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Enhancement of residential PV energy storage system by supercapacitor battery – high spatial resolution data analysis

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ABSTRACT

This article addresses frequent instability issues observed in the operation of typical residential photovoltaic (PV) microinstallations through a new approach to energy storage system (ESS) design. Based on high-resolution, long-term recordings of power fluctuations in a residential PV installation located in Tallinn, Estonia, various instability problems are identified and analyzed. A mixed ESS is proposed to provide rapid and effective compensation for the detected fluctuations. The study introduces a hybrid energy storage solution combining supercapacitors and batteries to mitigate these issues and ensure balanced system operation. Specifically, an innovative 32 Wh supercapacitor bank, integrated with the DC link of a standard PV inverter, is proposed to address both short- and long-term power fluctuations on the generation side. Peaks and dips in power consumption and generation are detected using a Z-score-based peak detection method. Experimental results comparing different ESS configurations are presented and discussed. Furthermore, the study demonstrates how the supercapacitor bank successfully mitigates several instances of generation fluctuations. The paper also explores how the incorporation of a supercapacitor ESS in a DC microgrid can affect battery lifespan, in addition to stabilizing PV generation.

1. Problem introduction: modern PV microinstallation challenges

Enormous growth has recently been observed in the photovoltaic (PV) home installations sector. The EU Market Outlook for Solar Power 2023–2027 report indicates that the residential rooftop market segment in the 27 EU member states expanded to account for 23% of the market share in 2023 [1]. At the same time, the whole rooftop segment achieved an impressive growth rate of 54% year-to-year. In various EU member states, such as Belgium, Slovenia, and Hungary, announcements about terminating net-metering programs led to a spike in interest in residential installations. For example, in Poland, the Institute for Renewable Energy Report [2] expects a linear growth of PV installation capacity, with the share of private microinstallations accounting for at least 30% until 2025 (Fig. 1).

In Estonia, the power generation capacity of solar installations has also rapidly scaled up in recent years due to high electricity costs [3]. In 2023, Estonia exceeded a cumulative PV power of 1 GW, reaching 800 W per capita and ranking among the top five countries in Europe [1]. Together with Poland, Latvia, Ireland, and Sweden, Estonia has already reached the 2030 goal – despite all difficulties and obstacles – and may meet half of its electricity demand with PV power within the next three years. The synchronization of the Baltic States' electricity system with the EU synchronous area, which occurred in February 2025, marked a significant milestone for Estonia's energy security. However, this event raised considerable concerns regarding energy production stability and proper system balancing.

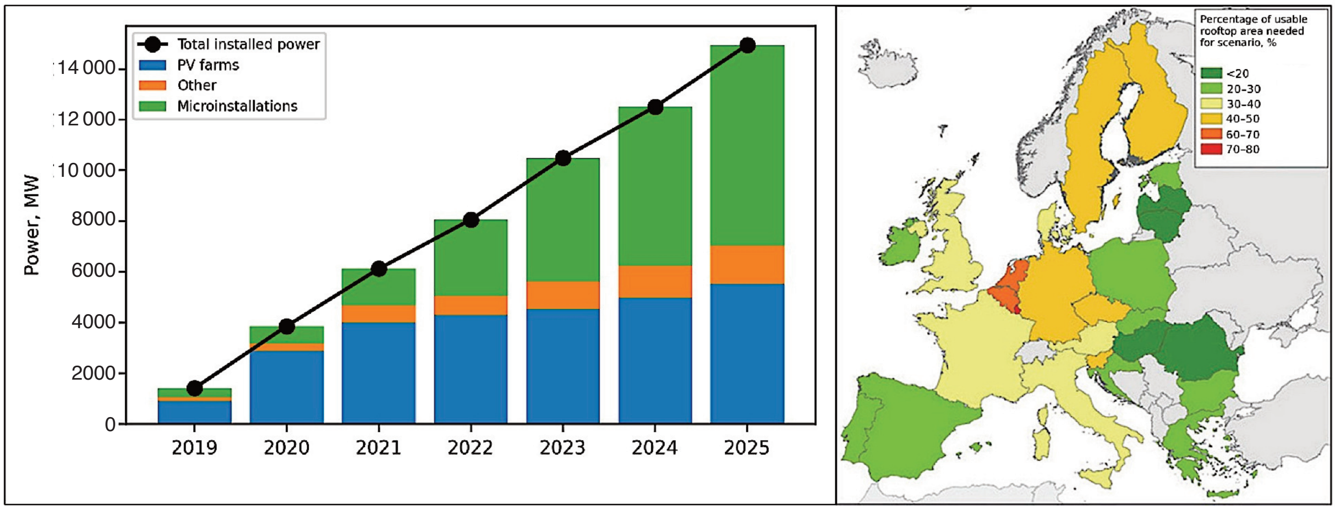

Fig. 1. Current capacity and forecast of installed PV power in Poland until 2025, compiled by IEO [2], along with the percentage of available rooftop area required in EU countries to meet the 2030 energy scenario under the Paris Agreement [4].

A key obstacle to the wider adoption of PV installations is the challenge of maintaining energy production balance. The typical problem of a single peak in production during the daytime, combined with frequent and unpredictable generation fluctuations, poses a serious threat to the credibility of the PV energy sector. As the share of renewables increases, feed-in tariffs will no longer be profitable enough to reach the break-even point for residential renewable energy installations. Therefore, there is a strong push towards self-consumption through the use of various energy storage technologies and control strategies.

Beyond maximizing self-consumption, an energy storage system (ESS) is frequently utilized to increase the stability of traditional alternating current (AC) microgrids. The use of different ESS types or algorithms to efficiently dispatch the storage system for preserving inertia in the microgrid is an extensively studied topic in the literature [5–7]. Furthermore, ESS converters can improve the reliability of direct current (DC) microgrids by providing or absorbing energy during abnormal conditions [8].

Due to the stochastic nature of renewable energy sources such as solar emission, fluctuations on the generation side are inevitable. Additionally, typical systems are subject to load fluctuations. A range of factors can disrupt PV energy generation, including voltage variations at the grid interface, voltage peaks caused by excessive integration of renewable energy, voltage flickering triggered by shading phenomena, unintended islanding events, power oscillations at the grid interface, and the repercussions of grid frequency variations, among others.

Nevertheless, numerous strategies exist to alleviate the volatility inherent in PV systems. These include the geographical dispersion of PV installations, the integration of control and prediction algorithms into converters, and the incorporation of energy storage solutions within PV installations [9]. In [10], the authors focus on the integration of intelligent converters with resource forecasting and management, real-time asset monitoring, and the incorporation of energy storage systems to alleviate fluctuations in PV systems.

Hybrid battery energy storage systems utilizing moving average control strategies have been proposed in [11] as a method to mitigate rapid and transient fluctuations in PV power generation. An enhanced adaptive moving average control method, alongside Volt-var control, is introduced in [12]. Nevertheless, the traditional moving average methodology is impeded by a phenomenon known as the memory effect. To overcome this limitation, the authors of [13] recommend the integration of hybrid energy storage systems linked to the converter's DC bus to alleviate fast power fluctuations.

In addition to the methods discussed, alternative strategies are utilized for the stabilization of fluctuations, including ramp rate control, low-pass filtering, and power limiting controls [14,15]. While all these methods are currently under development, the need for effective compensation methods remains evident.

In this study, a supercapacitor bank is employed to provide power during both short- and long-term fluctuations in a residential microgrid linked to a weak grid. The primary goal is to properly size the capacitor bank so that the converter can maintain stability under such conditions. Additionally, the authors propose an easy and effective method for integrating the supercapacitor bank into household PV microinstallations for both AC and DC systems. The presented work is based on prior studies and serves as a continuation of the analysis reported in [16].

2. PV microinstallation balancing concepts and methods

2.1. Typical architecture of residential PV microinstallations

Residential PV installations are frequently rated below 10 kW to achieve the best return on investment [17]. Power electronic converters perform maximum power point tracking (MPPT) and convert DC to AC to ensure compatibility with the utility grid. There are three main approaches for grid integration of such PV microinstallations [18]:

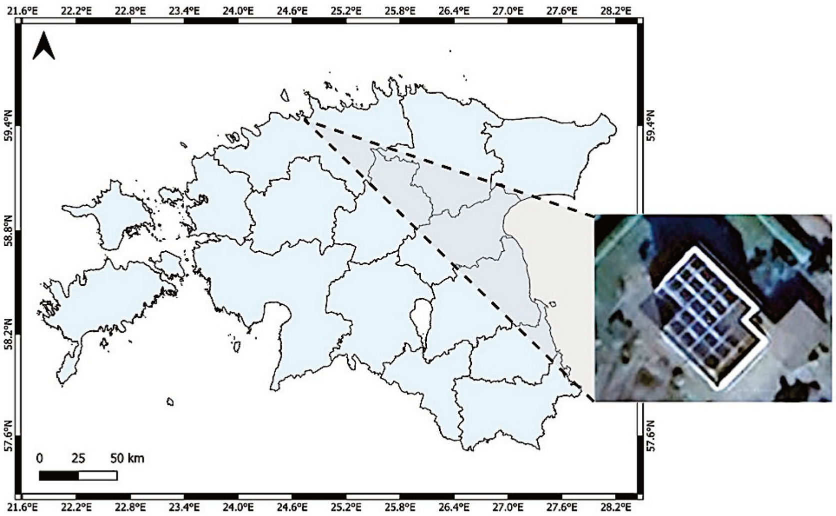

Fig. 2. Bird's-eye view of the considered residential house with rooftop PV installation in Tallinn. Map generated using schematic maps of county and municipality borders, administrative and settlement units, Estonian Land Board, 11/1/2024.

- PV modules can be connected in a series of strings, which are further connected to a PV inverter with one or more inputs that perform MPPT.
- This setup can be extended by adding a PV power optimizer to each module in the PV string, or only to those most exposed to shading, to maximize energy generation under shading conditions.
- Each PV module can be integrated into the utility grid using a PV microinverter. This approach provides the best scalability and resilience against component faults.

The latest research often addresses the parallel integration of PV modules, which removes a single point of failure – the string PV converter – and ensures the best scalability and expandability [19–21]. It also provides the opportunity for optimal MPPT for each PV module to maximize the performance of the PV microinstallation under shading conditions [22]. On the other hand, a hybrid PV string inverter can integrate a battery ESS with a PV string, which, however, does not guarantee the optimal operation of each PV module in the string. Nonetheless, parallel PV optimizers capable of integrating modular battery ESSs are also being developed [21].

2.2. Description of the test PV field installation

The simulation used data from an existing Estonian residential building, equipped with a wide range of electric loads. It is a two-story building with a heated area of 176.7 m^2 and is used as the main residence by a single family of four individuals. The bottom floor of the house consists of one large space and a kitchen, with three smaller living areas on the top floor. The residence draws power from the utility grid via a three-phase line voltage of 400 V.

Furthermore, the building includes a decade-old rooftop solar system of 5 kWp, which is composed of 20 PV modules rated at 250 Wp each. The roof orientation is exactly southeast, located at a geographical latitude of 59 degrees (Fig. 2). The solar PV array is linked to the AC grid via a 4.2 kW PV inverter (Kostal Piko 4.2). The PV modules are grouped into two PV strings of ten modules each and connected to the individual inputs of the PV inverter. Additionally, an electric vehicle is often used and is charged by a 2.4 kW single-phase charger at night. The house is heated by a heat pump (Thermia Atec HP 11) with a peak power of 11 kW. Aside from typical appliances, there is a 10 kW electric sauna, which is rarely used. Moreover, in this house, as is often the case, the loads are not equally distributed, so there will always be a phase imbalance, which will also impact PV generation.

Two Camile Bauer PQ1000 power quality monitors were installed on the utility meter and PV sides to log all data within the house. The placement and data acquisition setup of these two devices are depicted in Fig. 3. The two monitoring devices are configured to allow the assessment of both imported and exported energy from the electrical grid, as well as the PV generation. By subtracting the power recorded by the PV monitor from the readings of the first monitor, one can ascertain the electrical power consumed by the loads on each phase. The three current and voltage channels on the monitors interface with current and voltage transformers attached to each phase wire. Furthermore, both monitors are connected to a laptop that provides remote access for the retrieval of the logged data. The monitoring devices systematically record power consumption, energy generation, phase voltages, and anomalies, such as voltage sags, swells, frequency variations, and homopolar voltage. As a result, the data logger provides valuable insights into power fluctuations. This study uses a one-year dataset recorded at 10-second resolution [23].

The data collected at 10-second resolution was resampled to 20 seconds and segmented by daily periods to observe load

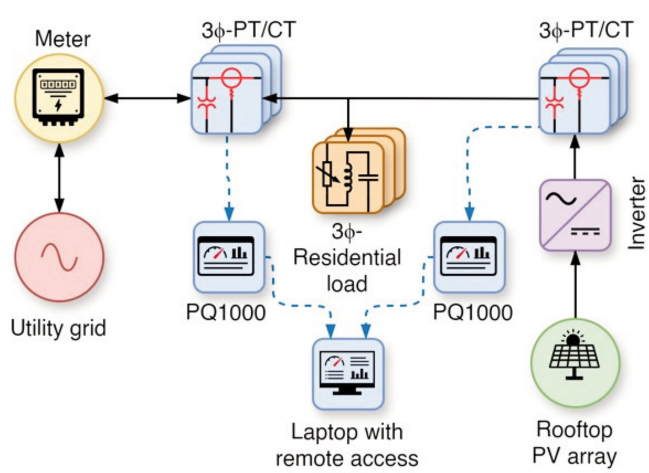

Fig. 3. Simplified diagram of the designed residential generation and consumption logging system.

and generation fluctuations. Furthermore, each day in a specific month was confined to a particular time range to align with solar energy availability. The data range considered for December to March was between 10:00 and 17:00; for April to August, between 6:00 and 21:00; and for September to November, between 8:00 and 18:00.

2.3. Analysis of supercapacitor features

Energy storage involves accumulating electrical energy so that it can be used by the consumer at a later time. In standard PV installations, energy storage systems provide power when solar energy production is limited or unavailable, such as at night. Another proposed application of energy storage is its integration on the DC side to reduce troublesome fluctuations in energy production caused by temporary shading from clouds or other obstacles. However, using standard energy storage devices, such as lead-acid batteries or lithium-ion cells, in this configuration would lead to frequent charging and discharging, which shortens their lifespan due to the limited number of charge-discharge cycles. An alternative may be supercapacitors, characterized by an exceptionally high number of charge-discharge cycles, provided that their basic operating limits are maintained.

Supercapacitors can be considered a viable ESS option that falls between standard batteries and electrolytic capacitors. They may have lower energy density than standard batteries, but due to their linear characteristics, they release stored energy with greater power while maintaining current density comparable to typical capacitors. Their unique properties result from the special structure of electrodes made of activated carbon nanotubes, which allows for obtaining a huge active surface of over 3000 m^2/g and high electrical conductivity. Energy is stored in the micropores of the electrode material and in the space between them and the electrolyte. Supercapacitors do not use a classical dielectric, as traditional capacitors do, but instead store energy in the EDLC (electric double layer capacitor) structure. The charge accumulation occurs physically, not chemically, which distinguishes supercapacitors from batteries, which rely on chemical reactions to store and release energy. Supercapacitor operation is based on the formation of an electric double layer at the interface between the electrode and the electrolyte. When voltage is applied to the device, ions from the electrolyte move towards the electrode surfaces, creating thin layers of charge opposite in polarity to those of the ions. This process occurs simultaneously on both electrodes, forming two layers of charge.

During charging, the voltage applied to the electrodes causes ions in the electrolyte to move: positive ions move towards the negative electrode, and negative ions towards the positive electrode. On each electrode's surface, a double layer forms in which the ions are separated from the surface by a thin molecular layer. Because these charges are physically separated, the energy is stored in the electric field created between the ions and the electrode surface.

When the circuit is closed and the supercapacitor begins to discharge, the ions in the electrolyte return to their original state. The energy stored in the electric double layer is released, and the charges flow through the circuit, delivering electrical energy. This recovery process demonstrates a high efficiency of 96–98% [24].

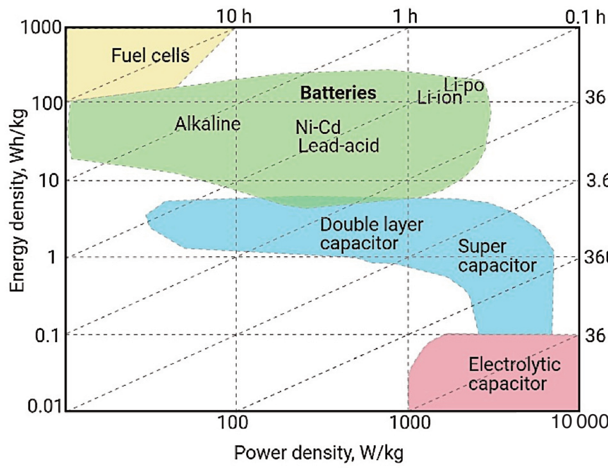

Fig. 4. Comparison of various types of energy sources by energy density and power.

Supercapacitors have many unique features that distinguish them from typical batteries. One of the biggest advantages is their exceptionally large capacitance, currently reaching up to 3000 F per single device. Combined with a noticeably short charging and discharging time, they can achieve very high-power densities, typically ranging from 1 to 10 kW/kg. This short charging and discharging time is possible due to their exceptionally low internal resistance of approximately 0.3 mΩ, which is about ten times lower than that of a typical battery. The greatest advantage of supercapacitors is their extremely long service lifetime, which can exceed one million charge-discharge cycles.

Despite these advantages, supercapacitors also have some significant disadvantages that limit their direct use as standalone energy storage. The most notable is their low energy density, amounting to only 20 Wh/kg, which is about 3.5 times less than that of typical batteries, as shown in Fig. 4 [24]. This makes them insufficient as independent energy storage solutions for microgrid implementations. Another issue is the low permissible voltage for a single element. Exceeding this limit may lead to electrolysis, which produces substantial amounts of gases that can cause a supercapacitor to explode. To increase the operating voltage of supercapacitors, they can be connected in series, which allows higher voltages to be achieved – but at the expense of reducing the total capacitance of the entire supercapacitor ESS [25].

3. Theoretical and practical analysis of experimental setup

3.1. Production and consumption profile of the analyzed household

PV generation and load consumption in the presented dataset (Fig. 5) reflect typical Estonian weather patterns. The coldest months begin in November and last until mid-March. Heating requirements during this period cause electricity consumption to rise. In contrast, solar generation is minimal due to limited sunlight availability. The weather is warmer from mid-March

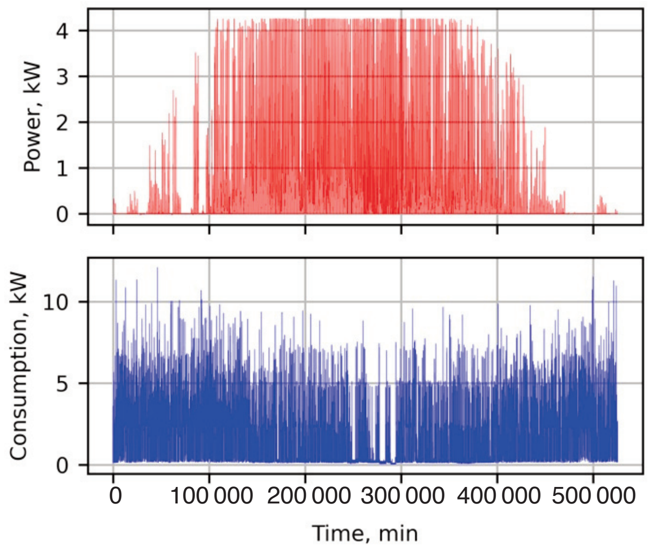

Fig. 5. Average hourly PV generation and power consumption by the residential building.

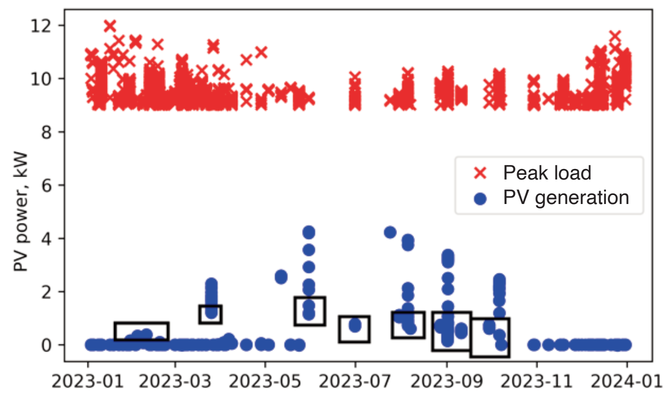

Fig. 6. Examples of PV generation dips (highlighted in black-colored boxes) during peak loads.

until the end of October, and sufficient sunlight allows to produce enough PV power, with a maximum recorded generation of 4.27 kW during summer and an annual generation of 560 W. Similarly, the consumption rate decreases during this period due to reduced use of heating and heavy loads. Aside from that, the EV charger contributes to consumption between overnight and morning. In the winter season, the peak energy consumed by the system climbed to 12.95 kW. This is due to the operation of the heat pump and the sporadic use of the electric sauna. Conversely, energy consumption during the summer months persists uniformly within the parameters of 1 to 2.5 kW. The lowest consumption recorded by the system was 30 W, with an average of 1.75 kW.

3.2. Power fluctuation profiles and their specifics

Residential microgrids primarily rely on energy storage and intermittent renewable sources to achieve maximum self-generation. In suburban and rural areas, where the grid is often weak, stabilizing generation with a fast-acting ESS is essential for ensuring robust operation. For instance, a highly inductive load may draw inrush current during startup. Instability can occur if the conventional ESS has an insufficient state of charge, or if the converter or ESS is undersized. In such scenarios, a smaller supercapacitor ESS can be useful.

Rapid instabilities are often manifested by sudden voltage and current peaks or dips. Such short-term events can be identified using Z-score-based peak detection on the consumption section of the dataset. Furthermore, correlating the PV generation data at the corresponding timestamps can indicate insufficient PV generation or generation dips during peak demand periods. Examples of such generation dips are shown in Fig. 6.

3.3. The design of an innovative energy storage system

In this work, we propose a solution aimed at reducing short-term fluctuations in energy production from PV installations by using a supercapacitor DC buffer on the PV module side. By using their greatest advantages, including fast charging and discharging, as well as an exceptionally large number of work cycles, it becomes possible to smooth the energy production curve in the considered installation. It is worth mentioning that the data used at this point concerns an operational installation, while the analysis of supercapacitor usage is based on simulations and calculations performed on the stored dataset for convenience. For the components used to build the buffer model in these simulations and calculations, we selected supercapacitors with the highest available capacity on the market, 3400 F, produced by Maxwell (Fig. 7). Typical parameters of the selected supercapacitor are shown in Table 1.

The rooftop PV installation on the building can be modified to handle short- and long-term power fluctuations. The proposed modified system is shown in Fig. 8. Given that the microgrid operates on an AC-based system, utilizing the DC link that exists between the MPPT buck-boost converter and the fast-response energy storage is a prevalent strategy employed to enhance the stability of renewable energy systems, including wind turbine and PV installations [26,27]. To implement the proposed system, the current PV converters within the household need to be modified and retrofitted, together with a supercapacitor bank and an interfacing converter. With a properly formulated control algorithm, the supercapacitor-interfaced converter can detect voltage instabilities within the DC link and supply power to alleviate fluctuations or absorb energy under anomalous conditions. However, in this context, the design of the control system was not addressed, as the primary emphasis of this study was exclusively on the optimal sizing of the supercapacitor bank to overcome short power dips. By ensuring the optimal sizing of the super-

Fig. 7. Maxwell BCAP3400P supercapacitor used in the considered buffer setup [28].

Table 1. Basic parameters of the supercapacitor BCAP3400P P300 [28]

Parameter	Unit	Value
Capacity	F	3400
Maximum voltage	V	3
Specific energy	Wh/kg	9
Stored energy	Wh	4.4
Continuous current	A	270
Peak current	A	2.8
Recharge cycles	Times	1 000 000
Internal resistance	mΩ	<0.25

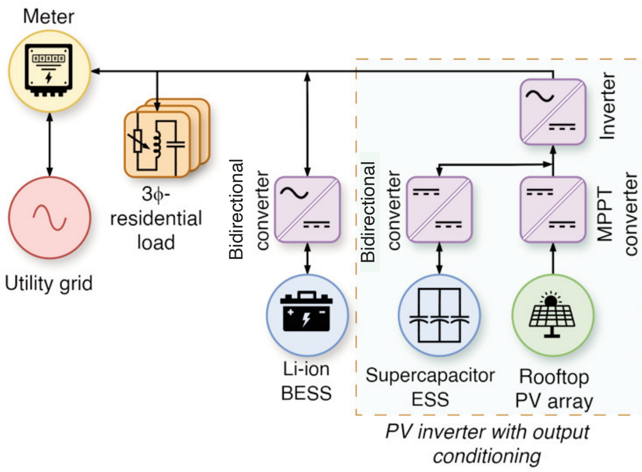

Fig. 8. Proposed PV microinstallation with a supercapacitor bank to stabilize generation.

capacitor bank, the PV microinstallation will be adept at mitigating power fluctuations that occur during peak load periods, as illustrated in Fig. 6. Apart from the supercapacitor bank, there will be a $LiFePO_4$ battery bank of 10.8 kWh coupled with a bidirectional inverter to increase self-consumption [29].

3.4. Supercapactior bank design, calculation, and analysis

Using data from the above-mentioned installation, an analysis and simulations were conducted to investigate the application of an energy buffer in the form of a supercapacitor. For a more comprehensive and accurate analysis, two types of buffers with different capacities were implemented:

- An 8 Wh system composed of two sets of 100 series-connected supercapacitors. These two chains were then connected in parallel to achieve a higher capacity.
- A 16 Wh system composed of two of the above-mentioned 8 Wh packs connected in parallel, creating the final storage unit.

Connecting as many as 100 supercapacitors in series is necessary due to the low permissible operating voltage of each individual unit. It is well known that series connections distribute the overall voltage across individual components, thereby increasing the resulting total output voltage.

One of the main challenges with supercapacitors is their charging process. High-capacity capacitors in a discharged state effectively behave as a short circuit to the power supply circuit. Therefore, a circuit is needed to limit the charging current so that it does not exceed a value safe for the power source. Additionally, it is crucial to ensure that the maximum allowable voltage of the supercapacitor is not exceeded during the final phase of charging.

Another problem to address is the uniformity of charging in a capacitor bank and the voltage distribution across individual elements. Due to differences in the tolerances of supercapacitors in terms of capacitance, resistance, and leakage current, there will be an imbalance in sectional voltages in a series stack. It is important to ensure that the individual voltages of each supercapacitor do not exceed their maximum operating voltage, as this can lead to electrolyte decomposition, gas generation, an increase in equivalent series resistance (ESR), and ultimately, reduced lifespan.

This imbalance in the initial phase of charging is dominated by differences in the capacitance of individual capacitors, which in extreme cases can reach even 20%, meaning that capacitors with lower capacitance will charge to higher voltages in a series connection. A cell balancing system must be implemented in the series connection to ensure that the individual component voltages do not exceed the rated voltage of the supercapacitors.

Two methods of potential balancing are commonly used:

- Passive method
- Active method

The passive method (Fig. 9) involves connecting resistors in parallel with individual capacitors. The purpose of these resistors is to reduce differences between leakage currents that cause uneven discharging of individual sections.

In the passive method, it is crucial to select appropriate parallel resistors, whose values should ensure that the current flowing through them is at least ten times greater than the leakage current of the capacitors. A higher ratio can be used for faster balancing. The trade-off is determined by the ratio of charging time to leakage current. The passive voltage balancing method is recommended only for applications that are not regularly charged and discharged, and only where the additional current load introduced by the shunt resistors is acceptable. Problems arise when such a capacitor bank undergoes cyclic charging and discharging.

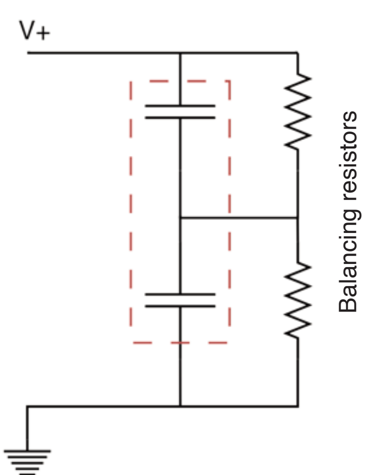

Fig. 9. Simplified schematic of resistor-based cell balancing.

For applications involving cyclic charging and discharging of capacitors, or in cases where significantly lower leakage current is required in steady-state conditions, such compensation requires higher currents only when cell voltage is imbalanced. An active system enforces equal voltage at the nodes of series-connected capacitors.

In addition to ensuring precise voltage balancing, active systems offer much lower steady-state current levels, requiring higher currents only when a capacitor's voltage becomes unbalanced. These features make active voltage compensation circuits ideal for applications involving frequent capacitor charging and discharging, as well as those with limited energy sources.

An active solution provided by the manufacturer of the supercapacitors used is a system known as balancers, which ensures highly precise voltage balancing across individual components. The balancing system begins operating only when the voltage on the capacitors approaches their maximum values.

The potential of each cell is monitored by an input circuit built around a simple voltage divider, whose signal controls the input circuits of a triggered control system. The signal from this trigger then drives an execution circuit based on bypass transistors. When the voltage across the connected supercapacitor terminals falls within the range of 0 to 2.7 V, the monitoring system does not activate the bypass circuit, allowing virtually all energy to be directed to the supercapacitor. When the voltage on one of the paired supercapacitors reaches the allowable maximum value, the control system triggers the transfer of excess energy from one supercapacitor to another, using an additional bypass circuit. Energy from the higher-voltage cell is directed to the lower-voltage cell, enabling more efficient energy use within the system. Once both supercapacitors in the paired configuration are fully charged, the charging process is halted. The application of this energy flow control method in paired supercapacitors increases efficiency and reduces losses [30,31]. Unfortunately, the manufacturer of this type of device does not provide information about the exact construction or operating principle of their device. An example of an active load balancing system is presented in Fig. 10.

When comparing the capacities of the two proposed buffers to the 10.8 kWh of the $LiFePO_4$ battery initially planned for this installation, it turns out that, in the first case, it amounts to just 0.007% of the total storage capacity, while in the second case, it is similarly 0.014%.

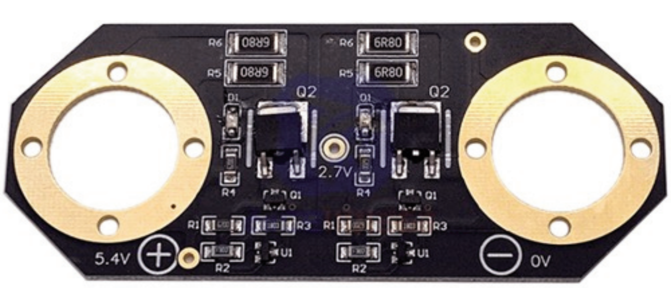

Fig. 10. Supercapacitor balancing system [32].

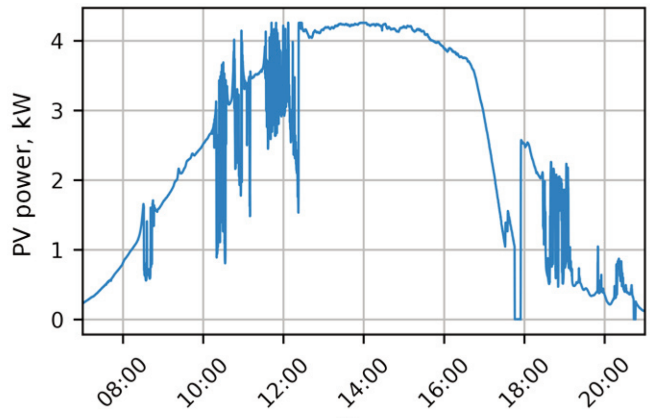

Fig. 11. Energy production on an example day in July.

For these battery-like supercapacitor buffers, an analysis was conducted on selected days from the entire dataset collected in the production-consumption database. The whole-year period was analyzed. As an example period, a high generation daytime with short- and mid-term fluctuations of different intensity was selected. A specific time interval was determined in accordance with the characteristics of generation variability on the day depicted in Fig. 11. Initially, the energy produced by the installation was calculated in each 10-second interval.

As we can observe in Fig. 11, the energy production pattern on the given day was relatively smooth, with only a few instances of variable cloud cover causing sudden and frequent changes in the power output of the PV panels. The periods of variable operation provided an excellent opportunity to demonstrate the functioning of both systems. For a more detailed analysis, two time intervals were magnified.

The first time interval was selected as a period of sudden fluctuations in energy production between 08:25 and 08:50.

As shown in Fig. 12, both types of proposed energy storage systems effectively reduce the amplitude of short-term fluctuations in energy production, resulting in a more stable energy flow. The 8 Wh storage system allows for the reduction of approximately 70% of significant changes in energy

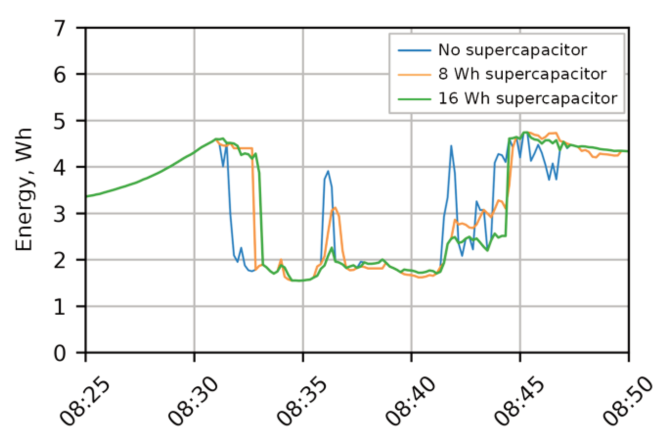

Fig. 12. Time interval 08:25–08:50 of the analyzed production curve, presenting basic generation flow and influence of 8 Wh and 16 Wh supercapacitor energy banks on the DC output.

production and up to 80% of smaller amplitude variations. The 16 Wh storage system operates even more effectively. According to the chart, with a larger storage capacity, significant fluctuations in energy production have been almost completely eliminated. The remaining fluctuations are related solely to the processes of fully discharging and recharging the storage system. For smaller variations, the larger storage system also demonstrates a clear advantage, particularly noticeable from around 8:45 – from that point, the target curve is almost entirely free of fluctuations.

In the case of higher energy values and larger fluctuations, the situation is somewhat less favorable, as shown in the time interval from 10:20 to 10:35 (Fig. 13).

The analysis of this time interval, characterized by significant fluctuations in the baseline pattern, indicates effective reduction of these fluctuations, although the efficiency depends on the capacity of the buffer used. Similar to the previous case, the larger capacity buffer performs better. However, as the amplitude of energy production fluctuations increases, the smoothing effect of the curves diminishes. For the 8 Wh buffer, only about 40% of significant amplitude fluctuations were reduced, while the larger buffer, as expected, allowed for the elimination of approximately 60% of these fluctuations.

For comparison of the operation of such a supercapacitor buffer, an example day in February is shown in Fig. 14, where the amount of energy produced is significantly lower than in July.

As we can observe, the distribution of energy production differs significantly from the previous one. Energy production starts practically around 11:00 and ends around 16:30. Moreover, the total yield on the presented day is significantly lower. To demonstrate a slightly different operation of the buffering system, a separate graph will show the beginning of production on this day.

Analyzing the initial phase of the day, the amount of energy produced was very low, which caused the process of fully charging the storage systems – implemented as a necessary prerequisite for operation – to take a relatively long time, especially for the 16 Wh storage system. As a result, the

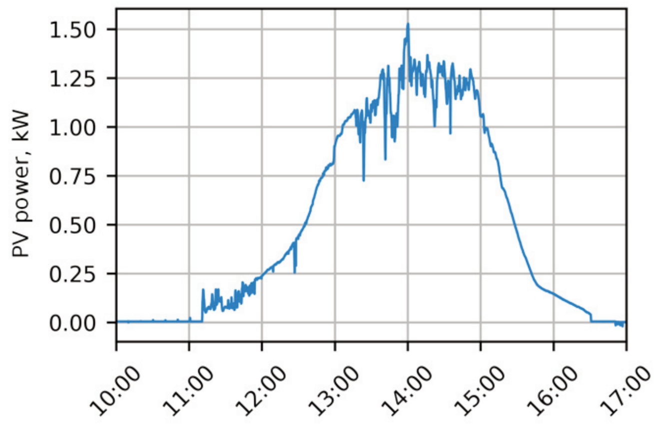

Fig. 14. Energy production on an example day in February.

first significant fluctuations, during which the supercapacitors stored energy, were already limited. As we can observe, both buffers exhibit slightly different initial operating characteristics, which stabilize around 11:55 AM, and subsequently, both traces appear nearly identical. Analyzing the below graph (Fig. 15), we can see that both types of supercapacitor buffers significantly reduce short-term fluctuations in energy production. This is, of course, related to the small magnitude of changes relative to the capacity of both storage systems. It can also be suggested that for such small energy values, the storage system with lower capacity proves to be significantly better, as it begins operating approximately ten minutes earlier and does not limit the initial moments of energy production. In the later stages of production, both storage systems reduce approximately 92% of fluctuations in energy production changes.

Later in the day, when fluctuations in energy production are significantly larger, both buffers behave similarly to the case observed on the July day, reducing fluctuations by approximately 65% for the 8Wh storage system and up to 85% for the 16Wh supercapacitors.

At high amplitude values, the filtering capabilities of energy storage systems are limited due to the restricted capacity of the supercapacitors used. While increasing the buf-

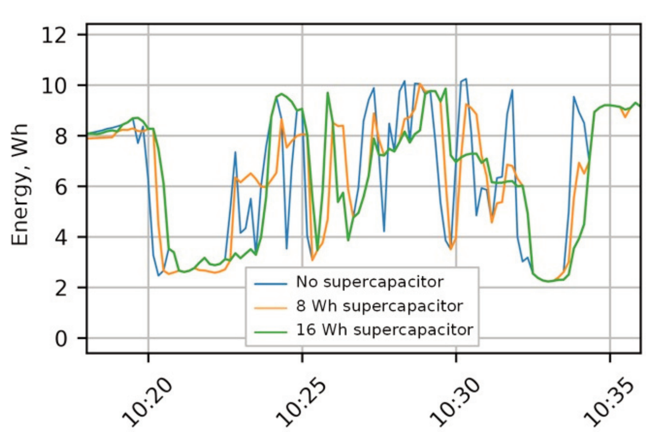

Fig. 13. Power fluctuations in the time interval 10:20–10:35 with an analysis of two proposed energy banks' influence on the DC power flow.

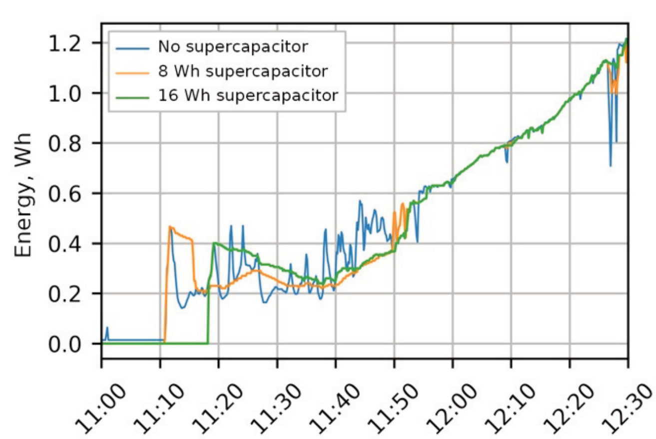

Fig. 15. Energy fluctuations in the time interval 11:00–12:30 with an analysis of two proposed energy banks' influence on the DC power flow.

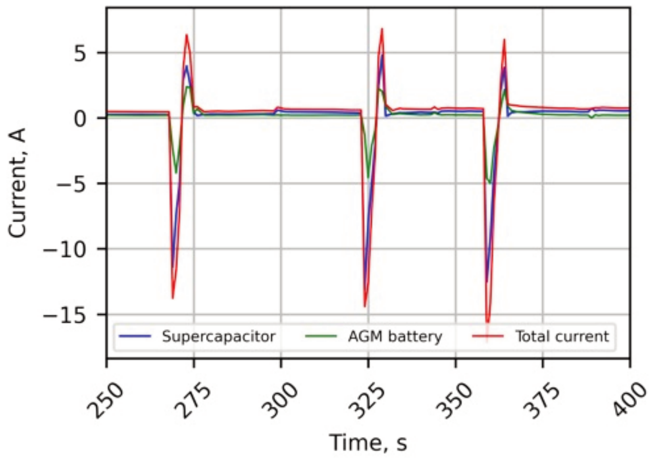

Fig. 16. Values of the current flowing in a hybrid storage system with a capacity of 65 Ah connected to a standard 2 kW PV installation.

fer capacity could yield better results, it would involve a significant rise in the cost of the storage system. Moreover, it would require the implementation of a specialized charging regulation system to control the operation of the supercapacitor array. Direct connection of the supercapacitors to the installation is inadvisable, as in the event of deep discharge, all available energy could be redirected to the supercapacitors, leading to additional fluctuations in the system.

Alternatively, DC voltage ripple can be mitigated by using an additional battery pack, such as lithium-ion batteries with significantly higher capacity. However, their limitation lies in the number of charge and discharge cycles. To overcome this drawback, a hybrid solution can be implemented, such as a parallel connection of a lithium-ion battery with a supercapacitor bank. A similar solution is presented in the doctoral thesis in [33], which describes the use of such an energy storage system integrated with a standard inverter. In this configuration, the supercapacitors were designed to limit sudden changes in the direction and magnitude of the current flow, thereby improving the performance parameters of a conventional ESS.

An example of the operation of such a hybrid storage is presented in Fig. 16. Analyzing this chart, we can observe that supercapacitors produce significantly higher current values both during charging and discharging than absorbent glass mat (AGM) battery pack. In this case, during discharging, which is characterized by negative current values, current peaks exceeding 15 A are achieved, with 73% to 91% of the total current being supplied by the supercapacitors, which is a desirable effect in the operation of a hybrid storage system. A similar relationship can be observed during charging, which is characterized by positive current values. In this process, the current supplied by the supercapacitors ranges from 62% to 71% of the total current delivered by the inverter to the storage system [33].

4. Reducing PV fluctuation and primary ESS cycling in a DC microgrid

Similar to how supercapacitor ESS stabilizes PV generation in an AC microgrid, it may also be employed as secondary storage in a DC microgrid to accomplish the same goals and other functionalities. Using an appropriate droop curve for the supercapacitor converter would be sufficient to mitigate the dips in PV generation and possibly reduce the cycling of the primary ESS. In Fig. 17, the simplified diagram for a DC microgrid with supercapacitor ESS is depicted. Compared to the previous scenario, where the ESS was linked to the DC link of the PV converter and inverter, it can now be directly connected to the DC bus. To allow the supercapacitor ESS to act earlier than the primary storage, the converter for the primary storage should have a deadband. In Fig. 18, a droop curve for the DC microgrid with the supercapacitor ESS is shown. Apart from having no deadband, the supercapacitor converter has a very steep inclination, making it the leading and fast-responding source in the system.

With this droop curve, a simulation was conducted for the same household, and the results were analyzed to find out where the PV dips occurred and the supercapacitor discharged rapidly to stabilize the fluctuation. A snippet of one day of generation is shown in Fig. 19, where the supercapacitor gets charged and discharged based on the PV generation and load demand. Highlighted discharge current spikes in the plot correspond to the generation fluctuation and dispatch of supercapacitor converter to stabilize the bus voltage. Since, a deadband is introduced in the battery converter curve and also

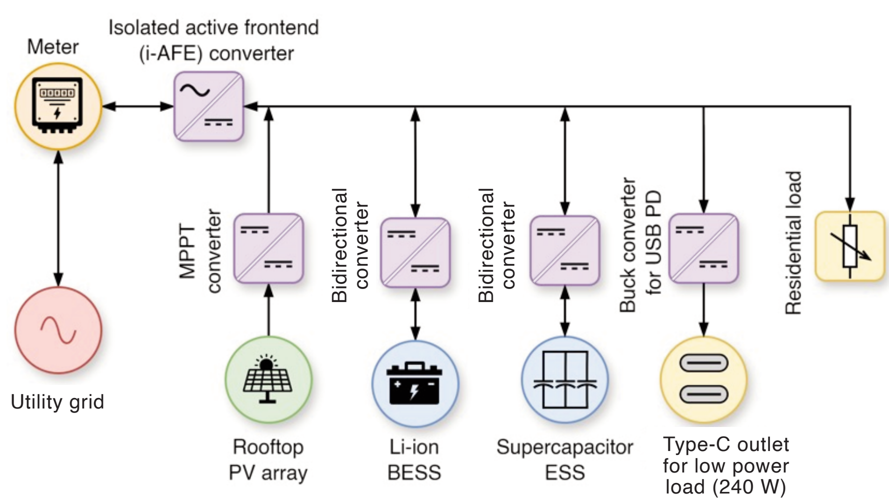

Fig. 17. Simplified schematic of a DC residential PV installation with a supercapacitor as secondary storage.

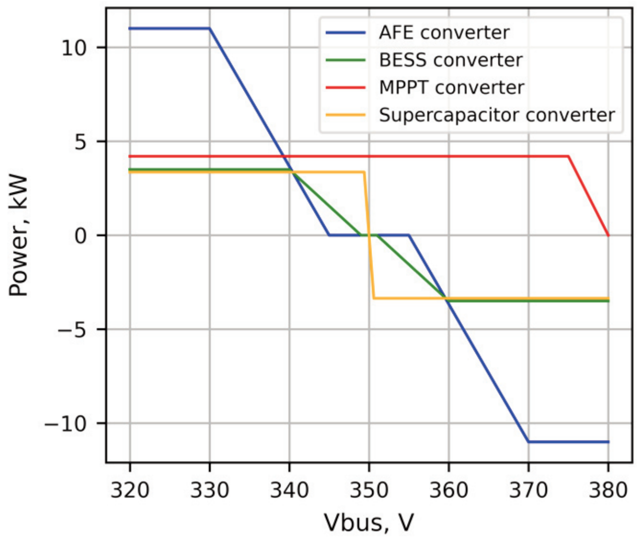

Fig. 18. Ideal droop curves of each component of the DC residential PV installation.

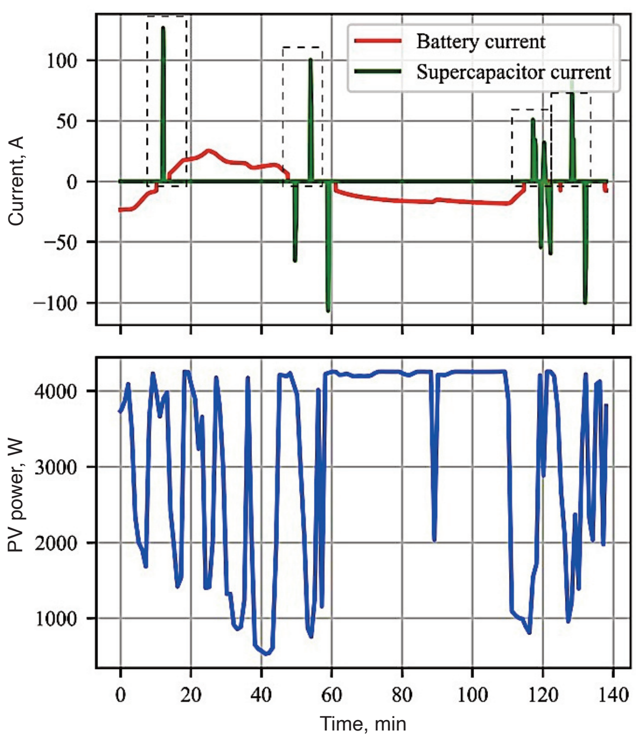

Fig. 19. Snippet of short-term PV power fluctuation mitigation through the supercapacitor in the DC microgrid. Highlighted current peaks are where PV generation dips occurred and the supercapacitor tried to stabilize the system.

the inclination is less sharp than the supercapacitor converter, it will response slower than the supercapacitor, as shown in the plot.

Since the supercapacitor converter stabilizes short-term peaks, the battery lifespan should be extended because it is not being cycled as frequently as before. Using Miner's rule and the rainflow counting algorithm, the total battery degradation was estimated using state of charge (SOC) and depth of discharge (DOD) for the entire year. Miner's rule estimates fatigue damage by summing the ratios of cycles at different stress levels to their allowable limits. The rainflow counting algorithm categorizes load cycles into major and minor cycles, which is essential for fatigue analysis. Together, these

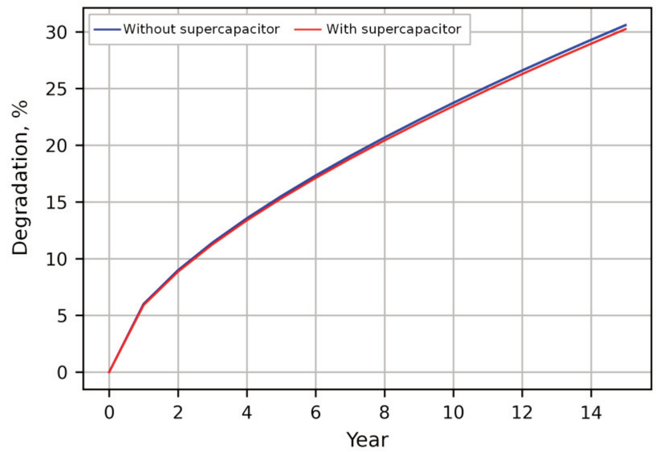

Fig. 20. Primary ESS degradation comparison for the system with and without a supercapacitor.

methods help predict the lifespan of structures under variable loading conditions by quantifying cumulative damage and effectively counting cycles. The rainflow algorithm provides the necessary cycle counts for Miner's rule, enabling a thorough fatigue analysis [34]. The estimated value was compared to the case where a battery converter is regarded as the leading source. From the comparison, it was found that adding supercapacitor storage to the system would reduce degradation of the primary ESS by 1.28%. Yearly ESS degradation comparison is shown in Fig. 20.

5. Summary and conclusion

Examining the current state of PV microinstallations highlights the critical role of accurately implementing an energy storage system. In addition to traditional battery systems, there is a growing emergence of alternative designs, such as innovative supercapacitor-based power buffers. As discussed in this work, when meticulously designed, these systems can be particularly effective in mitigating short-term generation fluctuations. Consequently, the crucial factors are the supercapacitor bank sizing, configuration, balancing, and control, as well as their integration with traditional energy banks.

Based on measurements and simulations, it can be established that, when designed and operated properly, this type of storage system can deliver fast, robust, and long-term stable solutions for residential PV microinstallations. This is particularly relevant for households with a plethora of electric DC and AC loads, as demonstrated in the tested example. Moreover, a similar case was simulated for a DC microgrid, where it successfully reduced fluctuations at the PV generation side and also reduced ESS degradation by 1.28%.

Future improvements of this study will involve the use of optimization algorithms to economically maximize the capacity of the ESS within the microgrid, as well as the integration of supercapacitor ESS into DC microgrids with modified droop control to serve during undervoltage conditions.

Data availability statement

All data generated or analyzed during this study are included in this published article.

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Elamu päikeseenergiasalvestussüsteemi täiustamine superkondensaator-patarei abil – täpne andmeanalüüs

Szymon Rogowski, Sayeed Hasan, Andrii Chub ja Maciej Sibiński

Artikkel keskendub sagedastele ebastabiilsusprobleemidele, mida täheldatakse tüüpiliste elamute päikese mikroenergiasüsteemide töös, kasutades uut lähenemisviisi energiasalvestussüsteemide (ESS) projekteerimisel. Tallinnas asuva päikeseenergiasüsteemi kõrge eraldusvõimega salvestatud pikaajaliste väljundvõimsuse muutuste põhjal tuvastatakse ja analüüsitakse erinevaid süsteemi ebastabiilsuse ilminguid. Tuvastatud võimsuskõikumiste kiireks ja tõhusaks kompenseerimiseks tehakse ettepanek kasutada kombineeritud ja täiustatud energiasalvestit. Uuringus tutvustatakse hübriidset energiasalvestuslahendust, mis ühendab superkondensaatorid ja akud, leevendamaks kirjeldatud probleeme ja tagamaks kogu süsteemi tasakaalustatud tööd. Täpsemalt pakutakse välja uuenduslik 32 Wh superkondensaatorsalvesti, mis on integreeritud standardse päikeseinverteri alalisvoolusiiniga, et kompenseerida nii lühi- kui ka pikaajalisi võimsuskõikumisi energiatootmise poolel. Energiatarbimise ja -tootmise tipud ja langused määratakse kindlaks Z-tulemusväärtustel põhineva tippväärtuste tuvastamise meetodi abil. Lisaks esitatakse mitmeid erinevaid energiasalvestite konfiguratsioone ning võrreldakse vastavaid katsetulemusi. Uuring näitab ka, kuidas superkondensaatorsalvesti suudab edukalt leevendada mitmesuguseid energiatootmisega seotud võimsuskõikumise juhtumeid. Samuti analüüsitakse, kuidas superkondensaatoril põhineva salvesti lisamine alalisvoolu mikrovõrku võib lisaks päikeseenergia tootmise stabiliseerimisele mõjutada elektrokeemilise aku eluiga.