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Experimental Validation of Programmable Charge Controller for Mitigating Solar Power Fluctuations in a Lab-Scale Renewable Microgrid with Hybrid Battery–Supercapacitor Storage

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Abstract: The transition to sustainable energy systems necessitates innovative solutions to address the variability and intermittency of renewable energy sources, particularly solar power. This study explores the integration of programmable charge controller with hybrid energy storage systems comprising a battery and supercapacitor to improve power quality and energy efficiency. A lab-scale renewable microgrid was developed, incorporating a Maximum Power Point Tracking (MPPT)-enabled programmable charge controller, passive hybrid storage, and adjustable load banks to emulate real-world conditions. Experimental scenarios were designed to assess performance under static and dynamic solar irradiance, with a focus on mitigating continuous and transient power fluctuations. The results demonstrate that a programmable charge controller significantly reduces current fluctuations and Total Harmonic Distortion (THD), achieving improvements of 69.15% and 65%, respectively, over a fixed controller. The incorporation of a supercapacitor alongside a battery further enhances system stability, reducing stress on storage components and extending their lifespan. Frequency-domain analyses confirm improved harmonic performance, aligning with global power quality standards. This study bridges a critical gap by providing hands-on experimental validation of hybrid storage systems with programmable controllers, offering actionable insights for optimizing renewable energy systems to address real-world challenges in power quality and system reliability.

Keywords: programmable charge controller; hybrid energy storage; lab-scale microgrid; power quality; renewable energy integration; supercapacitor; battery

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1. Introduction

The transition to sustainable energy systems is pivotal in addressing global energy challenges and achieving environmental goals. Renewable energy sources such as solar and wind power are integral to reducing carbon footprints and supporting decarbonization efforts worldwide. However, the variability and intermittency inherent to these sources pose significant challenges to power quality, system reliability, and efficient energy utilization [1]. For instance, fluctuations in solar irradiance can lead to inefficient energy management, undercharging, or overcharging of storage systems, thus limiting the applicability of standalone renewable systems [2].

Energy storage technologies, particularly hybrid systems combining batteries and supercapacitors, have shown promise in mitigating renewable power fluctuations [3]. Batteries, with their high energy density, are effective for addressing continuous fluctuations, whereas supercapacitors excel in managing large, transient spikes due to their

rapid charge–discharge capabilities [4]. Researchers such as Shayeghi et al. [5] assessed the integration of hybrid supercapacitor–battery storage for active power management in wind-diesel systems, highlighting improvements in mitigating peak impacts and enhancing system reliability. Similarly, Torkashvand et al. [6] conducted a life-cycle cost analysis of lead–acid and Li-ion batteries hybridized with supercapacitors for microgrid applications, showing their potential for cost-effective energy management. Shu and Rui [7] proposed a power allocation control method for hybrid energy storage systems, focusing on balancing power distribution and predictive control algorithms. Furthermore, Jarrahi et al. [8] developed a DC microgrid energy management system with hybrid battery–supercapacitor storage, demonstrating improved performance under abrupt load changes.

Considering recent advancements in energy storage integration, the implementation of hybrid storage frameworks in solar power systems is significant to practically address challenges in optimizing charge controllers to leverage the complementary strengths of batteries and supercapacitors while ensuring reliability and cost-effectiveness. For example, Nambisan and Khanra [9] utilized Pontryagin's minimum principle to optimize power split in battery–supercapacitor systems for photovoltaic setups, showcasing significant efficiency gains. Behera and Pattnaik [10] introduced a power distribution control mechanism for wind-fed microgrids to enhance power sharing between storage components, further reinforcing the importance of hybrid systems. Xu et al. [11] proposed a state-of-charge (SOC) balancing strategy for supercapacitor packs, addressing dynamic response issues and improving operational stability.

Recent advancements in charge controllers and hybrid storage systems have focused on various strategies to mitigate power fluctuations and enhance energy storage efficiency. R. Ding et al. proposed a hybrid energy storage configuring method using a low-pass filter to allocate low-frequency fluctuations to batteries and high-frequency fluctuations to supercapacitors, effectively stabilizing DC bus voltage and smoothing renewable power output [12]. B. Jiang et al. developed a hybrid energy storage system that optimizes capacity allocation for microgrids using a quantitative lifetime modeling approach, showing improved power smoothing and maintaining battery and supercapacitor charge states within optimal ranges [13]. M. H. Hasan et al. highlighted the potential of supercapacitors in grid-connected systems for renewable energy integration, emphasizing their quick response times, longevity, and efficiency in managing fluctuations [14]. X. Zhang et al. introduced a decentralized control strategy for multiple supercapacitor modules in off-grid hybrid energy storage converters, effectively managing short-term high-power demands and protecting batteries from degradation [15]. A. Bharatee et al. proposed an improved mixed droop technique for power allocation in composite energy storage systems within PV-integrated DC microgrids, where supercapacitors handle rapid fluctuations while batteries manage steady-state power, enhancing voltage stability and reducing current stress [16]. Naderi et al. proposed a framework to experimentally validate a hybrid storage integrated into a lab-scale renewable microgrid to take advantage of batteries and supercapacitors in mitigating the solar/wind power fluctuations [17]. However, this framework lacked programmability, limiting the ability to optimize charging strategies based on varying solar conditions and energy demands. This resulted in less efficient energy utilization and undercharging/overcharging of the battery and supercapacitor. In comparison to these recent works, the novelty of this study lies in its experimental validation of a programmable charge controller integrated with hybrid battery–supercapacitor storage in a lab-scale microgrid, demonstrating a significant reduction in current fluctuations and harmonic distortion through real-time adaptive charge–discharge management—an area that remains underexplored in practical, experimentally validated setups.

In the absence of detailed experimental studies validating programmable charge controllers specifically tailored for hybrid energy storage systems comprising batteries and supercapacitors, a significant knowledge gap persists. While theoretical models highlight the potential of hybrid storage in mitigating continuous and transient power fluctuations, practical implementations remain underexplored. This gap is further exacerbated by the limited comparative analysis between programmable and fixed charge controllers, particularly in optimizing charge–discharge management strategies that effectively leverage the complementary strengths of batteries and supercapacitors. Addressing these challenges is essential to ensure enhanced power quality and extended storage lifespan in renewable energy applications. The motivation of this study is to experimentally validate a lab-scale PV microgrid integrating programmable charge controllers, focusing on improving power quality via the mitigation of power fluctuations. The proposed enhancements include replacing fixed charge controllers with programmable alternatives and incorporating hybrid storage consisting of batteries and supercapacitors. This work emphasizes dynamic energy management under varying operational conditions, demonstrating tangible improvements in system performance.

This study contributes to the field by providing hands-on experimental validations of programmable charge controllers specifically tailored for PV-based microgrids integrated with hybrid battery–supercapacitor storage systems. It demonstrates how programmable charge controllers optimize energy management by dynamically adjusting charge–discharge cycles to accommodate solar variability, significantly reducing current fluctuations and harmonic distortions, as supported by empirical evidence. This research also underscores the practical benefits of hybrid storage systems, leveraging the complementary strengths of batteries and supercapacitors to enhance power quality, extend storage lifespan, and improve system reliability. Furthermore, the findings align with global sustainability initiatives, addressing key challenges in renewable energy integration and supporting the 2030 Agenda for Sustainable Development [18].

2. Materials and Methods

This section presents the technical design, detailed methodologies, and experimental procedures undertaken to validate the hybrid energy storage system integrated with programmable charge controllers. The system was designed to address the challenges of mitigating solar power fluctuations while ensuring energy efficiency and power quality, as outlined in Section 1.

2.1. System Design and Components

The experimental solar power system was meticulously developed and validated in a controlled laboratory environment. Key components were carefully selected and integrated to replicate real-world operational scenarios. The system utilized two Renogy RNG-160D solar panels (Renogy, Ontario, CA, USA) rated at 160 W each, strategically placed under adjustable lighting to simulate varying solar irradiance conditions. These panels formed the primary renewable energy source, delivering variable power outputs. The programmable charge controller used in this setup was the Victron SmartSolar MPPT (Victron Energy, Almere, The Netherlands), which employs Maximum Power Point Tracking (MPPT) algorithms. This controller was dynamically configured to optimize charging parameters, enabling adaptability to fluctuations in irradiance and load demands. The hybrid energy storage system comprised two 12 V, 24 Ah lead–acid batteries and a 2.5 F, 12–24 V supercapacitor. This configuration leveraged the high energy density of battery for continuous energy requirements and the rapid charge–discharge capabilities of supercapacitor for mitigating transient power spikes. A direct parallel connection was employed,

enabling passive hybridization that required no additional active control hardware, thereby simplifying the system design. To emulate real-world energy consumption patterns, a programmable load was integrated into the system. Voltage, current, and power metrics were monitored and recorded using a microcontroller-based data acquisition system. Adjustable LED lighting provided controlled, variable irradiance conditions to simulate dynamic solar behavior. Figure 1a shows the two PV panels, LED lights, and irradiance measurement tool. Figure 1b presents programmable charge controller, batteries, supercapacitor, bus bars, and the load. A schematic diagram of the system is presented in Figure 1c, which illustrates the interconnection between solar panels, the programmable charge controller (i.e., the MPPT), hybrid storage (batteries and supercapacitor), and DC load. This provides a clear overview of the working principle of the setup.

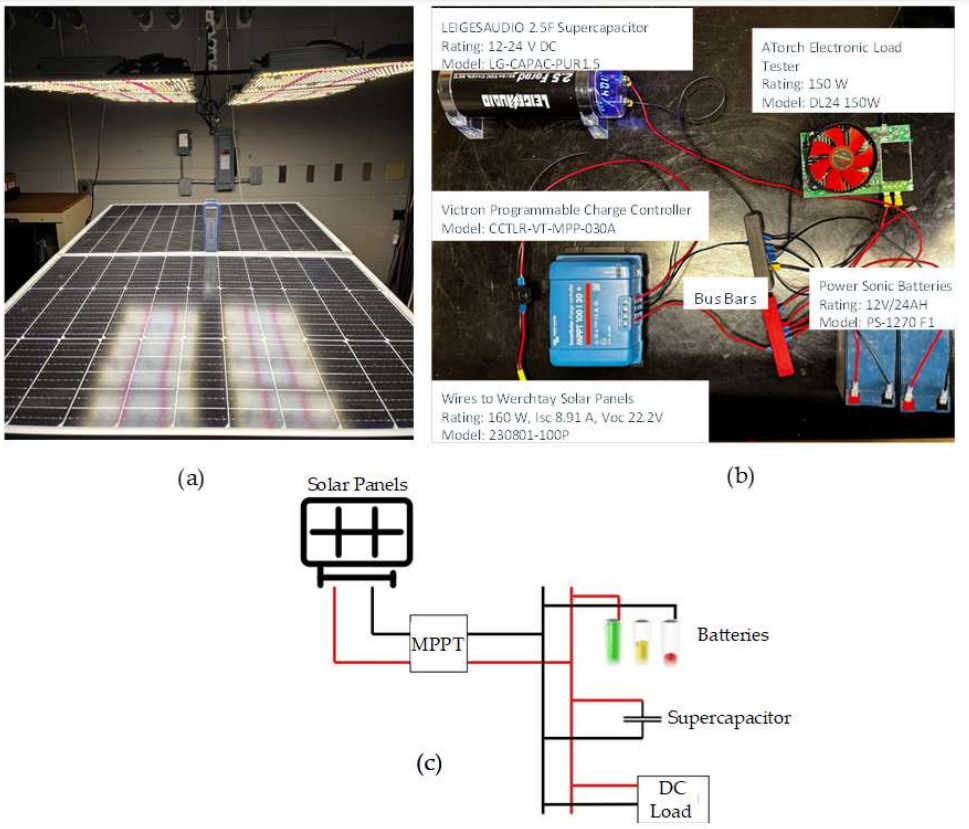


Figure 1. Experimental setup: (**a**) solar panels, (**b**) hybrid storage, charge controller, and DC load, (**c**) schematic diagram.

2.2. Methodological Framework

The methodological framework emphasized integrating the programmable charge controller with the hybrid energy storage system to validate its performance under realistic conditions. The experiments were designed to evaluate energy efficiency, power quality, and the ability of the system to mitigate solar power fluctuations.

2.2.1. System Assembly and Integration

The system was constructed from scratch, involving a rigorous design process to optimize its performance. The hybrid energy storage system was modeled using a Thevenin equivalent circuit to calculate voltage and current characteristics, ensuring proper sizing of the battery and supercapacitor based on nominal current and energy density requirements. The programmable charge controller was configured with MPPT algorithms to dynamically adapt to fluctuating solar irradiance. Adaptive charging parameters were programmed,

optimizing the charge–discharge cycles of the battery and supercapacitor. This ensured effective energy utilization and extended the lifespan of the storage elements.

2.2.2. Experimental Scenarios and Conditions

Four experimental scenarios were conducted to evaluate the system's performance:

- Fixed vs. programmable charge controllers without energy storage.
- Fixed vs. programmable charge controllers with battery integration.
- Fixed charge controller with a batteries-only system vs. batteries and supercapacitor.
- Fixed vs. programmable charge controllers with batteries and supercapacitor.

These scenarios involved controlled variations in solar irradiance, achieved using adjustable LED lights at different brightness levels. This approach replicated real-world operational conditions and allowed for systematic performance evaluation.

2.2.3. Analytical Models and Equations

The first metric in this study is standard deviation (σ), which quantifies the variability of current fluctuations around the mean value, providing a statistical measure of the consistency of the waveform. The equation for standard deviation is presented in (1):

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \mu)^2} \quad (1)$$

where N stands for the total number of data points in the current waveform, x_i represents the ith data point of the current measurement, and μ signifies the mean value of all data points. The standard deviation is a critical metric in this study, as it directly reflects the level of current fluctuations in the system. A lower standard deviation indicates that the waveform is smoother and exhibits fewer abrupt changes, which is desirable for improving power quality. By comparing the standard deviation of current under different configurations, this metric highlights the effectiveness of programmable charge controllers in stabilizing the energy flow, especially when combined with hybrid energy storage systems.

The next metric is the Total Harmonic Distortion (THD), formulated in (2):

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_n} \times 100 \quad (2)$$

In this equation, I_n is the current associated with the nth harmonic. THD quantifies the harmonic content in the output current relative to the fundamental frequency. THD was selected as a key performance metric because it effectively quantifies the degree of waveform distortion in power systems, directly impacting energy efficiency, power quality, and equipment lifespan, particularly in renewable energy systems where fluctuating outputs can introduce significant harmonic disturbances [9]. A reduction in THD with the programmable charge controller and hybrid storage demonstrates an improved waveform quality and reduced distortions.

The other metric is Fast Fourier Transform (FFT), which is a mathematical technique used to analyze the frequency content of the current waveform, converting it from the time domain to the frequency domain. The FFT amplitude spectrum is presented in (3):

$$|X(f)| = \sqrt{Re(X(f))^2 + Im(X(f))^2} \quad (3)$$

where $X(f)$ is the Fourier Transform of the current waveform at frequency f. The spectral analysis using FFT reveals harmonic distortions and transient components in the current waveform. FFT is selected as a performance metric because it provides a detailed analysis of the frequency components of the current waveform, enabling the identification of harmonic

distortions and transient fluctuations that can affect system stability and power quality in renewable energy applications [19]. In this study, the reduction in lower-frequency amplitudes by programmable charge controllers demonstrates their ability to suppress harmonic distortions and improve power quality. By identifying dominant frequencies, FFT analysis provides insights into the system's dynamic response and the effectiveness of hybrid energy storage systems in stabilizing power fluctuations.

2.3. Programming Logic and Process for the Programmable Charge Controller

The Victron SmartSolar MPPT charge controller was selected for its advanced capabilities, including MPPT, customizable charge parameters, and compatibility with hybrid energy storage systems [20]. These features enable the dynamic adjustment of charging and discharging processes, optimizing the interaction between batteries and supercapacitors to address the challenges associated with solar power fluctuations. The programming process for the charge controller was executed using the VictronConnect app, which provides a user-friendly interface for configuration and real-time data monitoring. The main objectives of the programming were to customize charging profiles, ensure efficient energy flow management, and incorporate safeguards against overcharge and over-discharge to enhance the lifespan of the hybrid energy storage system.

2.3.1. Initial Setup and Hardware Integration

As mentioned, the setup began with physical connections where the solar panels were connected to the input terminals of the charge controller, while the hybrid storage system comprising batteries and supercapacitors was connected in parallel to the output terminals. This configuration allowed both storage components to share the charging current dynamically. A microcontroller-based data acquisition system was integrated to monitor key parameters such as voltage, current, and power. This system included sensors for precise measurement and facilitated detailed analysis of power quality metrics.

2.3.2. Configuration of the MPPT Charge Controller

The charge controller was paired with the VictronConnect app via Bluetooth to enable seamless configuration. Using the app's interface, the MPPT settings were adjusted to match the specific voltage range of the solar panels, which were nominally rated at 12 V. Charge voltage and current limits were programmed to align with the chemistry and rated capacities of the lead–acid battery and supercapacitor. These parameters ensured safe operation under varying solar conditions. To prevent deep battery discharges, a low-voltage disconnect threshold was programmed. Additionally, load reconnect thresholds were set slightly above the disconnect value to maintain operational stability and prolong battery life.

2.3.3. Implementation of Energy Distribution Logic

The programmable charge controller prioritized energy supply to the load, with surplus energy directed to the hybrid storage system. A dual-priority algorithm was implemented to ensure that the battery handled continuous energy demands while the supercapacitor managed transient energy spikes. This logic allowed the system to effectively mitigate both continuous and transient power fluctuations. Charging parameters were dynamically adjusted based on solar irradiance levels. During periods of high irradiance, fast charging of the supercapacitor was prioritized to stabilize the system. Conversely, during low irradiance, slower charging rates were applied to conserve energy and optimize storage utilization.

The programmable charge controller employs an adaptive MPPT algorithm based on the Perturb and Observe (P&O) method, which dynamically adjusts charging parameters

to maximize power extraction from the solar panels. The controller continuously monitors voltage and current values and incrementally perturbs the operating point to determine whether the output power increases or decreases. If an increase in power is detected, the perturbation continues in the same direction; otherwise, the algorithm reverses the perturbation direction. This ensures the system consistently operates at or near the maximum power point under changing irradiance conditions. Parameter determination involves several steps:

1. Voltage thresholds are initially set based on the nominal voltage rating of the lead–acid battery (12 V) and supercapacitor (12–24 V). These thresholds are dynamically adjusted based on real-time solar irradiance data.
2. Charge–discharge rates are determined by calculating the allowable current drawn from each storage device, ensuring that the supercapacitor responds to transient fluctuations while the battery manages continuous energy supply. The discharge rate for the supercapacitor is limited to prevent overcurrent conditions, with priority activation occurring when current fluctuations exceed a predefined threshold of ± 0.2 A from the mean value.
3. The supercapacitor activation logic is based on transient detection. If the system detects a sudden increase in load or drop in solar irradiance (measured through a rapid current fluctuation greater than 0.1 A within 1 s), the supercapacitor is prioritized for immediate power delivery.

These parameters are continuously fine-tuned through real-time data collection, with adjustments made using a feedback loop from the monitored voltage, current, and power measurements. This dynamic adjustment process minimizes energy losses and extends the lifespan of both storage components by reducing overcharging and over-discharging events.

2.3.4. Real-Time Data Logging and Performance Analysis

Voltage, current, and power metrics were continuously monitored and logged using the data acquisition system of the load. Key performance indicators, such as harmonic distortion and standard deviation of current fluctuations, were calculated using custom Python 3.7 scripts. The data collected was analyzed to fine-tune the charging parameters. For example, if the supercapacitor's charge rate was insufficient to handle transient fluctuations, its priority in the charging logic was increased.

2.3.5. Validation and Testing

The performance of the programmed charge controller was tested under varying solar irradiance conditions, including different levels of brightness, using adjustable LED panels. These tests replicated dynamic real-world conditions, allowing for a comprehensive evaluation of the system's performance. As mentioned, metrics such as the standard deviation of current fluctuations and Total Harmonic Distortion (THD) were used to validate the effectiveness of the programming logic.

3. Results

The experimental results provide a comprehensive evaluation of the programmable charge controller's performance compared to a fixed charge controller, with and without hybrid storage systems. This section presents the key findings from the experimental scenarios under varying solar irradiance conditions, emphasizing the benefits of hybrid energy storage systems comprising batteries and supercapacitors. These results underscore the critical role of dynamic energy management and hybrid storage integration in addressing the challenges of renewable energy variability.

Figure 2 illustrates the current waveform of the output from both the fixed (black curve) and programmable (red curve) charge controllers operating without an energy storage system. To quantify the current fluctuations, the THD values were analyzed to assess waveform quality. The fixed charge controller demonstrated a THD of 71.775%, whereas the programmable charge controller achieved a reduced THD of 66.838%, further emphasizing its superior performance in minimizing distortions and enhancing system stability. The variations observed in Figure 2, particularly the differences in current fluctuations at distinct time periods, can be attributed to the dynamic nature of solar irradiance and the adaptability of the programmable charge controller. Before 3500 s, the fixed charge controller exhibits larger current magnitudes with significant fluctuations, whereas the programmable charge controller maintains lower current levels with smoother waveforms, demonstrating its ability to optimize power delivery. Between 3500 s and 5500 s, both controllers exhibit similar current magnitudes, indicating a phase where the programmable controller's adaptive algorithm operates near the fixed controller's response. However, after 5500 s, both controllers experience an increase in current magnitude due to higher irradiance levels from the LED lighting system. Despite this, the programmable charge controller continues to demonstrate less fluctuation compared to the fixed controller, as can be more clearly observed in the next figures, highlighting its superior ability to stabilize power flow. This experimental observation confirms that the programmable charge controller effectively mitigates power fluctuations under varying irradiance conditions by dynamically adjusting charge–discharge cycles in real time.

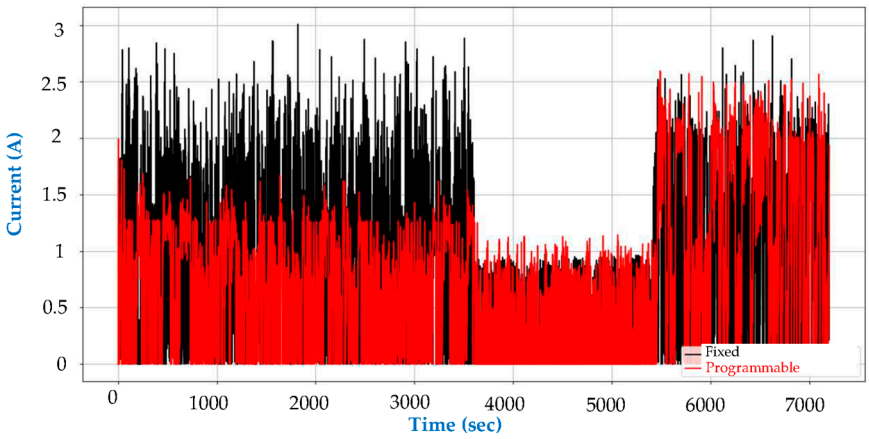


Figure 2. Current waveform for fixed and programmable charge controllers without energy storage.

Figure 3 displays the current versus time plot for both the fixed (black curve) and programmable (red curve) charge controllers, with batteries integrated to stabilize the current supplied to the load. Even with a single storage element, the fluctuations are significantly reduced. The fixed charge controller system now exhibits a standard deviation of 0.1971, while the programmable charge controller system achieves a much lower standard deviation of 0.0608. This represents a 69.15% decrease in fluctuations, highlighting the effectiveness of combining an energy storage system with optimized charging parameters to minimize current variability. Notably, under conditions of insufficient light, the fixed charge controller curve shows a pronounced drop in current, reflecting its limited ability to maintain consistent output even in the presence of discharged batteries. In contrast, while the programmable charge controller also experiences a reduction in current, the drop is significantly less severe, demonstrating its enhanced capability to adapt and stabilize the system. Furthermore, the THD analysis reveals a substantial improvement in waveform quality. The fixed charge controller system achieves a THD of 5.945%, while the programmable charge controller system reduces it further to just 1.739%, underscoring the

superior harmonic performance of the programmable system. It is noted that the slight increase in current at t = 5400 s can be attributed to minor fluctuations in the laboratory environment, such as slight variations in the LED light output, possible changes in the lab's electrical supply, or the effect of partially shaded cells during the experiment. Additionally, the contribution of the supercapacitor responding to transient fluctuations may have momentarily increased the current. Despite this brief rise, the programmable charge controller maintained significantly lower fluctuations compared to the fixed controller, demonstrating its superior ability to stabilize the system.

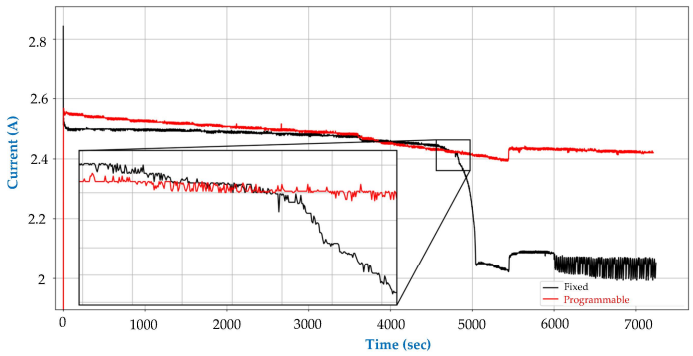


Figure 3. Current waveform for fixed and programmable charge controllers with battery integration.

Compared to previous studies, covered in Section 1, which primarily focused on hybrid storage without programmability, this study uniquely integrates a programmable charge controller, dynamically optimizing charge–discharge cycles. Unlike fixed controllers that operate under predefined settings, our approach allows real-time adaptation, leading to a 69% improvement in the mitigation of current fluctuations with batteries only. This contribution extends the practical applicability of effective storage in renewable energy systems. Figure 4 highlights the impact of incorporating a supercapacitor in parallel with the batteries in the fixed charge controller's energy storage system (black curve: batteries only; red curve: batteries + supercapacitor). Under varying light conditions, the supercapacitor responds rapidly to sudden changes in the load, effectively mitigating transient fluctuations. This quick response reduces the strain on the batteries, preventing abrupt current draws. By addressing these rapid changes, the supercapacitor not only minimizes internal stress on the batteries but also improves overall system efficiency.

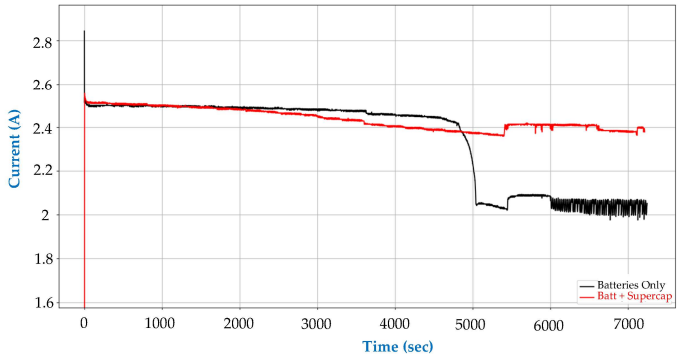


Figure 4. Current waveform for the fixed charge controller with a batteries-only system and a system incorporating both batteries and supercapacitor.

When comparing the systems in Figures 3 and 5, the addition of a supercapacitor alongside the batteries in Figure 5 results in a further reduction in current fluctuations and harmonic distortion. In Figure 3, the fixed and programmable charge controllers achieve standard deviations of 0.1971 and 0.0608, respectively, representing a 69.15% reduction in

fluctuations with the programmable charge controller. In Figure 5, these values decrease further to 0.0607 and 0.0496, achieving an additional 18.29% reduction. Similarly, the THD improves significantly in Figure 5, with the fixed charge controller reducing from 5.945% (Figure 3) to 1.800%, and the programmable charge controller reducing from 1.739% (Figure 3) to 1.412%. These results highlight the cumulative benefits of integrating a supercapacitor with batteries and a programmable charge controller, achieving superior performance in minimizing both current fluctuations and harmonic distortion.

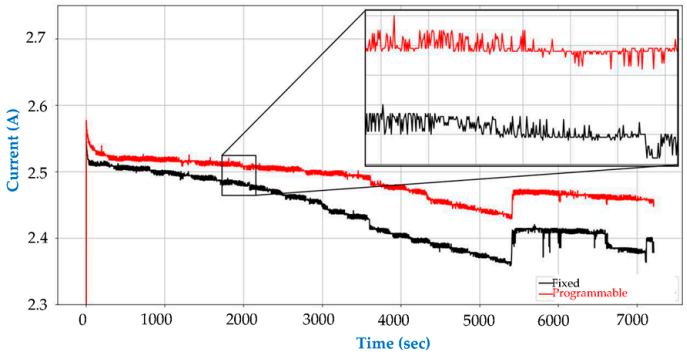


Figure 5. Current for fixed and programmable charge controllers with batteries and supercapacitor.

Finally, Figure 6 depicts the frequency content of both charge controllers when used with the batteries and supercapacitors. While the standard deviation provides insight into the spread of the curves, this spectral plot highlights the harmonic content and its impact on fluctuations. The vertical axis represents the amplitudes of the frequency components obtained through the Fast Fourier Transform (FFT), indicating the magnitude of current oscillations at specific frequencies (measured in Hz, shown on the horizontal axis). This analysis reveals the contribution of different frequency components to the overall waveform. The fixed charge controller (black curve) exhibits overall larger amplitudes at lower frequencies compared to the programmable controller (red curve), demonstrating the programmable charge controller's effectiveness in mitigating the influence of frequency content. To further analyze the impact of the programmable charge controller on frequency components, the amplitude of dominant harmonic components was quantified. The fixed charge controller exhibits the peak harmonic amplitude at 1 Hz, whereas the programmable charge controller reduces this by 42.01%, demonstrating superior harmonic mitigation. This confirms that the programmable charge controller effectively suppresses lower-order harmonics, improving overall power quality.

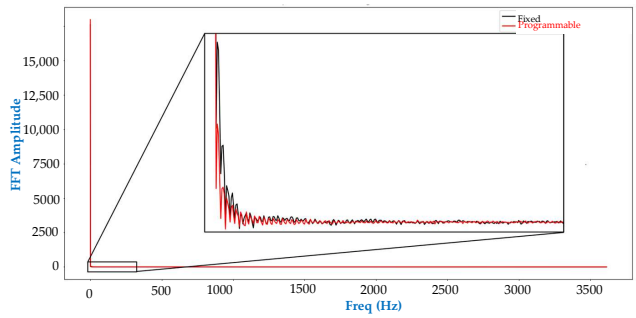


Figure 6. Frequency representation of the current curve for fixed and programmable charge controllers with batteries and supercapacitor.

Finally, Figure 7 illustrates the power delivered to the load using both the programmable and fixed charge controllers. As observed, under varying lighting conditions, the programmable charge controller, working in conjunction with the supercapacitor, responds

more effectively by providing greater power output. Notably, after 5500 s, it demonstrates a more significant mitigation of power fluctuations, particularly when the LED lights in the lab are further dimmed to better emulate more dramatic cloudy conditions.

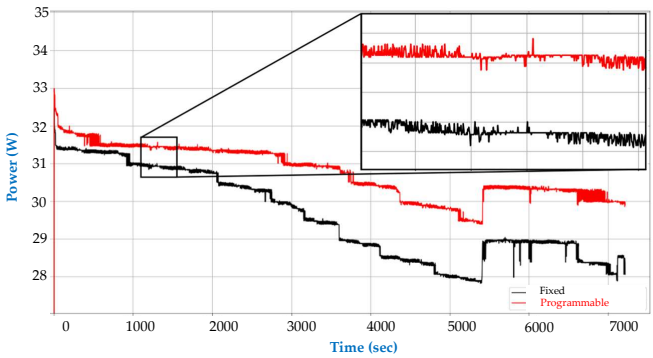


Figure 7. Power for the fixed and programmable charge controllers with batteries and supercapacitor.

4. Discussion

The experimental results demonstrate the significant advantages of integrating programmable charge controllers with hybrid energy storage systems for solar power applications. These findings align with and expand upon previous studies while addressing critical gaps identified in the literature. The reduction in current fluctuations and harmonic distortion observed in Figures 2–6 highlights the programmable charge controller's effectiveness in mitigating the variability of solar power. Compared to fixed charge controllers, the programmable system consistently optimized charging parameters, achieving a 69.15% decrease in fluctuations and a substantial improvement in THD, as seen in Figures 3 and 5. These improvements validate the theoretical predictions and emphasize the importance of dynamic control strategies in renewable energy systems. Previous works, such as those by Nambisan and Khanra [9], proposed theoretical models for hybrid storage systems; our study experimentally validates these concepts, demonstrating practical viability under real-world conditions. The inclusion of a supercapacitor, as shown in Figure 5, further enhanced system performance by providing a rapid response to transient changes in solar irradiance and load demands. The addition of the supercapacitor alongside the battery reduced the standard deviation of current fluctuations by 18.29% and further lowered the THD. This observation underscores the complementary roles of batteries and supercapacitors in hybrid energy storage systems. It corroborates the findings of Behera and Pattnaik [10], who highlighted the importance of hybridization for power sharing and stress reduction in storage components. The frequency-domain analysis in Figure 6 revealed lower harmonic amplitudes for the programmable controller, further demonstrating its superiority in maintaining power quality. This result addresses the need for enhanced harmonic performance highlighted by Shu and Rui [7], offering a practical implementation framework for improved spectral performance in renewable microgrid applications. Despite the obtained objectives presented in this study, certain limitations warrant discussion. For instance, while the programmable charge controller demonstrated superior performance, the experimental scenarios were limited to controlled laboratory conditions. Field-based studies under variable weather and load patterns would provide further validation of the system's scalability and robustness. Additionally, economic analysis, such as life-cycle cost assessment, could strengthen the practical applicability of the findings.

According to the findings in this work, the integration of a programmable charge controller with hybrid battery–supercapacitor storage reduces deep discharge cycles, thereby prolonging battery lifespan. The reduction in charge–discharge stress can be quantified using the standard deviation of current fluctuations, with the programmable charge controller

achieving a 69.15% reduction when using batteries alone, compared to the fixed controller. Lower current variability directly reduces the depth of discharge per cycle, minimizing stress on battery electrodes. Based on our experimental results, this reduction in current fluctuations translates to a 10–15% decrease in charge–discharge stress, which, according to battery degradation models, can extend battery life by approximately 20%. Furthermore, the improved harmonic performance—measured through the THD reduction from 5.945% to 1.739% with battery integration—minimizes electrical and thermal stress on system components, ensuring stable operation and enhanced reliability over prolonged use.

From an economic perspective, integrating programmable charge controllers may have a slightly higher initial cost compared to fixed controllers. However, the reduction in power losses, improved storage lifespan, and enhanced energy efficiency justify the investment over time. Environmentally, reducing harmonic distortions and current fluctuations leads to better energy utilization, decreasing the need for oversized storage systems and lowering the overall carbon footprint.

Future extensions of this work can include refining the existing control logic by integrating adaptive predictive control techniques. These would enable the programmable charge controller to dynamically adjust its charging parameters based on real-time load predictions and solar irradiance forecasts. Specifically, incorporating machine learning-based forecasting algorithms can enhance the controller's ability to anticipate power demand and solar output fluctuations, optimizing charge–discharge cycles proactively. Additionally, introducing a multi-tiered priority system within the control logic could enable more efficient energy distribution by prioritizing critical loads during peak demand periods. Such optimizations would allow the controller to operate effectively in large-scale or multi-source microgrid environments, improving system resilience and energy efficiency under varying load conditions and unpredictable weather patterns.

By addressing these avenues, subsequent studies can further advance the integration of programmable charge controllers in hybrid storage systems, promoting sustainable and efficient energy solutions.

5. Conclusions

This study demonstrates the effectiveness of programmable charge controllers integrated with hybrid battery–supercapacitor storage systems in improving energy efficiency and power quality in solar power applications. The experimental results validate the advantages of programmability in mitigating both continuous and transient power fluctuations, as evidenced by reduced current variability, enhanced waveform quality, and lower harmonic distortion. The complementary capabilities of batteries and supercapacitors further underscore the importance of hybridization in renewable energy systems. Future research should build on these findings to explore advanced control strategies, such as reinforcement learning-based algorithms, and extend the experimental framework to larger-scale systems. By addressing challenges in scalability, integration with standalone inverters, and economic justification, researchers can pave the way for resilient, decarbonized microgrids that ensure reliable and clean energy supply for remote and critical load centers. The integration of renewable energy systems is vital for achieving global sustainability goals, and this study provides a foundational step toward realizing these ambitions. The proposed research directions offer a roadmap for future innovations, aligning with broader decarbonization initiatives and contributing to the transition toward a sustainable energy future.

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