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Research Article

A Novel Approach in Hybrid Energy Storage System for Maximizing Solar PV Energy Penetration in Microgrid

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Nowadays, energy storage system is utilized in many countries for energy planning in the future. The changes in solar radiation lead to the overproduction of electricity in a solar photovoltaic generator. A hybrid energy storage system would play an important role in enhancing the reliability of power generation using the solar system. The microgrid is the indispensable infrastructure of the smart grid in photovoltaic systems. In this paper, the energy storage system within the microgrid of the PV system is analysed. The storage system configuration and topologies of the microgrid are analysed with power electronic interference, control scheme, and optimization of the renewable source and energy storage system. A general sizing technique for HESS in a PV system based on pinch analysis and design space. The size of HESS scales that connect generator ratings to storage capacity is created by utilizing the pinch analysis on load and resource data. The design space is a feasible combination of a short-, long-, and medium-sized energy storage system in a PV generator.

1. Introduction

Due to increasing fossil fuel shortage and environmental pressures, new generation high-efficiency sources such as fuel cells and microgas turbines, as well as renewable energy sources (RESs) such as wind and solar power, are rapidly becoming the most significant Distributed Energy Resources (DERs) today. Distributed and renewable energy sources will account for a growing share of total electric power generation [1]. With a growing trend, renewable energy sources have been widely employed to meet electrical energy demands and minimise greenhouse gas emissions. The intermittent nature of renewable energy sources has a negative impact on power generation, posing a problem for ensuring an uninterrupted and consistent supply of electricity to consumers and endangering grid operations in terms of many operational and technical aspects [2, 3].

The local reliability and flexibility of the electric power system is improved with the microgrid (MG), which includes the DER and energy storage unit [4]. A MG in combination with renewable energy sources (RES) and distributed generation (DGs) sources might be a better answer to rising energy problems and accompaniment to today's centralized contemporary power grids. Due to their limited capacity, MGs' regular operation may be subject to random power exchange between the provider and the loads, making operational capability and power quality difficult to ensure [5, 6].

The RES energy output will fluctuate because to the strong reliance of many RES and DGs on climatic and meteorological conditions, particularly for a localised small-capacity MG with more than 10% of the RES occupation. ES is now the most important piece of equipment in an MG since it is a clever approach to mitigate potential power fluctuations and handle difficult demand-supply imbalance issues [7]. The term Distributed Energy Resources (DER) refers to nonrenewable and renewable energy systems. Distributed generation systems distribute electricity across the electrical network by using smaller generators that are closer to the loads. DER systems, unlike traditional distribution systems, use a variety of sources and loads to provide power which is required for the power network to deal with uncontrolled generators. When multiple uncontrolled sources are added to the electrical system, various technical issues, including power quality [8].

Solar PV electricity uses the sun as fuel, which, although abundant, is unpredictable. As a result, the output power of these systems fluctuates and is proportional to the sun's unpredictability [9]. The quantity of energy generated by a solar power system will change as the amount of sun radiation varies. Because the voltage on the medium-voltage network is always rigorously regulated, the concerns with PV and wind power penetration may be restricted to low-voltage networks [10]. This paper analyses energy storage system within the microgrid of the PV system. The storage system configuration and topologies of the microgrid are analysed with power electronic interference, control scheme and optimization of the renewable source and energy storage system. A general sizing technique for HESS in a PV system based on pinch analysis and design space.

2. Related Works

2.1. Technical Problem with Grid PV System. The power quality is the significant problem in the PV microgrid. From the customer's perspective as well as the utility's, power quality is critical. The power systems are made to run on a sinusoidal voltage with a certain voltage and frequency [8]. The issue in power quality is defined as any substantial change in the frequency, voltage magnitude, or purity of the waveform. The microprocessor-based controller is used in recent electrical equipment, and power electronic devices are more sensitive to voltage fluctuations [11].

Variations in solar radiation create variations in the operating point of solar cells, i.e., operating voltage and current. The voltage can be regulated because of power supply system with no current, every effort must be made to keep the voltage within a set and acceptable range to ensure that PV generators connected to distribution networks do not degrade power quality [12].

When there is a large concentration of roof-top PV systems, the instantaneous power output can occasionally surpass the immediate power consumption [13]. As a result of the power imbalance, power flows to the low voltage transformer, which forms the medium voltage transformer, suggesting that net power flows backwards to low-voltage transformers from the medium voltage. As a result, determining the maximum amount of PV penetration that can be delivered into a power network without generating power system difficulties is crucial [14].

Setting a limit to maximize possibilities is significant, and the production of harmonics by DER is another issue of concern. Solar PV systems produce direct current, which necessitates the installation of an inverter to connect to the electrical grid. Harmonic currents come from these inverters. Inverter technology has advanced substantially in recent years, and as a result, the number of harmonics produced by inverters has significantly decreased [15].

2.2. Advantage of Microgrid-Based Energy Storage System. The purpose of an ES element is to act as a buffer or backup in the event of a power discrepancy between both the upstream and downstream sides. This approach was first used in the early stages of power systems, such as when the DC electrical transmission system was implemented in New York City in the early 1800s. Lead-acid cells subsequently already provided energy for lighting bulbs, allowing the engines to be deenergized at night [16]. Grid-connected solar PV systems create power on demand, ensuring that electricity is delivered to the load in the most effective manner, and in many situations, the solar PV generating pattern matches the consumption pattern. The power providers and customers are attentive in dispersed generating systems, albeit from opposite perspectives, due to the benefits of the grid-connected PV. The grid-connected PV appeals to utilities because it allows them to create and sell power to their consumers over their current network. Some utilities consider large-scale grid-connected PV systems as a way to reduce the need for traditional network reinforcement. The benefit of having energy PV from the perspective of electricity consumers is that they can benefit from a standby power generation [17].

3. Materials and Methods

3.1. System Description. The microgrid with a renewable energy system consists of the DC bus and Power Electronic Converter (PEC), which is utilized to connect the microgrid subsystem. The ESS is utilized to conduct the load and power flow [16]. HESS is in the form of a battery and ultracapacitor. The voltage controller connects the microgrid with the PV panel. The layout of the microgrid system is shown in Figure 1.

The output power in PV system:

$$\begin{aligned} P_{pv} &= V_{pv} \times I_{pv}, \\ P_b &= V_b \times I_b. \end{aligned} \tag{1}$$

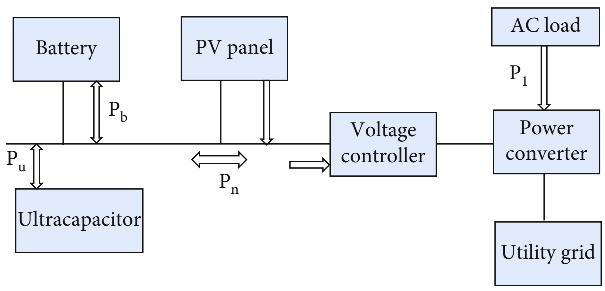

Figure 1: Layout of microgrid.

This indicates the output power and current of the battery:

$$P_c = V_c \times I_c. \quad (2)$$

This indicates the output power of the ultracapacitor. The power from the load is represented as P_l, and the power exchanged using the utility grid is P_u. The battery and ultracapacitor are utilized in the energy storage system, in which one component is not enough to conduct the changing power. The microgrid occupies little space and creates a low resistance of the line.

3.2. Hybrid Energy Storage Topologies. Different topologies can be used to link HESS to MG. To integrate HPS with HES, several topologies can be used. There are three types of power converter topologies: passive, semiactive, and active. Two storages with the same voltage are easily linked in a passive topology, which is an efficient, simple, and cost-effective architecture. The power distribution between HPS and HES units is mostly governed by internal resistances and the characteristic of voltage-current, as the storages' terminal voltage is not regulated. As a result, the HPS has a very limited amount of energy accessible, and it functions as a low pass filter for the HESS [18].

The power converter in semiactive topology is placed at the terminal of one storage system, and another storage system is connected directly to the DC bus. Although the addition of a converter increases installation space and costs, the architecture gives better controllability and dispatch capabilities. The additional converters in this architecture increase the HESS's operating range.

Active HESS topologies are made up of two or more energy storage units, connected to the storage system through a power converter separately. Although the system's losses, complexity, and cost rise, this type of topology offers certain benefits. The benefits of this setup are that all storage powers may be actively managed [19].

3.3. Energy Storage System Configuration. An ESS is an essential component of an MG's efficient operation. It provides the customer with dispatch capability of dispersed sources like solar panels and wind turbines. Along with generation sources, it is the primary contribution to balancing power demand. The collected power might be used to provide power during periods of high demand. As energy storage capacity is enhanced, manufacturing and controlling the ESS become more complicated and expensive. Small-scale and distributed energy storage can therefore be utilized to create flexible and efficient power control [20]. DER with various interfaces is linked with the ESS unit in the distributed ESS setup. The DC interface is required for solar PV. In general, a DC chopper is easier to use and less expensive than a DC converter. The advantage of connecting the grid with DER and ESS is that it increases the cost of electrical interference and increases efficiency. Because they only have to deal with one sort of source, these systems are usually straightforward. Before storing the electricity generated by the renewable resource, it is transported over the transmission line, offsetting the concentrated power flows on the line and the benefits of delayed line construction. Despite the fact that both the DER and ESS power electronics interfaces can be separately adjusted, with interfaces and line impedances which are connected to two facilities, losses are incurred in the storage process. MG, a combination of distributed and aggregated ESS, may be the greatest solution in the future [21].

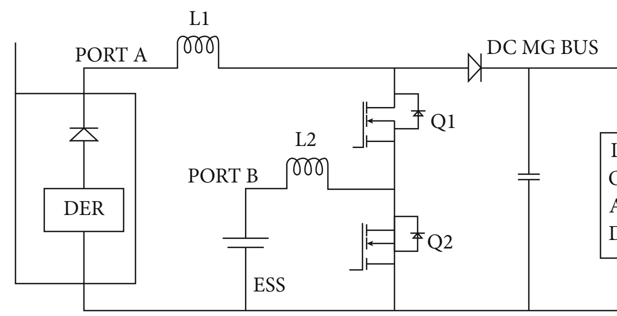

Figure 2: Power interface of energy storage system.

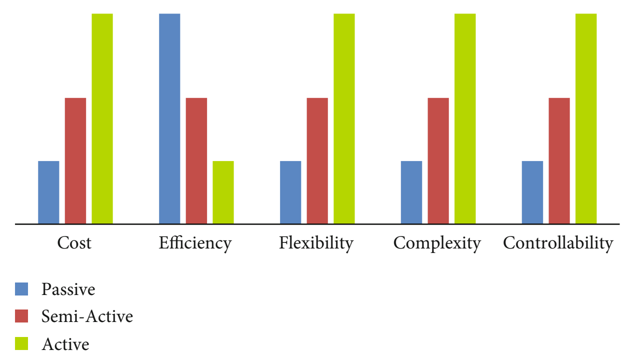

Figure 3: Comparison of HESS topologies.

3.4. Power Electronic Interface of Energy Storage System. Power interface of the energy storage system is shown in Figure 2. Unlike conventional converters, which only work when the primary source is accessible, the ESS interface will work continually to keep the MG operating for a long time. As a result, reliability and efficiency are the most important factors to consider while selecting converter topologies. High-frequency MG, line-frequency MG, and DC MG are the three most common forms of MG, and each requires a

Table 1: Evaluation of different HESS topologies.

Topology	Cost	Efficiency	Flexibility	Complexity	Controllability
Passive	Low	High	Low	Low	Low
Semiactive	Medium	Medium	Medium	Medium	Medium
Active	High	Low	High	High	High

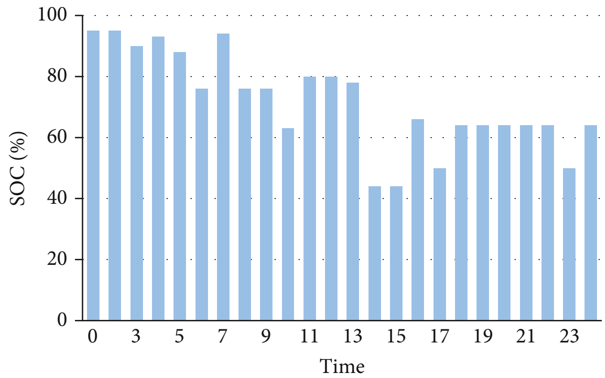

Figure 4: State of charge for ESS.

Table 2: Impact of SOC on energy storage system.

SOC	3500 kW	10000 kW
35	0.42	0.27
45	0.42	0.29
55	0.42	0.35
65	0.42	0.45
75	0.42	0.51
85	0.442	0.53
90	0.448	0.54
95	0.45	0.55

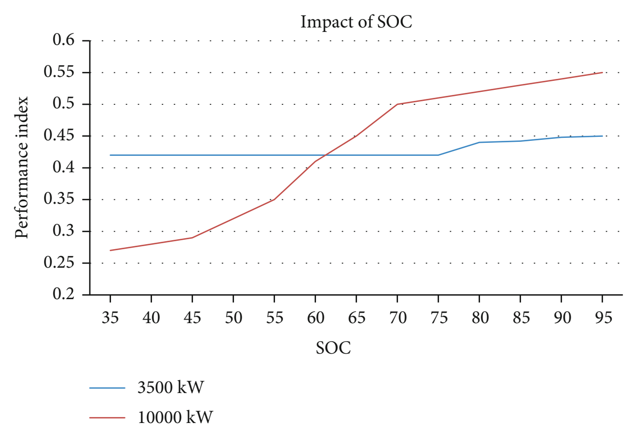

Figure 5: The performance comparison on impact of SOC with 3500 kW and 10000 kW.

distinct approach to ESS access. For simplicity, all ESSs are considered to be DC sources because ESSs have a DC link or can be converted to DC [22].

Separate DC converters can be utilized to link DERs and ESS to the common DC bus. In comparison to the original separate converter system, the use of a combined multiport converter offers cheap cost, great efficiency, and dependability. A buck-boost converter is one of the multiport converter topologies that may be used for high-voltage ESS, whereas a boost converter can be used for low-voltage ESS. However, because the system is based on a mixture of original common elements, it is difficult to extend because there is no way to add more sources without redesigning it [23].

3.5. Hybrid Energy Storage System. Determining the right storage capacity is one of the most significant challenges in HESS applications. Various techniques for sizing storage capacity have been presented. Some techniques are created to assess the HESS capacity of a specific technology, while others may be used to size all sorts of storages independent of technology. The methodologies for sizing batteries and their applications in various RESs are examined. The overall cost of the system, as well as its dependability, should be addressed throughout the HESS sizing approach [24].

The most significant drawback of renewable energy sources is that, unlike traditional energy sources, they cannot be stored for later use. As a result, it is critical to extract as much energy as possible from them while they are still available. Furthermore, because they are dependent on the climatic conditions of the location, they cannot be guaranteed to remain constant and concentrated at all times. As a result, they are erratic and unreliable. The electricity supplied by solar PV is particularly susceptible to harmonic distortions and associated mistakes, which might impair the system's functioning, due to the highly unpredictable behaviour of solar [25].

In such circumstances, HESS is required to smooth out the anomalies and enhance the power quality. Controlling the power outputs and delivering ancillary services as needed are other important functions of ESS. As a result, they are an essential source of energy for achieving high levels of renewable system penetration. HESS may compensate for any power imbalance between the load and the generating units by acting as a buffer or backup. A microgrid in islanded mode will rely on HESS to maintain real and reactive power balance in the event that certain DGs fail [26].

Even if the situation is solved by load shedding or bringing up additional producing units, HESS is essential for quickly filling the power gap. ESSs are required while the MG is in grid-connected mode in order to preserve power quality and manage reactive power. The HESS scaling techniques may change depending on the application's objective. The capacity size is determined using the pinch analysis approach.

Table 3: Comparison of ESS with power interface.

SOC	ESS		ESS with power interface	
	3500 kW	10000 kW	3500 kW	10000 kW
35	0.415	0.28	0.46	0.35
45	0.415	0.3	0.465	0.38
55	0.415	0.35	0.47	0.4
65	0.42	0.4	0.475	0.42
75	0.43	0.45	0.48	0.48
85	0.45	0.5	0.49	0.49
95	0.455	0.55	0.495	0.495

3.6. Pinch Analysis. Pinch analysis is a straightforward and adaptable technique for evaluating the lowest energy locations in a utility heat exchanger network. This technique is a substantially light technique that can be employed in a renewable microgrid [27]. In HESS implementations, pinch analysis is used. This strategy is based on variations in energy storage generation, load, and discharge times. Sizing curves for varying intervals scales are calculated by applying PAM to resource and load information. The produced curve denotes a set of data storage that is viable for the given time scale. Pinch analysis has proven to be effective in saving a variety of resources. Pinch analysis tools are used to develop isolated energy systems. The need of setting targets before designing is recognised by pinch analysis. This enables multiple process design objectives to be assessed before the process is designed in detail. Pinch analysis also provides diagrammatic tools to the system architect for easier visualisation and management over decision-making processes. Pinch analysis tools can be used to solve generalised resource conservation challenges by distributing generalised flows from various sources to various needs while satisfying generalised quality criteria [28].

3.7. Power Control System. A hybrid ESS's control method is substantially more difficult. Power system redistribution and ESS properties should be examined in relation to personal charge/discharge. When battery and supercapacitors are used to meet load requirements, for example, ultracapacitors can give faster response with peak power with than the battery, but they last less time. As a result, the batteries drain or charge slowly and surely, supercapacitors can control excess intermediate and strong and decisive battery current. Both the battery and the supercapacitors must be controlled by two separate loops in this situation. Batteries/supercapacitors must be recharged or drained according to the manufacturer's instructions in order to accomplish a long lifespan, maximum power, and maximum efficiency [29]. Traditional lead-acid batteries, for example, necessitate a lengthy low-current charge to eliminate sulfation from the lead plates. The rechargeable ESS can be recharged frequently while adjusting for MG Power fluctuations (SOC). When a device is less than totally depleted and so less than entirely recharged before even being drained again, it is known as the SOC operation with low output. The charge and discharge concerns are addressed by designing a sophisticated battery/supercapacitor management system. The two most common charge modes in energy storage devices are constant current and constant voltage. Constant power charging uses the periodic state-feedback control strategy, whereas constant power charging utilizes voltage or current double-loop control. A voltage or current double-loop technique is also required for ESS discharging control. Many advanced control approaches, including neural network, fuzzy control, and self-adaptive control which perform well for discharging and charging highly nonlinear behavior of the starting to charge process. Variation in cell parameters, uneven charging, connection between discharging process, ESS ageing problems, and other issues should all be carefully examined [30].

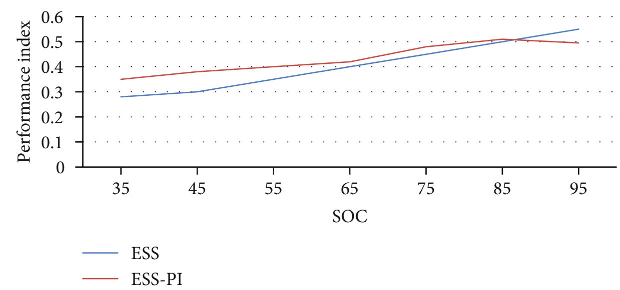

Figure 6: Performance comparison of energy storage system with power interface (10000 kW).

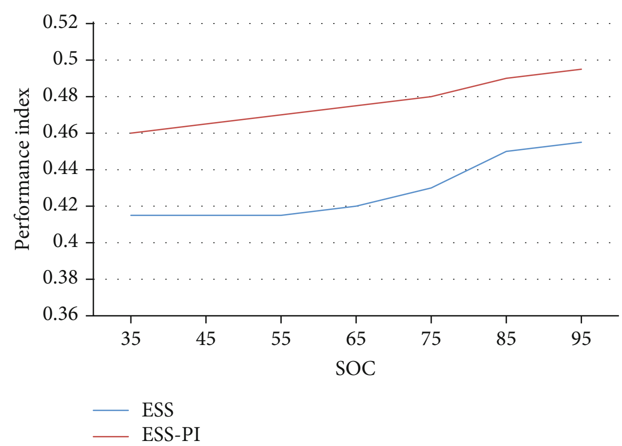

Figure 7: Performance comparison of ESS with power interface (3500 kW).

Table 4: Comparison of power capacity and confidence level.

Power capacity	Confidence level (%)
100	60
200	94
400	96
500	97
600	98

4. Result and Discussion

4.1. Comparison of HESS Topologies. The topology of the HESS has a direct influence on the energy storage approach.

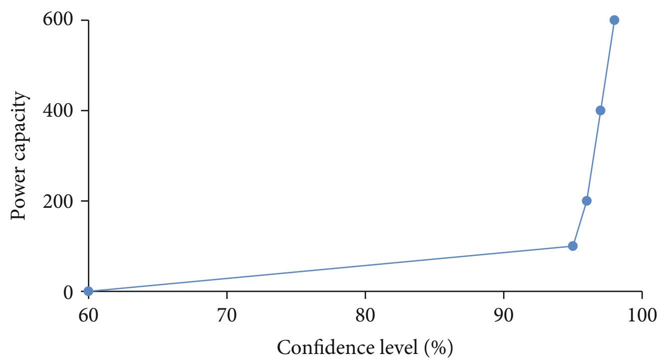

FIGURE 8: Power capacity of HESS at different confidence levels.

The power stored in a passive topology has no direct control. The storage of one output power is uncontrolled in the semi-active architecture. The active structure uses a rational control method to manage the outgoing or incoming power including both storages, albeit at the cost of lesser efficiency. Expenses, effectiveness, predictability, complexity, and adaptability should all be considered while choosing the right topology. The HESS topologies are compared in Figure 3 from various operational perspectives. The passive topology is modest and low cost, but it is uncontrollable. The active topology performs best at the moment of flexibility and controllability while taking into consideration inherent limitations such as SoC, but it comes with a high efficiency. Table 1 shows the evaluation of different HESS topologies.

Figure 4 illustrates the HESS's SOC and the storage scheduling system for the initial load requirement, which includes charging and discharging choices. With the availability of information, the energy storage problem is no longer dynamic, and each hour of the schedule period may be improved independently. Table 2 illustrates the impact of SOC on ESS.

Figure 5 illustrates the performance comparison on impact of SOC. The HESS performance is better with increase in the state of charge level. The system with a larger battery size had a performance index that was more sensitive to variations in SOC. Comparison of ESS with the power interface is shown in Table 3.

Figures 6 and 7 illustrate the variation in the size of battery and the initial state of charge which provide better performance in the energy storage system with power interference compared to the normal energy storage system. While initial SOC was raised, ESS-PI was able to achieve greater performance in a smooth and consistent manner. However, until the SOC level reached a specific amount, ESS did not work properly. Furthermore, as can be seen, the ESS-PI performance index when considering battery life is greater than the PI value, indicating that ESS-PI performs better while charging and discharging the battery, allowing the battery to survive longer. Comparison analysis result for various power capacities with confidence level is represented in Table 4.

The power capacities of HESS can be estimated by calculating the confidence level, in which the confidence level has a significant effect on the life cycle of the ES in the microgrid system which is shown in Figure 8.

5. Conclusion

In this paper, the energy storage system within the microgrid of the PV system is analysed. The storage system configuration and topologies of the microgrid are analysed with the power electronic interference, control scheme, and optimization of the renewable source and energy storage system. Typical sizing technique for HESS in PV system based on pinch analysis and design space. The sizes of HESS scales that connect generator ratings to storage capacity are created by utilizing the pinch analysis on the load and resource data. The energy storage system for the microgrid system is demonstrated, and the impact of the state of charge and power control system with the load demand is analysed. The energy storage system with power interference system in the microgrid provides better performance compared to the energy storage system without power interference. The performance of HESS is sensitive to change in the state of charge. The HESS with a higher battery size maintains the high performance of the microgrid.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

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