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Enhancing Energy Power Quality in Low Voltage Networks Integrating Renewable Energy Generation with High Intermittency: A Case of Study in a Microgrid Located in a High-Altitude Equatorial City

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Abstract: Nowadays, energy decarbonization due to the integration of renewable energy sources presents important challenges to overcome. The intermittent nature of photovoltaic systems reduces power quality by producing voltage variations and frequency deviations in electrical systems networks, especially, in weak and isolated distribution systems in developing countries. This paper presents a power smoothing method improving the low pass filter and moving average for grid-connected photovoltaic system, the novel method includes state-of-charge monitoring control of the supercapacitors energy storage system to reduce the fluctuations of photovoltaic power at the point of common coupling. A case study for a microgrid in a high-altitude city in Ecuador is presented with exhaustive laboratory tests using real data. The ultimate goal of this research is to improve energy power quality in electrical distribution systems to cope with the growth of renewable penetration.

Keywords: power smoothing; photovoltaic generation system; low pass filter; moving average; monitoring control; microgrid

1. Introduction

Nowadays, the generation of electrical energy with renewable sources is increasingly widespread, with the aim of decarbonizing the current and future economy [1]. Photovoltaic (PV) energy is considered one of the most promising renewable sources; however, the fluctuating nature of large-scale grid-connected solar PV seriously affects power quality [2]. The impact of power fluctuations over long distances are further intensified, making large PV plants a threat to the safe operation of the system. To aid in grid stability, some power companies or research studies have imposed ramp rate restrictions on PV plants [3]. For this reason, PV output power that exceeds the grid connection criteria must be controlled [4]. Adding fast-response energy storage systems, e.g., supercapacitor (SC) to reduce power fluctuations can significantly improve the grid penetration rate of PV. High power density storage systems used to smooth out PV power fluctuations can significantly reduce the impact of a solar farm's power output on the grid [5]. There are several power smoothing techniques applied to PV systems, low-pass filtering [6], moving average (MA) filtering [7], corrective predictive methods [7,8], experimental methods [9], multi-objective optimization systems [10]. The challenge lies in controlling the operability of the SC, in order to meet the grid connection requirements and make the storage system operate within certain permitted limits without compromising its lifespan.

In the literature, there are various methods of reducing PV output power fluctuations using SCs, e.g., Ref. [11] proposes an SC-based power smoothing methodology using a Karlman filter, the results show that the method is effective to smooth the power minimizing the stress on the converter. A multi-objective optimization model to limit the PV energy through SC and batteries is presented in [12], to prevent the SC from operating at its lower limits, the authors propose a state-of-charge (SOC) correction strategy, the results of the simulation indicate that the proposed method is more economical compared to conventional methods. Ref. [13] adopts a novel control strategy for a hybrid energy storage system with batteries and SC, the Low Pass Filter (LP) scheme maintains control in terms of power balance at the output of the fluctuating renewable system. The application of SC as a power fluctuation reduction element is also studied in Ref. [14], the results of the fuzzy logic algorithm show that SC achieves a resulting profile of smoothed voltage and a constant current. Ref. [15] proposes an optimal control strategy for an independent PV system with SC and batteries combining the LPF method and a fuzzy logic controller. The results of the proposed system reduce the operating current of the battery and reduce the dynamic stress prolonging the lifespan of the energy storage system. The authors in [16] present a study on the use of an SC hybrid system and batteries to smooth the output power by adjusting the parameters of the filter time constant of the system in real time according to the SOC. However, it is not possible to dynamically control the SOC of the SC by dynamically effectively stabilizing the operability of the SC.

A comparative study of power smoothing control methods has shown that the MA method is one of the most used in this application due to its simplicity and high accuracy [17], after performing exhaustive simulations, the authors conclude that the MA method is useful to have a comparative frame of reference with new algorithms proposed by researchers. Ref. [18] presents a PV smoothing control method using the spline function, the authors carry out comparative simulations with the MA method to demonstrate the validity of the new method. Researchers have widely chosen low-pass filter power smoothing and MA methods, in Ref. [19] the authors present a review where the advantage of applying this algorithm is discussed, these suggestions will contribute to decrease the storage capacity and degradation of energy, causing an increase in the lifespan of the battery and the SC. Among other relevant results, an optimization based on Ref. [20] is proposed to smooth voltage fluctuations due to various intermittent sources, to increase the lifespan of storage systems, the authors control the minimum SOC of batteries by applying the MA method improved, which eliminates the lag problem of MA conventional algorithm. Moreover, one can be referred to the works conducted in [21], where the authors present a novel optimization strategy to reduce the power losses in a wind farm and PV system, a numerical method based on a genetic algorithm is deployed to smooth the output power using a MA method to generate the reference signal, the results with a case study is used to verify the usefulness of the proposed power smoothing approach. The suppression of PV output fluctuation to smooth the power delivered to the grid is presented in [22], the authors proposed a model predictive control to manage the SOC in batteries. Moving average filter is used to generate the output reference signal; the simulation results show that the proposed method is able to improve the output power efficiently.

Most of the mentioned references apply the MA and LP to smooth the PV output power, despite these interesting features that this method can be offer, there are several aspects that should be cover, e.g., the control of SOC. To fill the gaps in the available literature, this paper presents a comparative study of the effectiveness provided by power smoothing methods a novel power smoothing method based of MA and LP filter for a grid connect PV/SC system. A novelty is introduced to such methods by providing them with a dynamic control feature of the SOC of SC to prevent the SC from operating outside its safe charge limits, thus ensuring high reliability of this storage system. The primary focus of this study revolves around the enhancement of power smoothing techniques. Specifically, the LP method is utilized to effectively manage the SOC of the SC, thereby preventing the SC from operating at its limits. The overarching objective of this research endeavor is to mitigate power fluctuations in grid-connected PV systems by refining the widely employed methods. To comprehensively investigate this matter, extensive laboratory tests have been conducted to validate the proposed approach. The experimentation site chosen for this purpose is the city of Cuenca, Ecuador. Situated

in the Andean region within the equatorial zone, this city is characterized by sunny days accompanied by the presence of persistent cloud cover. Moreover, it is noteworthy that the Micro-Grid laboratory of Universidad de Cuenca is located in this area.

The subsequent sections of this paper are structured as follows: Section 2 delineates the methodology, outlining the novel proposed method. Within Section 2.1, the LP filter is comprehensively defined, while Section 2.2 expounds upon the MA method. Subsequently, Section 2.3 introduces the innovative control mechanism for the SO) of the SC. Section 2.4 encompasses the detailed presentation of the chosen case study. Moving forward, Section 3 encompasses the comprehensive analysis of the obtained results and subsequent discussions. Finally, Section 4 provides the conclusive remarks and implications derived from this study.

2. Materials and Methods

Figure 1 shows the methodology proposed to lead this study. The input data is the real PV output power measured in the laboratory in a conventional day. In the first place, the methods of LP filtering and MA power smoothing have been presented and defined. From the data logger, the supervisory control of the energy storage system is studied, the novel method applied at this stage is used in each LP and MA power smoothing method comparatively. In this document, the energy storage system is proposed to take advantage of the high high-power density storage of the supercapacitor-based energy storage system (SC-ESS) to achieve the desirable performance. The results are experimentally validated under several technical and economic criteria. Finally, an analysis of variability and energy are presented.
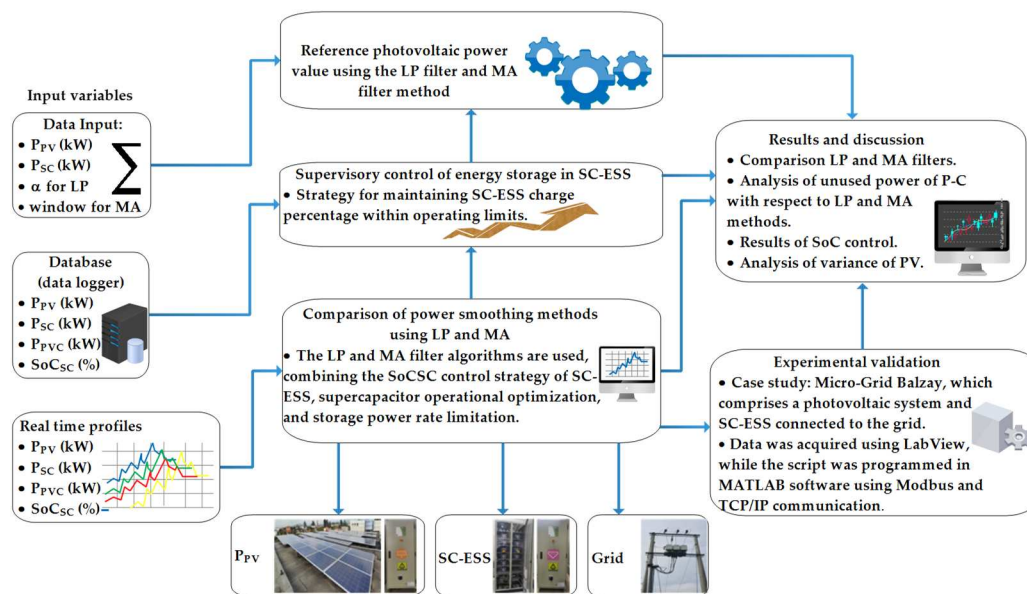

Figure 1. Representative scheme of the proposed methodology.

2.1. Design of power smoothing algorithm based on low pass filter

Typically, the LP power smoothing method is used in signal processing to remove high frequency from signals [23], which can be useful to reduce the power fluctuations in solar farms. Thereby, this paper constructs a mathematical design of LP to smooth the power peaks of PV system with 15 kW of capacity. The equation (1) shows the typical form of the voltage at the terminals of a capacitor in a series RC circuit in the frequency domain. In this expression, which corresponds to that of a first-order low-pass filter, V_o and V_i denote the output and input voltages to the RC circuit, respectively, R and C are the resistance and capacitance values, respectively, and s is the Laplace operator. Then, this equation is rearranged in order to obtain a transfer function $G(s)$ as expressed in (2) the voltage with respect to capacitance and resistance. In order to have an expression that allows the digital implementation of the filter, equations (3)–(6) show the conversion process of the transfer

function $G(s)$ in the discrete space. In order to control the dynamics behavior to the filter proposed, it is necessary to express equations (2)–(6) in the time domain by applying the Z-transform [24].

$$V_o(s) = \frac{\frac{1}{Cs}}{R + \frac{1}{Cs}} V_i(s) = \frac{1}{1 + RCs} V_i(s) \tag{1}$$

$$G(s) = \frac{V_0(s)}{V_i(s)} = \frac{1}{1 + RCs} \tag{2}$$

$$G(z) = (1 - z^{-1})z \left[\frac{1}{s(1 + RC)} \right] = \frac{\left(1 - e^{-\left(\frac{T}{RC}\right)}\right)z^{-1}}{1 - e^{-\left(\frac{T}{RC}\right)}z^{-1}} \tag{3}$$

$$\tau = RC \tag{4}$$

$$v_o[k + 1] = e^{-\frac{T}{\tau}} v_o[k] + \left(1 - e^{-\frac{T}{\tau}}\right) v_i[k] \tag{5}$$

$$\alpha = e^{-\frac{T}{\tau}} \tag{6}$$

Equation (7) expresses the voltage in function of its time constant, where α can be adjusted according to the smoothing requirements. By definition (6), this parameter is within the range $0 < \alpha < 1 (0 < \alpha < 1)$.

$$v_o[k + 1] = \alpha v_o[k] + (1 - \alpha)v_i[k] \tag{7}$$

In this context, the variable v_i is substituted with the PV input power P_{PV}, while the variable v_o is replaced with the filtered power output of the PV system. The disparity between the filtered power and the input power determines the amount of power to be injected by the SC-ESS, denoted as P_{SC}. It is important to note that the parameter α governs the extent of power smoothing to be applied, wherein higher values of α approach unity, signifying a more pronounced smoothing effect, while lower values tend towards zero, indicating minimal smoothing. To provide a visual representation of this power smoothing process and its associated variables, Figure 2 depicts the corresponding flowchart.

- First, the inputs variables are collected from microgrid $(P_{PV}, P_{SC}, \alpha, SoC_{SC})$, then auxiliary variables are assigned (aux, i). Both SC-ESS overcharge and over-discharged produce severe effects on the lifespan.
- Then, in order to avoid this these issues, the SOC of SC need to be limited. If during the smoothing actions provided by the SC-ESS its SOC approaches its lower threshold, the proposed method will prioritize the SC-ESS load until the SOC is raised to a safe level to continue the control tasks. An analogous reasoning explains what would happen if the SOC reaches its upper limit. This feature is achieved by a supervisory control of the energy storage, which generates the value of the limit constant k shown in the diagram in Figure 2. Further details of this supervisory control are presented in Section 2.3. The constraints of SC-ESS depend on α. Therefore, if the SOC of SC-ESS is lower than minimum SOC (SoC_{SC}), the energy generate of PV charges the SC-ESS until to reach the upper limit as show in Figure 5. Is important to mention that, all variables have been stored separately for further analysis.
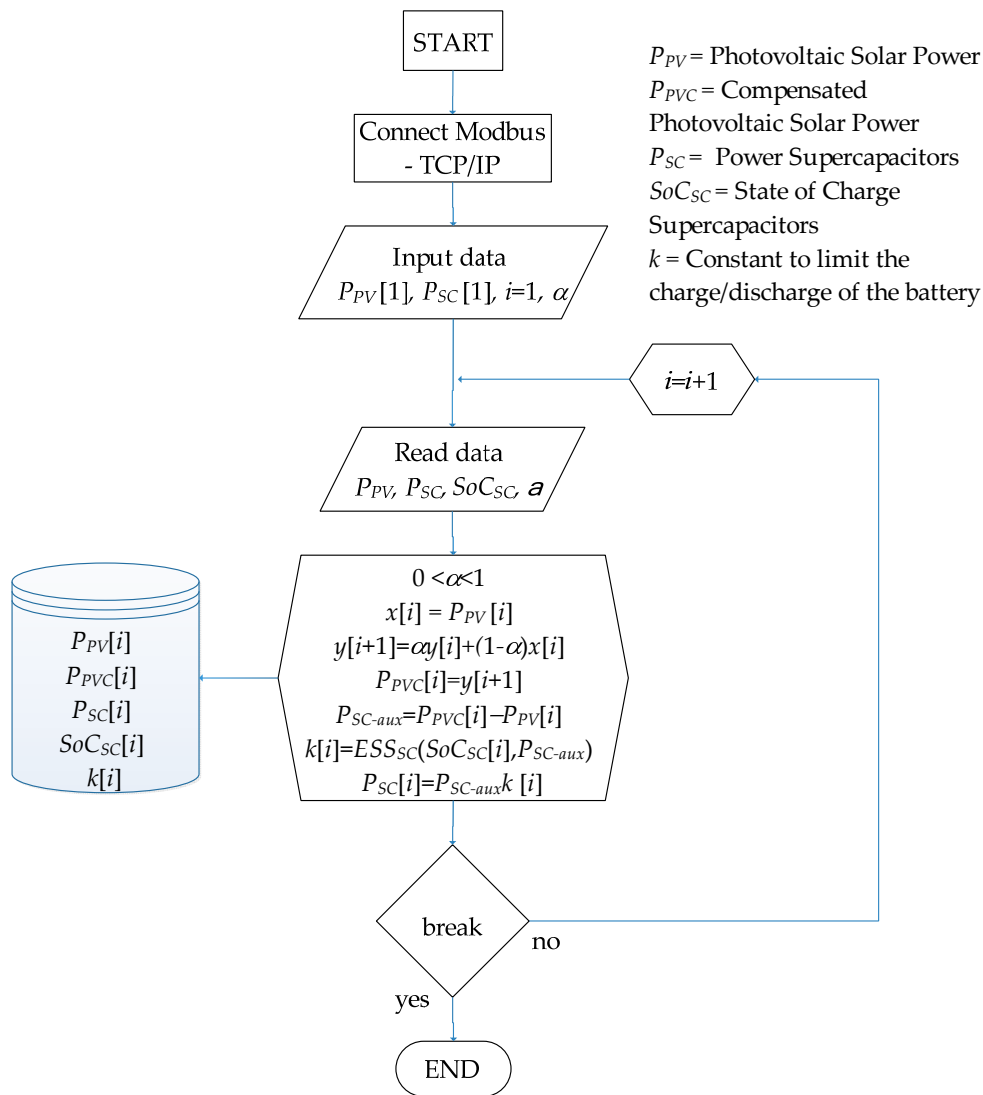
Figure 2. Flowchart to the LP filter-based power smoothing method implementation.

2.2. Design of power smoothing algorithm based on moving average

The moving average method is a statistical method based on time series analysis [25]. The core idea of the algorithm is to determine the average of a group. The equation (8) represents the MA filter presented in this paper [26].

$$P_{PVC}[k] = \left(\frac{1}{N}\right)(P_{PV}[k] + P_{PV}[k-1]+\ldots+P_{PV}[k-N+1]) \qquad (8)$$

where P_{PV} is the PV output power, P_{PVC} is the output power of the moving average filter and N is the samples inside the time windows. After the specified number of iterations, the variable P_{PV} is replaced by the smoothing power of the PV (P_{PVC}). The difference between the smoothed power and the input power is the result of P_{SC} power flow sends to the grid. The specific process showed in Figure 3 is as follows:

- First, the input variables are defined ($P_{PV}, P_{SC}, N, SoC_{SC}$), similarly to previous case, the input variables are assigned its auxiliary variables (aux, i).
- Then, find the individual extreme values of each target function corresponding to minimum and maximum state of charge in SC, where N are defined by the number of samples in time

windows by the power smoothing, the calculations are performed by obtaining the outputs value $(PT = P_{PV} + P_{SC})$ that can be seen in the system.

- Finally, as in the previous case, the SOC of the SC-ESS is maintained at safe levels thanks to the implementation of a supervisory control of the energy storage, which is described in the following subsection.
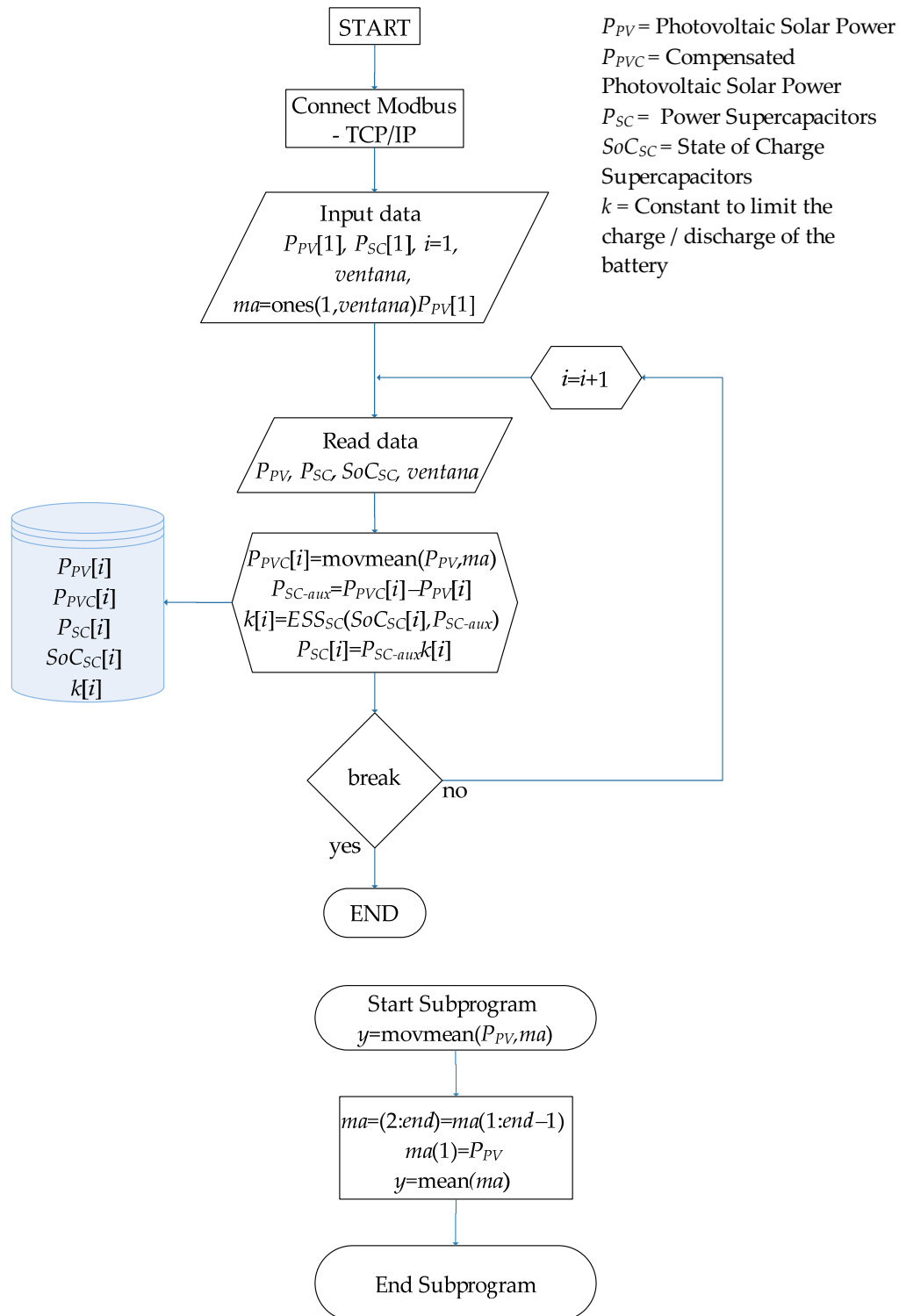

Figure 3. Flowchart to the moving average filter-based power smoothing method implementation.

2.3. Supervisory control of energy storage

To consider the constraint values in the supervisory control, it is important to monitor the SOC of the SC-ESS, SoC_{SC}, and regulate the charge and discharge process through an auxiliary variable (k), that can be inside the interval ($0 < k < 1$), which is multiplied to the power value P_{sc-aux} before sending it to the SC-ESS, the proposed control rules under charging state are shown in Table 1. The rules presented in this section are defined to improve the performance of the in LP and moving average filters while preserving the integrity of the SC-ESS by forcing it to operate within the safe limits of its SOC. The conditionals for supervision the percentage of SOC_{SC} are explained below:

- When the $SOC_{SC} > 80\%$, the SC-ESS absorbs a power limited by the constant ($k = 0.1$), however the SC-ESS is able to send deliver its maximum power capacity if $k = 1$.
- If the $20\% < SOC_{SC} < 80\%$, the SC-ESS operates normally delivery or absorbing the fully power with $k = 1$.
- If the percentage of charge of the SC falls below 20%, the storage system is considered to be in a low range, and priority is given to its charging to maintain its operation. For power values of the SC (P_{sc-aux}) greater than zero, a minimum value is assigned to the constant "k" in order to minimize the discharge of the SC ($k = 0.1$). For power values lower than zero (P_{sc-aux}), a maximum value of the constant "k" equal to 1 is assigned to ensure its charging and achieve normal operating values (see Figure 5). These conditions within the algorithms ensure that the SC remains within its safe operating range, thereby preserving its SOC and extending its lifespan.

Table 1. Rules for output power control and SoC_{SC} in power smoothing.

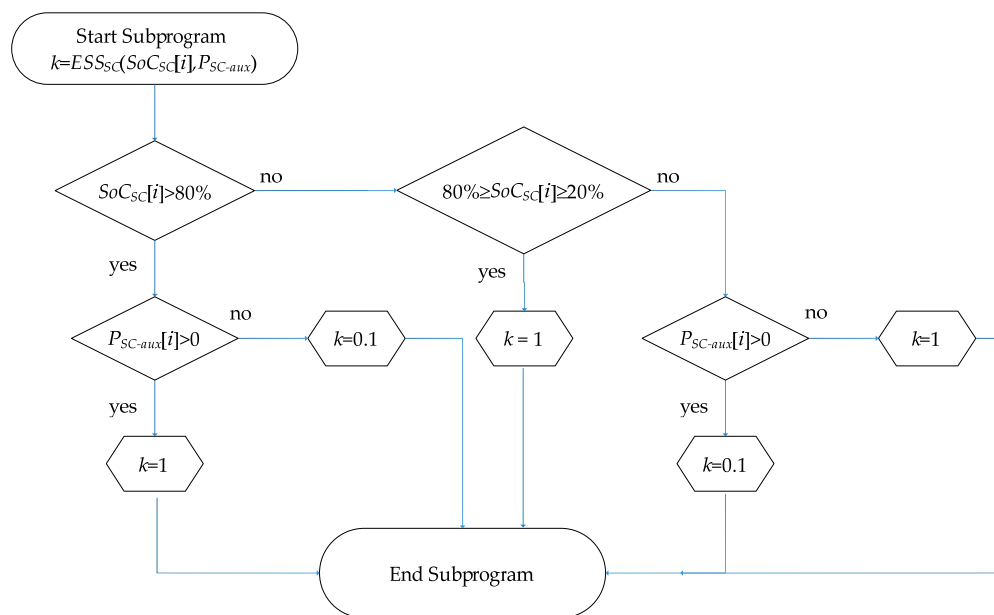| Condition	SoC_{SC}	P_{SC-aux}	k
$SoC_{SC} > 80\ y\ Psc_{aux} > 0$	> 80	> 0	1
$SoC_{SC} > 80\ y\ Psc_{aux} \le 0$	> 80	≤ 0	0.1
$80 \ge SoC_{SC} \ge 20$	$20 - 80$	-	1
$SoC_{SC} < 20\ y\ Psc_{aux} > 0$	< 20	> 0	0.1
$SC_{SOC} < 20\ y\ Psc_{aux} \le 0$	< 20	≤ 0	1

Figure 4. Flowchart for implementing conditionals to optimize the charging/discharging of an ESSSC.

3. Case of study

In this paper, algorithms developed in MATLAB were utilized to carry out tests on a real-time grid-connected microgrid. The microgrid consisted of poly-crystalline solar panels with an installed capacity of 15 kW (PV1) and a 30 kW SC-ESS (Supercapacitor Energy Storage System). The Micro-Grid laboratory for microgrids at the University of Cuenca (CCTI-B), Ecuador was used for this specific case study [27]. The equipment was configured to create a network. Figure 6 illustrates the presence of a main protection breaker (S1), a transformer connected to CCTI-B with a capacity of 150 kW, a secondary protection breaker (S2) specific to CCTI-B, a protection breaker for the PV array (S3), and a protection breaker for the SAE-SC (S4) along with its respective three-phase transformer (T2). It is important to note that the inverter operates at a different voltage (440 VAC) compared to the main grid (220 VAC). All of these components are connected to the public distribution grid network (B-01).
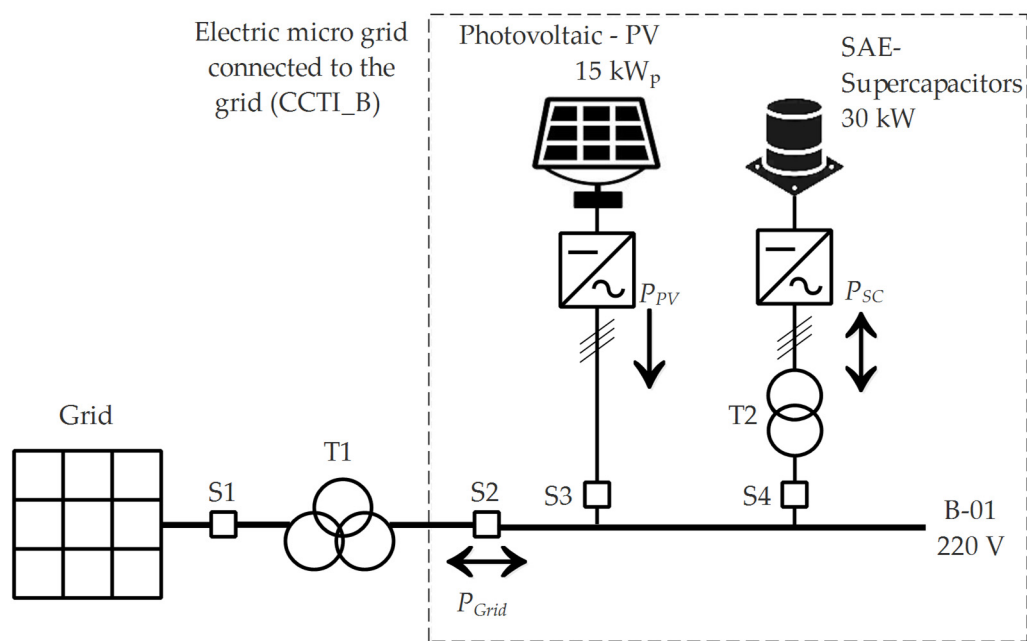

Figure 5. Grid-Connected microgrid at the Micro-Grid laboratory (CCTI-B).

3.1. Implementation of the power smoothing system in the experimental platform (CCTI-B).

The system consists of PV1 (Photovoltaics 1) and SC-ESS (Supercapacitor Energy Storage System), designed to store excess energy generated by the PVs and compensate for variations in energy generation. This stored energy is utilized to mitigate fluctuations in energy generation. To achieve efficient and accurate communication among the equipment, a configuration and MATLAB code were designed for Ethernet Modbus TCP/IP connection and communication (see Figure 8). The control and monitoring of the system are carried out from the Micro-Grid Laboratory at CCTI-B, utilizing a SCADA system with an interface developed in LabVIEW [27].
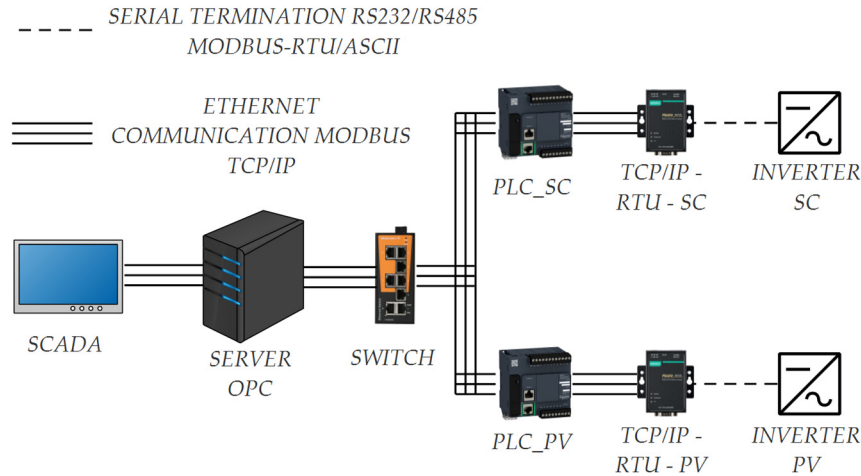
Figure 6. Architecture of connected equipment at CCTI-B.

3.2. Types of daily PV power curves.

It is important to consider that variability in daily PV production can significantly impact the operation and performance of both grid-connected and off-grid PV systems, as well as the design and sizing requirements of energy storage or energy management systems. Depending on the specific conditions and requirements of each project or application, analyzing and understanding the daily solar production curve with high and low fluctuations is of great importance in the planning, operation, and optimization of solar energy equipment. For this specific case, two types of randomly generated PV power curves have been considered throughout the year. Depending on the climatic conditions, geographic location, and characteristics of the PV system, the PV generation curve can vary significantly from one day to another. Figures 9 and 10 depict two potential daily PV power curves with high and low variability, respectively. These two profiles are from actual records measured on the rooftop of the Micro-Grid laboratory building in the city of Cuenca, Ecuador (-2.891918819933002, -79.03857439068271 WGS84 coordinate system).

The daily PV power curve with high variability (Type I) shown in Figure 9 exhibits the daily PV behavior, which varies significantly throughout the day due to climatic factors such as solar radiation variability, the presence of clouds, or shadows from nearby obstacles. For instance, on cloudy days or during rapid changes in cloud coverage, the power output of the solar cells will abruptly change within a short period of time, resulting in substantial fluctuations in the daily electricity generation curve. This curve may display sharp peaks and drops in generation throughout the day, indicating the presence of power fluctuations.
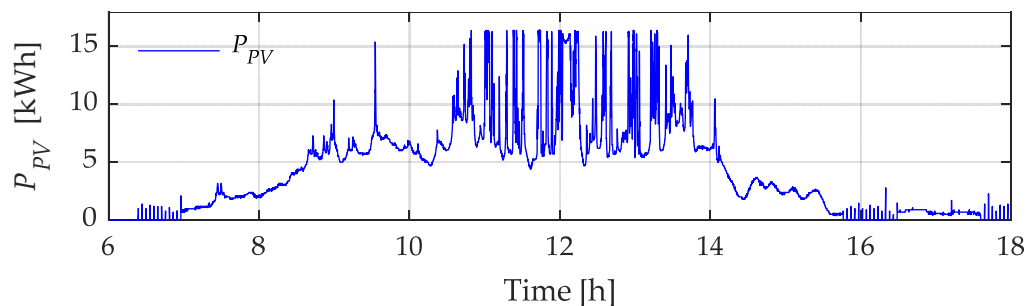

Figure 7. Photovoltaic power curve of a Type I day, with high variability.

On the other hand, the daily PV power curve with low variability Type II shown in Figure 10 indicates that the daily PV power production remains relatively constant throughout the day with minimal changes due to climatic factors. This can occur under conditions of continuously high solar radiation, clear skies, and no shadows or obstructions in the solar system. This curve can provide a

more stable and uniform PV electricity production throughout the day with smooth and gradual changes in electricity generation.
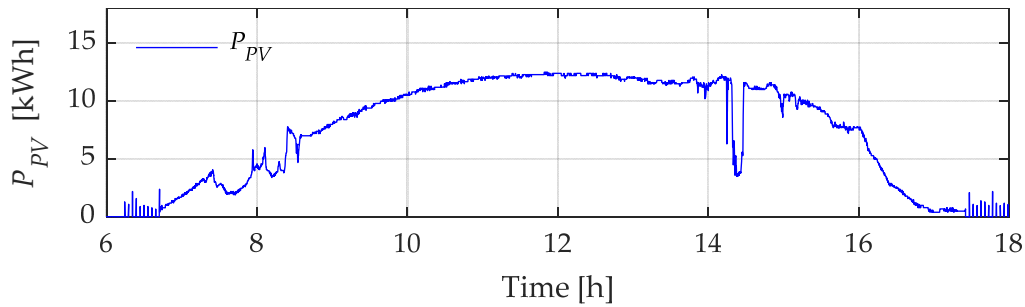

Figure 8. Photovoltaic power curve of a Type II day, with low variability.

For laboratory testing and verification of the proposed methods' efficiency, approximately 1.5 hours of the Type I curve (see Figure 9) were emulated (See profile highlighted in red in Figure 11). This specific segment of the Type I curve was chosen for emulation due to its behavior, which includes an initial power peak, followed by a decrease and then a plateau with high variability. This selection enables a more appropriate evaluation of the proposed methods. In Figure 11, the emulated curve is depicted in red, aiming to test the two methods in real-time under the same PV solar power conditions, thereby enabling a better assessment of the SC-ESS behavior. It should be noted that an energy storage system based on lithium-ion batteries (Li-Ion BESS), available in the laboratory and connected to the B-01 busbar of the microgrid (Figure 6), is used for the PV-delivered power emulation.
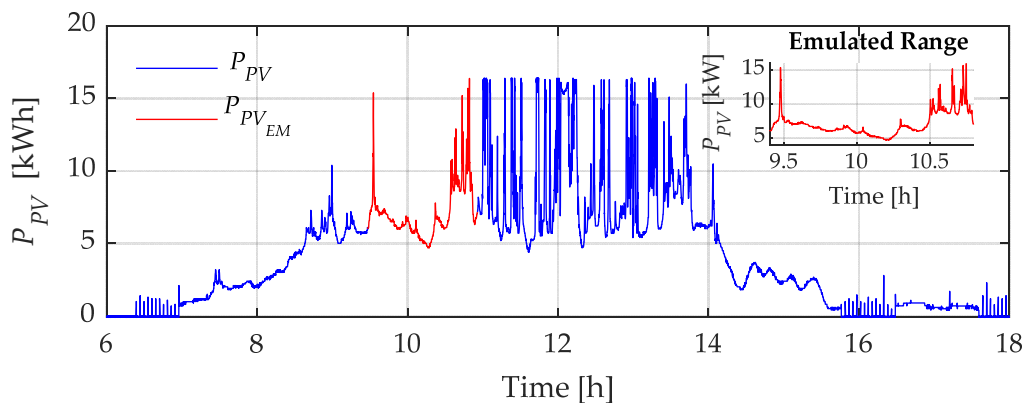

Figure 9. Emulated photovoltaic solar generation ($P_{PV_{EM}}$) in the laboratory of the Type I curve (P_{PV}) for real-time testing.

4. Result and discussions

In this study, the use and effectiveness of two methods for power smoothing were evaluated: a low-pass filter and a moving average filter, considering in each case employing three conditions based on the SoC_{SC} percentage initial state of charge of the SC-ESS.:

- Case 1: SC-ESS at maximum state of charge (overcharged condition)
  Under these circumstances, it is mandated that the supercapacitor (SC) be charged to a level exceeding 80% of its state of charge (SOC) prior to perform the power smoothing tasks.
- Case 2: SC-ESS in a medium state of charge
  In this scenario, a requirement is established for the SOC of the SC to be maintained within the range of 20% to 80% as an initial condition.
- Case 3: SC-ESS at minimum state of charge (undercharged condition)

Lastly, for this specific undercharged state, the SC-ESS starts its compensation work with a value below 20% of its maximum storage capacity.

4.1. Low Pass filter based power smoothing method resutls

The experimental results are summarized in Figures 12–14, displaying the emulated profiles of PV power (blue line), SC-ESS power (green, purple, and yellow lines, according the case of study), and the smoothed power output to the grid (red line). Figure 15 presents an overview of the SoC_{SC} percentage behavior for each case study, demonstrating satisfactory performance as the system maintains its operation within safe values (20%–80%), showcasing the effectiveness of the proposed method in this particular case.
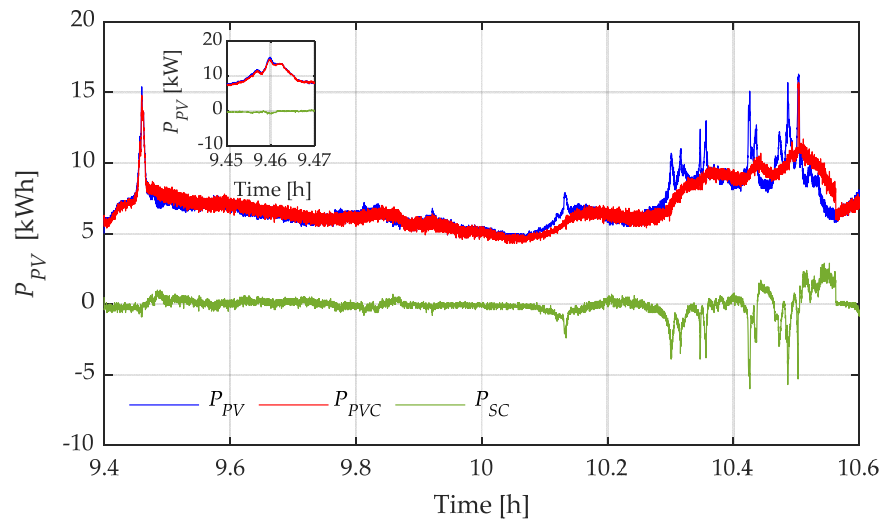

Figure 10. Results of the response of SC-ESS (Case 1) to input PV solar power fluctuations P_{PV} with the LP filter and its compensated PV solar power response P_{PVC}.
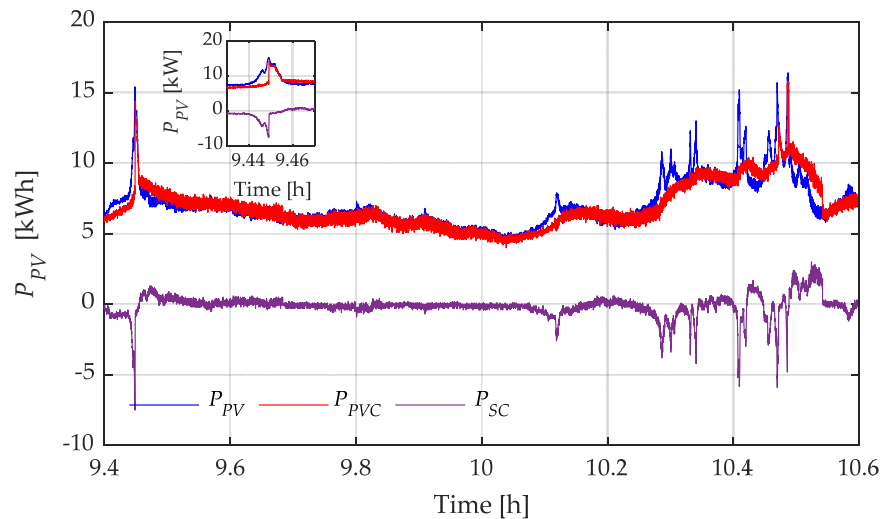

Figure 11. Results of the response of SC-ESS (Case 2) to input PV solar power fluctuations P_{PV} with the LP filter and its compensated PV solar power response P_{PVC}.
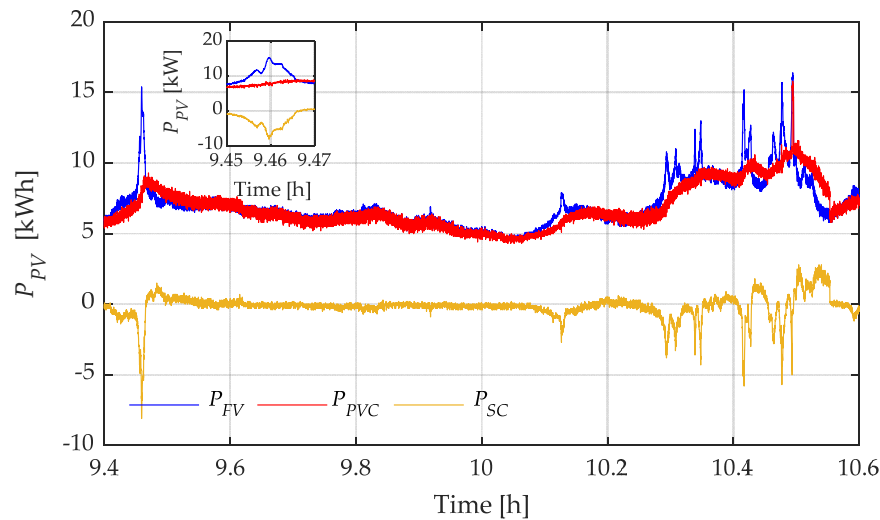
Figure 12. Results of the response of SC-ESS (Case 3) to input PV power fluctuations P_{PV} with the LP filter and its compensated PV solar power response P_{PVC}.
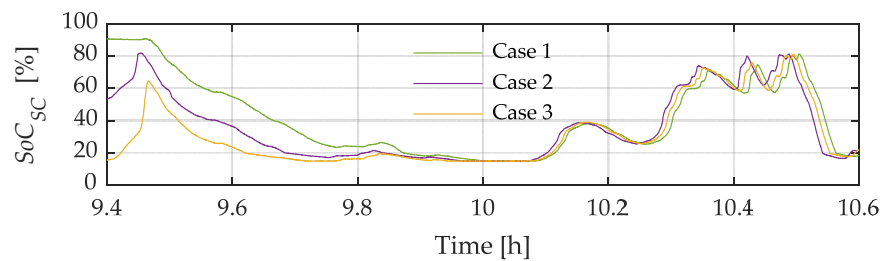

Figure 13. Response of SC-ESS to the LP filter under its three SoC_{SC}, conditions. Case 1 with SoC_{SC} around 90%. Case 2 with SoC_{SC} around 50% and case 3 with SoC_{SC} lower than 20%.

Table 2 shows the results of the LP filter, indicating that by implementing the three conditions based on the SoC_{SC} percentage, a reduction in the variability of renewable energy generation was achieved. The first condition threshold was set slightly above 80% of SoC_{SC}, the second between 80% and 20%, and the third below 20%. The implementation of these conditions allowed the filter to deliver more or less energy when the SoC_{SC} percentage was within the specified range, thereby enabling the filter to effectively smooth out the generated energy.

Table 2. Results of PV power output with and without the LP filter for power smoothing.

[%]SoC_{SC} initial	Variance without SC-ESS	Variance with SC-ESS	Variance reduction [%]	PV energy delivered without SC-ESS [kWh]	Delivered compensated PV energy with SC-ESS [kWh]	Energy difference [kWh]
$SoC_{SC} > 80$	2.99	2.65	11.4	8.24	8.14	0.09
$SoC_{SC} = 50$	2.92	2.56	12.3	8.42	8.26	0.15
$SoC_{SC} < 20$	2.99	2.49	16.7	8.19	7.99	0.19

4.2. Moving average based power smoothing method results

The experimental results are summarized in Figures 16–18 depicting the emulated profiles of PV power (blue line), SC-ESS power (green, black, and orange lines, depending on the case of study), and the smoothed power output to the grid (red line). Figure 19 presents an overview of the SoC_{SC} percentage behavior for each case study, demonstrating satisfactory performance by maintaining operation within safe values (20%–80%) and showcasing the effectiveness of the proposed method in this particular case.
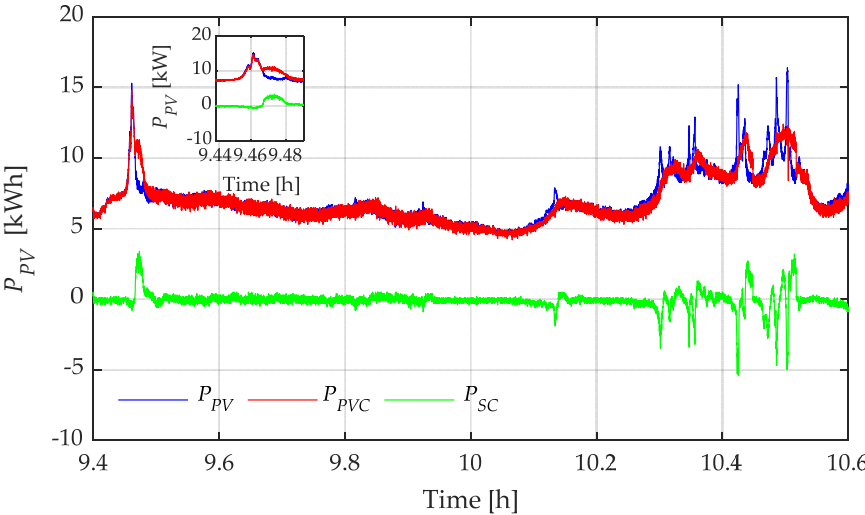
Figure 14. Results of the response of SC-ESS (case 1) to fluctuations in the input PV power P_{PV} with the MA filter and its compensated PV power response P_{PVC}.
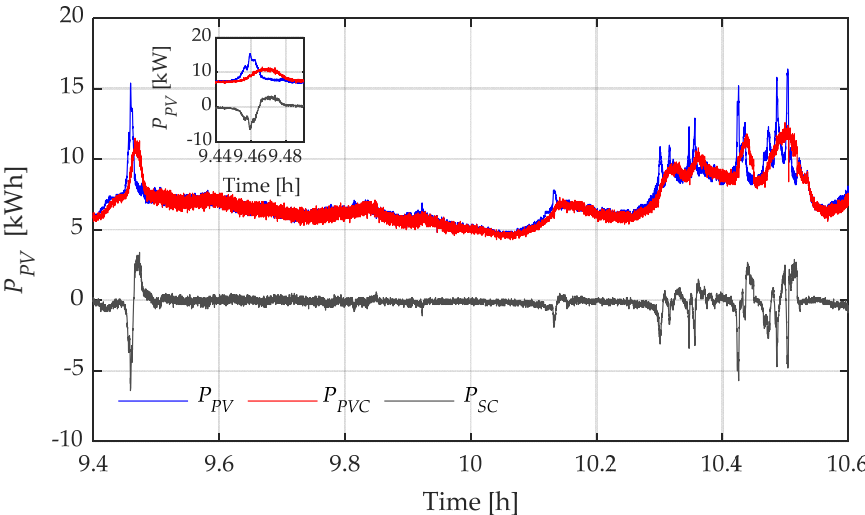

Figure 15. Results of the response of SC-ESS (case 2) to fluctuations in the input PV power P_{PV} with the MA filter and its compensated PV power response P_{PVC}.
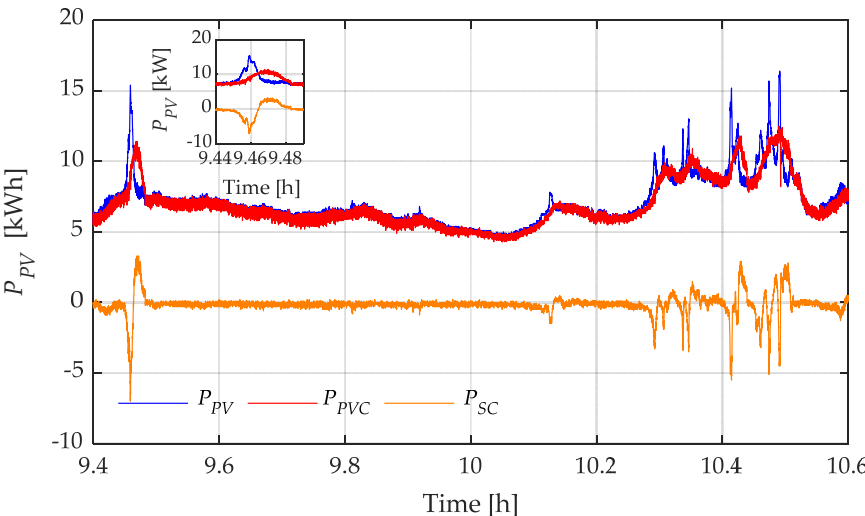

Figure 16. Results of the response of SC-ESS (case 3) to fluctuations in the input PV power P_{PV} with the MA filter and its compensated PV power response P_{PVC}.
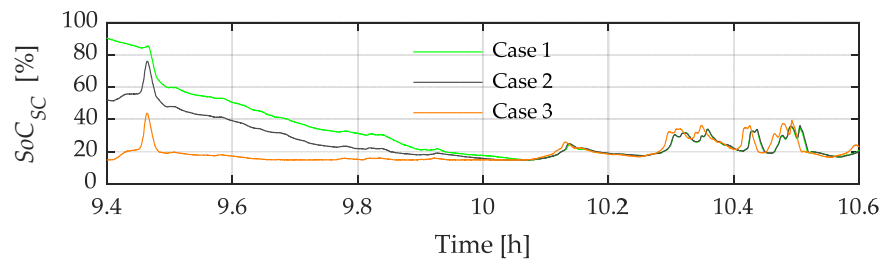
Figure 17. Response of SC-ESS to the MA filter in its three SoC_{SC} conditions, case 1 greater around than 90%, case 2 around 50%, and case 3 less than 20%.

Table 3 shows the results of the moving average filter, applying the same approach of three conditions based on the SoC_{SC} percentage. It was observed that the MA filter achieved a greater reduction in the variability of the generated energy compared to the LP filter. The three condition thresholds were set similarly to the LP filter method. In this case, the implementation of the conditions allowed the MA filter to deliver more or less energy in a similar manner to the LP filter, further improving system stability.

Table 3. Results of PV solar power output with and without MA filter for power smoothing are presented.

[%]SoC_{SC} initial	Variance without SC-ESS	Variance with SC-ESS	Variance reduction [%]	PV energy delivered without SC-ESS [kWh]	Delivered compensated PV energy with SC-ESS [kWh]	Energy difference [kWh]
$SoC_{SC} > 80$	2.97	2.84	4.4	8.28	8.20	0.07
$SoC_{SC} = 50$	2.98	2.69	9.7	8.29	8.16	0.13
$SoC_{SC} < 20$	2.94	2.68	8.8	8.28	8.11	0.17

Based on the results, it can be observed that applying the SC state of charge control algorithm for the emulated time, the LP filter method achieves greater power smoothing. On the other hand, when considering the energy delivered to the system at that specific time, the MA method performs better as it delivers more energy. The LP-based method delivers less energy because the SC-ESS stores a greater amount of energy compared to the MA method. This can be attributed to the fact that the SC-ESS has a higher energy storage capacity in relation to the MA method (see Figure 15 and Figure 19).

4.3. Comparison between Methods

In this section, we present a comparison between the LP filter method and the MA method in terms of their performance for power smoothing in the PV system. The LP filter method demonstrates a higher degree of power smoothing, effectively reducing the variability of power output. It achieves a smoother power profile, resulting in a more stable power output to the grid. However, it is worth noting that the LP filter method delivers less energy to the system at a given time. This is due to the higher energy storage capacity of the SC-ESS, which results in a higher energy retention compared to the MA method. On the other hand, the MA method performs better in terms of energy delivery to the system. It provides a higher amount of energy, making it more advantageous in terms of power availability. However, it may exhibit slightly lower power smoothing compared to the LP filter method.

Overall, the selection between the LP filter method and the MA method hinges upon the specific requirements and priorities of the PV system. If the primary goal is to mitigate power fluctuations and ensure a consistent power output to the grid, the LP filter method is highly recommended. Conversely, if the emphasis is on maximizing energy delivery, the MA method may prove to be more suitable. It is essential to conduct thorough analysis and consider the system's requirements in order to make an informed decision regarding the choice of method. Lastly, Table 4 provides a concise overview of the advantages and disadvantages associated with the implemented filter methods, based on the findings of this research.

Table 4. Summary of the advantages and disadvantages of the implemented assessed power smoothing filter methods.

		Moving Average Filter	Low Pass- Filter
Advantages		Easy to implement	Preserves the characteristics of the original power signal
		Can reduce random power noise	Suppresses high variability power noise
		Eliminates power peaks and smooths variable power signals	Improves the quality of the power output to the grid
			Maintains the SoC_{SC} levels above 50%
Disadvantages		Not suitable for power signals with rapid changes	It can overly smooth the power signal in its output to the grid
		Ineffective in reducing high variability power noise	Delay in the filtered power signal
		Prone to be affected by extreme values	Requires more complex calculations
		Less effective in eliminating impulsive power noise Maintains the SoC_{SC} levels below 50%	

5. Conclusions

This paper introduces an advanced power smoothing method that enhances both the low-pass filter (LP) and moving average (MA) techniques for grid-connected photovoltaic systems. The novel approach incorporates monitoring and control of the state of charge of the supercapacitor energy storage system to effectively mitigate photovoltaic power fluctuations at the common coupling point. A case study of a high-altitude microgrid in a city in Ecuador is presented, accompanied by comprehensive laboratory testing utilizing real-world data.

In conclusion, both the LP filter and MA filter methods have demonstrated their effectiveness in power smoothing for renewable energy systems. However, the LP filter has exhibited a slightly higher level of effectiveness compared to the MA filter, particularly when considering conditions based on the percentage state of charge of the supercapacitor.

Under energy storage conditions, the LP filter effectively keeps the state of charge percentage below 50%, allowing for greater energy absorption and providing enhanced smoothing when there is an increase in solar PV generation. Conversely, if the LP filter maintains the state of charge percentage above 50%, it can result in exceeding 80% of the supercapacitor's state of charge when absorbing energy due to the rise in photovoltaic solar generation. As a consequence, the smoothing effect is diminished, leading to smaller and less smooth peaks in the output.

The LP method demonstrates high efficiency in power smoothing compared to the MA filter. It follows the original envelope of the input PV power while maintaining the supercapacitor's state of charge at around 50%, irrespective of the initial state of charge. On the other hand, the MA filter method offers simplicity in implementation for supercapacitor drivers due to its lightweight computational design, enabling faster response times compared to the LP filter. The MA filter effectively smooths unpredictable power fluctuations and maintains the supercapacitor at a low state of charge, which is an advantageous feature for preparing the supercapacitor to rapidly respond to significant variations in PV power through quick energy absorption.

In summary, the LP filter method demonstrates superior effectiveness in power smoothing, particularly when considering specific state of charge conditions, while the MA filter method offers simplicity and rapid response capabilities. The choice between the two methods depends on the system requirements, the desired level of smoothing, and the prioritization of energy absorption efficiency versus response speed.

The article provides valuable insights to enhance the efficiency of power smoothing in renewable energy systems using supercapacitors and control algorithms. Further research and experimentation are recommended to evaluate the performance of these filters under different conditions and scenarios.

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