point (such as a wallbox) throughout the simulation period. It is operated in the default mode. Relatively high PV generation (PPV) along with small power consumption (P_load) result in the surplus energy that can be used to charge the EV batteries. The high rated power of the drive inverter (used to charge the EV) and the big capacity of EV batteries make the self-power consumption possible.

The developed control algorithm controls not only the power balance in the prosumer installation, but also the SOC of the EV battery. V2H functionality can be used for several purposes, including:

- The control power exchange (P_{net}) with the supplying network, so there is no reverse power flow (P_{net} values are always positive);
- The stabilization of the P_{net}—there are no fluctuations due to changes in the PV generation and loads (the stabilization of the P_{net} can be an additional service contracted with the DSO).

In Figure 5a, during the low-price tariff (green rectangles), the EV can be charged from the supplying network. The charging rate additionally depends on the potential energy deficit the next day (due to weather conditions). The yellowish rectangle highlights the moment when the EV is being discharged even during the low-price tariff. This is due to another aim of the control algorithm, which is to keep the P_{net} constant (whenever possible). If there is surplus energy from the PV, the charging rate changes dynamically. During the high-price tariff (orange rectangles), the P_{net} can be minimized. The blueish rectangle highlights the period when the EV is charging and the ESS is discharging. It is possible because the ESS operation is based on the timer while the EV battery is controlled to consume the surplus energy from the PV.

The controller schedules the operation of the EV battery controlling the SOC, too. In Figure 5b, one can note that during the V2H service, the EV SOC never drops below 20% or rises above 80%. Reserving the minimum SOC guarantees the needed EV range at all times and keeping it below the upper limit protects against overcharging. The greenish rectangles in Figure 5a,b highlight the moment when the discharging was stopped due to too low SOC_{EV}. 
Scenario 2 is quite unlikely (the vehicle is parked all the time) but shows the possibilities of energy management in the prosumer installations with a large ESS. In most cases, investing in such an ESS would not be reasonable from an economic point of view. However, in the case of the EV, the perspective is different.

(c) Scenario 3—the PV, the ESS and the EV connected, V2H services activated, the EV in the custom mode

Scenario 3 (Figure 6) is the most real one. During the simulation, the EV is used for driving, so it is available for the V2H service only periodically when parking. As the EV battery storage is time-dependent, it means that the external controller must deal with the periods when the EV battery is not available due to driving and the changed SOC after each drive.

The examples of the V2H operation are highlighted using colored rectangles:

- The blueish color illustrates the custom mode (Figure 6a)—the EV user requested a specific SOCeV (Figure 6b) and the time of departure. The EV battery SOC changes from the default 20% to the requested 70% (Figure 6b). The EV charging power is controlled so the $P_{net}$ does not exceed the rated power of the main feeder (15 kW).
- The black rectangles in Figure 6b illustrate the periods of driving. Since the V2H service is not available, the $P_{net}$ can be negative (reverse power flow).
- The yellowish color highlights the EV charging in the custom mode. However, in this case, the high PV generation resulted in additional energy transferred to the EV.

Figure 5. Scenario 2. EV connected to the prosumer installation during the whole analyzed duration.
(which is acceptable as long as the upper threshold—80% is not exceeded). Consequently, at the moment of departure, the EV SOC is 55% instead of the requested 40% (SOC_in). Before the EV charging started, the system operated in the default mode so whenever it was possible, the EV battery was used for the V2H service.

- The greenish color is used to show the “priority” charging during the default mode. After driving, the EV SOC dropped below 20% (Figure 6b). In such a case, V2H services must be disabled until the SOC reaches a lower threshold.

![Figure 6](image_url)

**Figure 6.** Scenario 3. Home installation operation with time-dependent storage.

Note that the custom mode can be easily extended to the “fast-home” charging option. The charging power might be increased if the external controller forces the ESS to discharge (override its default operating scheme) and the controllable loads are disabled (like the air-conditioning system or the washing machine, etc.). If the PV generation is high, the EV charging power might be significantly greater than the nominal power of the main feeder. It is limited only by home installation so the EV charging circuit should be inspected in the scope of overcurrent protection.

The presented tests have shown that such a system can be successfully applied without the extensive cost of the prosumer installation upgrade. Actually, the cost can be minimal if the prosumer already uses a type of building management system, such as BMS.

6. Conclusions

The increasing deployment of intermittent distributed energy sources and a growing popularity of electromobility create new technical and organizational challenges for the
LV distribution network operators. The conversion from traditionally passive LV networks to smart grids might become a necessity.

Although smart grids offer the possibility to use the digital and other advanced technologies to monitor and manage the distribution of electricity, it may turn out to be insufficient in the future (due to a high number of prosumers). Hence, it is reasonable to reduce the potentially negative impact of prosumers resulting from the reverse power flows (due to high intermittent PV generation) or the opposite—the overloading (due to the EV charging).

The local energy management can be beneficial not only for the DSO, but also for the prosumer. With the use of energy storage systems, the prosumer could effectively manage the energy flow and reduce the costs of energy. Unfortunately, investment in the high-capacity ESS may be questionable. Therefore, the adoption of the EV drive inverter and its battery as a time-dependent storage device in the home installation may be an interesting and valuable option for prosumers who have their own EV.

The paper shows the developed strategy of controlling the operation of the EV battery integrated with the control of other devices and thus creating a hybrid prosumer installation. The simulation results confirm that EVs, when parked and connected to the home installation (thanks to the high-power drive inverter and high-capacity batteries), can offer a similar functionality to a large ESS. The benefits for the prosumer are clear: Without extensive additional costs, the prosumer installation gets assets to effectively manage the local energy consumption and generation. Furthermore, the prosumer additionally gets the option of the EV “home-fast” charging.

The authors did not analyze the design of the EV battery type and inverter in detail, assuming only that the inverter must be capable of bidirectional energy transmission and the battery properties can be included in the constraints introduced to the algorithm controlling the operation of the EV inverter.

The proposed strategy has been derived without quantifying the EV user’s behavior. This simple approach required introducing priority for driving and, in consequence, resulted in some limitations in the management algorithm operation. In future work, the authors plan to use some predictions of driver’s behavior to improve the effectiveness of the system. Moreover, dynamic energy tariffs will be taken into account, which we believe will be forced by the widespread use of RES. Prices will determine the economic effects of the developed algorithms, which can be demonstrated by simulating long periods of EV operation with a controlled scenario and a reference scenario not controlled by the algorithm.

The satisfactory results obtained from the simulation performed to validate the presented control strategy of the hybrid prosumer installation prove that the electromobility should be an important element of the future smart grids. There is some analogy between electric vehicles and the mobile phones that are not used anymore, not only for calling but also for work and entertainment. The future of EVs might be similar. Actually, it would even be unreasonable not to use their full potential. In some cases, the option of V2H functionalities can encourage potential EV buyers because with the electric vehicle, they gain not only an environmentally friendly vehicle, but also more efficient home infrastructure.

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