

Electrical Design and Integration of Solar Energy Systems with Supercapacitors for Enhanced Storage Efficiency

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ABSTRACT

Background: Solar photovoltaic systems are popular in generating sustainable energy, although the performance of the system is hampered by intermittency and lack of efficient storage of energy. The classic battery systems cannot handle the rapid changes well and that is why efficiency is compromised and the system becomes unstable.

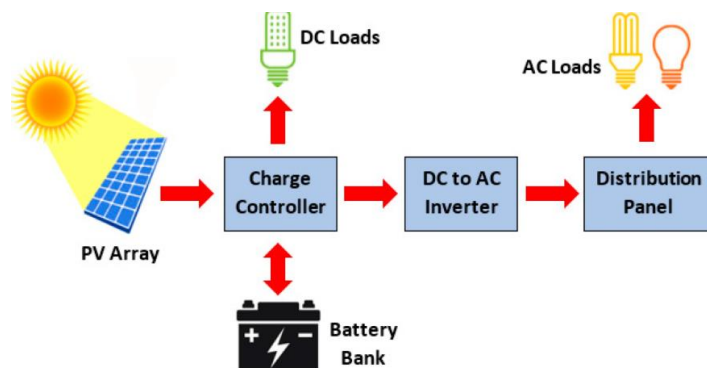
Purpose: In this study, the researcher seeks to design and test the electrical capabilities of solar energy systems together with supercapacitors to increase the storage efficiency and the general performance of the system.

Procedure: An energy storage system was modeled through a simulation-based approach that utilizes MATLAB/Simulink in order to simulate a hybrid energy storage system of a PV array, supercapacitor and a battery. The use of maximum power point tracking and rule-based system of energy management aims at regulating the power flow under different irradiance and load settings.

Findings: The findings show that the incorporation of supercapacitors enhances the efficiency of systems, voltage stability and the response time to load change is considerably lower. The energy loss was minimized and the hybrid system proved to be better in performance than the conventional battery only systems.

Conclusion: Supercapacitors integration with solar PV systems constitutes an efficient strategy to enhance the efficiency of energy storage, system reliability, and dynamism and hence a promising method in the contemporary renewable energy application.

Keywords: Solar Photovoltaic, Super-Capacitor, Hybrid Energy Storage System, Energy Efficiency, Voltage Stability, Renewable Energy.

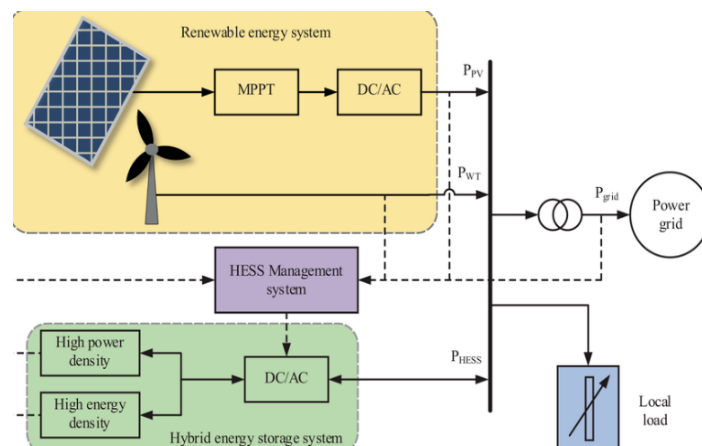


Introduction

The increased need, and enthusiasm towards clean and sustainable energy in the world has enhanced the pace at which solar photovoltaic (PV) systems are being used as a starting point to renewable energy. Solar energy has an immense

potential with massive environmental and economic positive contribution, yet the inherent intermittency and variability of the energy is the key factor in the matter of constant power production and provision. Standalone PV systems and grid-connected systems are unstable because of the fluctuating output caused by irradiance and weather variations, the day and night cycles, and hence limit the efficiency and stability of PV systems (Benoy et al., 2022; Hu et al., 2024). This has seen the introduction of the sophisticated electrical design solutions, to fit the effective power storage technology, as part of being able to guarantee power supply at all times as well as improving the performance of the set up (*Figure 1*).

The variation of solar power of power generation and demand is reduced by the storage of energy systems. Li-ion batteries are quite popular nowadays due to the high energy density but with such flaws like slow charge-discharge, thermal instability, and low lifespan in case of frequent cycling (Ramesh et al., 2024; Liu et al., 2025) limitations. It is these shortcomings that explain why more storage technologies are needed in order to enable it to handle the rapid variations in power and transient loads with a view to increasing the overall efficiency and reliability of solar energy systems. Super-capacitors are a new promising alternative or complementary power storage system since it has high power density, quick charge-discharge rate and long life. Supercapacitors are able to sustain the millions of charge cycles with a little degradation as compared to batteries due to their application in specific applications that require exchange of energy within a short time span and support peak power (Umoru, 2023; Benoy et al., 2022). The energy density however is relatively low and hence they can not store a lot of energy in the long run and hence they cannot be used in autonomous application in the renewable energy generation but must be used in conjunction with other storage devices (*Figure 2*).



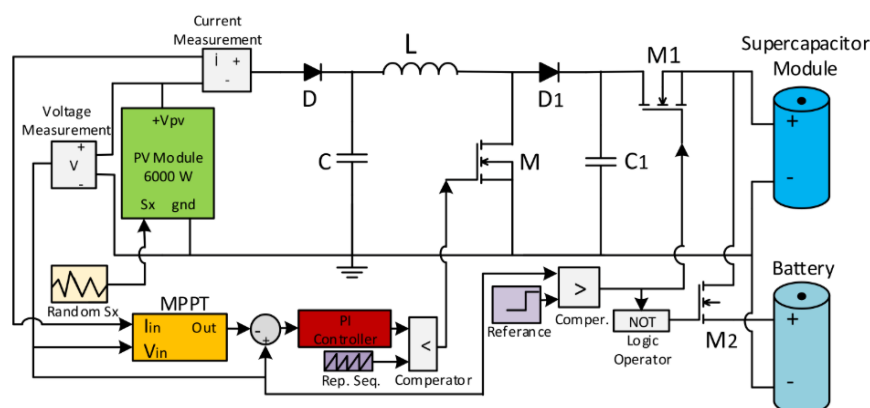
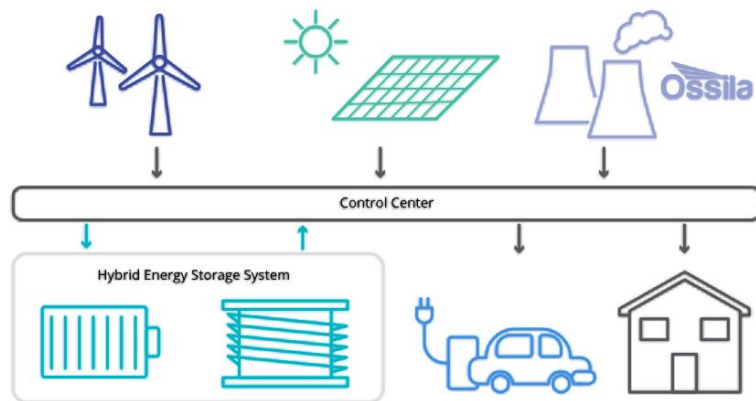
Having solar PV systems with super-capacitors (often as part of hybrid energy storage system, or HESS) has been a focal point of research in the integration of the two technologies to achieve a unanimous benefit. Within these systems, short-term fluctuations

of power and the transient loads are addressed by supercapacitors but long-term energy storage is addressed by batteries resulting in increased stability and efficiency of the system (Poudel et al., 2025; Han et al., 2025). It is also developed, because the control measures, which include data-based intelligent energy management systems, enhance a coordination of the elements of storage, which assures the maximum circulation of power, the constant value of voltage, and reduced load on the particular equipment (Hu et al., 2024; Kascak et al., 2025) (Figure 3).

Electrical design-wise, the concept of the integration of supercapacitors and solar energy systems is linked to complex requirements, including DC-DC converter topologies, the voltage balancing process, and the two-way power flow control. The design of the system must enable easy interaction of PV array, storage units and load and minimize the conversion losses and maintain the DC bus voltage constant. The importance of optimized converter models and real-time algorithms, in turn, to regulate energy consumption in systems, which predominantly belong to the microgrid and distributed energy realm, has been demonstrated in recent literature

(Ramesh et al., 2024; Poudel et al., 2025)).

Those developments demonstrate the greater usage of the combination of electrical design techniques in the new systems



of renewable energy (Figure 4).

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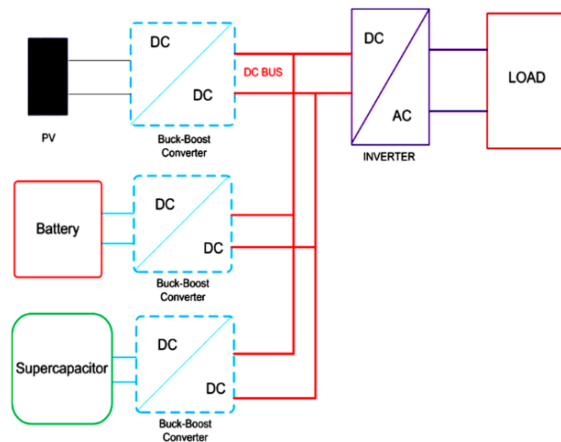
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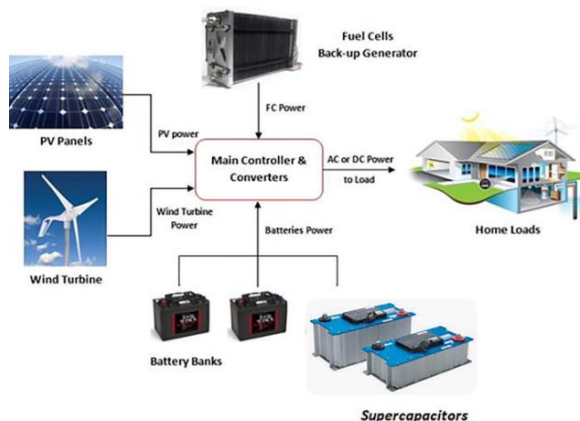
Despite the fact that a lot more progress has been achieved, some barriers still exist in order to successfully introduce solar energy systems with supercapacitors, and these are high costs of implementation, complexity in control and lack of energy density. Moreover, the existing systems are not necessarily well coordinated in their approaches in order to leverage on the complementary nature of the hybrid storage technologies. The issue that this research paper aims to address is that the solar energy systems are not as efficient and stable due to the lack of the integration of the high-performance storage solutions (Figure 5). This research may be significant as it can reach a greater efficiency of energy storage, reliability of the system, and the duration of existence of storage elements in solar applications. This paper aims at establishing and analyzing an optimized electrical integration of solar energy systems and the introduction of supercapacitors to achieve the high storage efficiency and system performance.



Method

The research design of the current study is a quantitative research design whereby it is a simulation based to investigate the electrical design and integration of solar photovoltaic systems (PV) and supercapacitors to enhance the storage efficiency. The system is modeled by a hybrid energy storage system which comprises of a PV array, super-capacitor bank and optional battery component to illustrate the performance of the system. The mathematical model of PV system is based on the standard single diode equations, but the irradiance and temperature variations have been introduced to reflect the real environmental conditions. Some MPPT technique, such as the Perturb and Observe (P&O) technique is used with the goal of offering the best power collection by the PV array under varying conditions. It is an integrated system that is being modeled and simulated in MATLAB/Simulink to analyze the energy flow, voltage stability, and load variation efficiency (Sutikno et al., 2022; Rekioua et al., 2023).

Electrical-integration the bidirectional DC-DC converter design is such that it can implement the process of effective charge and discharge between the storage unit and the DC bus. Voltage balancing schemes are also provided in order to overcome the low voltage rating of single cell supercapacitors in series (Figure 6). To control the amount of energy flow through the PV array, supercapacitor, and load, a system of energy management (EMS)



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is developed. The EMS is controlled by preset control logic according to which the supercapacitor is prioritised to lock out the transient fluctuation of power, peak load requirement without changing the steady DC bus voltage. The opportunities of the systems are fully utilized by means of more sophisticated control mechanisms such as rule-based and data-driven ones to minimize the load on the storage elements (Hu et al., 2024; Rahi and Alwash, 2024). Additional significant electrical performance measures are also taken into consideration like converter efficiency, switching losses and system response time.

In order to identify the effectiveness of the proposed system, a variety of simulation scenarios is performed, including the steady-state operation, sudden load variations, the conditions of the unstable solar irradiance areas. Enhancements that are made to such measures of performance are energy efficiency, voltage regulation, response time, and utilization of storage which are compared to the traditional battery-only systems. The interpretation of results and validation of the improvements obtained are performed through the checking of the statistical and graphical analysis of the achieved results in order to demonstrate the improvement of the results gained with the help of the use of supercapacitors. The evaluation of the long-term cycling performance and energy loss reduction is also looked at to determine the veracity and soundness of the system. The methodology aimed is to provide an extensive analysis of the hybrid system, which offers realistic value of optimizing the solar energy storage efficiency and finding out the system stability (Adeyinka et al., 2024; Ramesh et al., 2024).

Results

Table 1: *System Performance under Different Solar Irradiance Levels*

Irradiance (W/m ²)	PV Output Power (W)	Load Demand (W)	Super-capacitor Contribution (W)	System Efficiency (%)
1000	980	900	80	94.5
800	760	900	140	92.8
600	550	900	250	90.2
400	360	900	400	87.6
200	180	900	620	84.1

The findings indicate that the contribution to load demand rises with a decrease in solar irradiance to sustain the demand. But efficiency of the entire system is reduced a little because of the augmented usage of stored energy and conversion losses.

Table 2: *Voltage Stability Comparison*

Condition	Without Supercapacitor (V)	With Supercapacitor (V)
Steady State	48	48
Sudden Load Increase	42	47
Sudden Load Decrease	52	49
Fluctuating Irradiance	40–53	47–49

The incorporation of the super-capacitor brings in high stability in voltage when there is dynamism. Fluctuation of voltages are reduced and the DC bus voltage is kept in a

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very thin and acceptable range.

Table 3: Response Time to Load Variations

Scenario	Without Supercapacitor (ms)	With Supercapacitor (ms)
Load Increase	120	35
Load Decrease	100	30
Sudden Irradiance Drop	150	40

The hybrid system also shows a very quick response to abrupt changes much more than the conventional system. This means that the transient conditions are well addressed with the use of super-capacitors; that is, they can quickly charge and discharge.

Table 4: Energy Storage Efficiency Comparison

Storage Type	Charging Efficiency (%)	Discharging Efficiency (%)	Overall Efficiency (%)
Battery Only	88	85	86.5
Supercapacitor Only	95	93	94.0
Hybrid (Battery + SC)	92	90	91.0

The efficiency of super-capacitors is more efficient than that of batteries because of the reduced internal resistance and the quicker transfer of energy. The hybrids are the balance between the two technologies and are effective in terms of overall efficiency than the battery-only systems.

Table 5: Energy Loss Analysis

Component	Power Loss (W) Without SC	Power Loss (W) With SC
DC-DC Converter	45	38
Battery Loss	60	35
Transmission Loss	20	18
Total Loss	125	91

Combination of super-capacitors minimizes the system losses, especially the stress and losses in the battery. This results in better use of energy and increased efficiency of the system.

Discussion

This research paper has demonstrated that such combinations as solar photovoltaic (PV) systems along with the usage of supercapacitors is relatively efficient in improving the overall system performances, particularly in intermittent environmental and loading conditions. The specified enhancement in the efficacy of the system can be explained by the prior research, which discovered that hybrid energy storage systems (HESS) prove efficient to mitigate the issue of intermittency that could arise as a result of solar energy production (Sutikno et al., 2022; Zhang et al., 2023). With the downtrend in the irradiance of the sun, the increasing element of the super-capacitor will give continuity to the power supplies and this is what makes it as a dynamic element of the elements of energy balance maintenance. The specified

behavior is consistent with the complementary property of the super-capacitors and standard storage systems where the reaction speed of high performance stricter the flexibility of the system (Adeyinka et al., 2024).

The parameter of voltage stability is an important parameter in the solar energy arrangement and as per the findings, the implementation of supercapacitors minimizes the variation of the voltage during transient events to the minimum. It is logical that the voltage regulation in this study is improved as compared to other findings by Rekioua et al. (2023) who pointed out the stabilization of DC bus voltage in PV systems through the combination of hybrid storage. Supercapacitor acts as an absorbent to sudden variances in the load and variations of irradiance and consequently, prevents instances of voltage dips and spikes that can lead to negative implications on sensitive electrical devices. It is essential that microgrids and standalone systems work on a sustainable basis, which cannot be achieved without the stabilization (Hu et al., 2024).

The other interesting finding is that once the supercapacitors have been included the response time to the system has been significantly decreased. It is established that the hybrid system can react to the changes in load much quicker than battery-only systems. This observation supports the past studies that argue that the power density and charge-discharge characteristics of supercapacitors are high because the ability to deliver instant supply of energy in the windy conditions of transient conditions is achievable (Ramesh et al., 2024; Gao et al., 2025). The long response times result in improved power generation and system stress required in highly reliable and energy balancing systems.

The energy efficiency analysis also reveals that supercapacitors are more efficient than battery as far as charging and discharging efficiency is concerned. Although batteries contain a lot of energy, they contain lower kinetics and resistance within and thereby generate more loss of energy in the long run. The hybrid system provides balanced performance due to the conglomeration of the benefits of the two storage technologies and this yields to the overall effectiveness. This is supported by Liu et al. (2025) who discovered that hybrid storage systems are the most suitable when it comes to optimization of energy consumption and reduced instances of unnecessary loss of energy in renewable systems.

It is the energy losses minimization that is realized in the study that represents the achievement of the integration of super-capacitors in mitigating the inefficiencies of the systems. Reduced loss in converters, reduced stress in batteries also contributes to system life-saving in operational cost. These findings are consistent with those of Rahi and Alwash (2024), who concluded that the strategies of optimized power control in hybrid systems lead to a substantial reduction in the energy losses and system reliability increase. Super-capacitors can also take the peak loads to reduce battery loads and this almost doubles the lifecycle of the battery and reduces the maintenance requirements.

Overall, the discussion testifies the fact that the proposed electrical design and integration strategy can be considered a good solution to the problems of the solar energy systems. The hybrid solar-supercapacitor systems are the potential of the energy infrastructure of the future due to the complex of enhanced efficiency, increased response, better voltage stability, and reduced energy losses. This can be

related to the current trends in the hybrid energy storage systems where they say that sustainable and efficient energy systems can only be achieved through smart integration and control mechanisms (Mahmoud & Guven, 2025).

Future Direction

The future of the research is the emergence of more advanced intelligent control systems, including intelligence-based energy control methods using artificial intelligence and machine learning to further automatize the work of hybrid energy storage systems. More studies should also take place on cost effective materials and scalable designs of supercapacitors in order to enhance the level of energy density and cost effectiveness. Experimental validation of the suitability of the proposed system in real-world contexts through hardware implementation and real-time testing in microgrid environments would also provide a practical insight and support of the suggested system.

Limitations

This research has limitations but the encouraging outcomes can be achieved. The models of the simulation are very much dependent in the analysis and the analysis may not be sufficient to depict the real life complexities of functioning such as the uncertainty in the environment, the degradation of components used and the nonlinearity of the system. Additionally, the cost and the cost-effectiveness of the huge use of the supercapacitor-based hybrid systems were not properly researched. These deficiencies imply that more experimental and economic studies should be made to contribute to and enhance the proposed approach.

Conclusion

In conclusion, we can make a conclusion that one of the most effective methods to enhance the efficiency of the storage, stability of the system and its performance is electrical design and integration of solar energy systems and supercapacitors. The hybrid solution is highly applicable in the defeat of the limitations of the conventional storage system since it presents prompt response to the changing environment and reduction of energy wastage. The conclusions are that hybrid systems based on supercapacitors can potentially be a viable and effective alternative to renewable energy sources in the modern world, and it aids in the creation of the sustainable energy technologies.

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