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TECHNOLOGY AND USES FOR ENERGY STORAGE'S INCORPORATION INTO SMART GRIDS

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A B S T R A C T

The fact that they are unpredictable and unreliable, renewable energy sources (RES) are increasingly crucial to the electrical power grid's ability to maintain energy continuity. The challenge of energy sustainability can only be solved by energy storage technology. Regarding a Hybrid Energy Storage System (HESS) powered by a 4-wire, 3-phase grid connected solar Photovoltaic (PV) power system, a novel Smart Energy Control Technique (SECT) with a Whale optimization algorithm is presented in this work. The sustainability of energy via solar PV power generating systems is achieved by using HESS, which consists of batteries and ultra-capacitor storage devices for energy. The suggested SECT has been used for the analysis and experimental testing of several HESS operating scenarios. During experimental testing, the load status of a single sunny day and the PV power outline were constructed and dynamically assessed by utilizing SECT; some test findings in eight distinct operating modes are included in this paper. The system uses 1320W of electricity to charge the battery group, and in one of its modes of operation, the leftover energy is sent to the grid using 5% present harmonics. And because of the system's high power density, quick reaction, and great efficiency, the HESS is a highly efficient energy storage method. Simulation findings and laboratory testing have validated the suggested system.

1. INTRODUCTION

The Electricity storage prices continue to drop and new possibilities are identified across a range of business sectors and applications, energy storage and its influence on the grid and transportation sectors have increased substantially in recent years. However, unlike electric cars, grid-scale energy storage does not have to adhere to strict power and weight restrictions, which makes it possible for a wide range of storage technologies to compete to provide both existing and future grid flexibility

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services. Examining different technologies and fairly comparing their prices and performance becomes more crucial as the grid storage sector continues to expand and evolve (Mongird et al., 2020). Power system flexibility may be provided through energy storage, which can store excess electricity production. A generation-integrated ESS is a kind of power storage that, at some point, stores power as well as the process of turning primary energy sources into electricity. Since innovative energy storage systems and generation-integrated energy storage systems are still in their infancy and provide some technical, economic, and financial potential, it is important to investigate their economic and financial advantages. In order to assess the economic and financial aspects, this research introduces and uses a cutting-edge model (Lai and Locatelli 2023) & (Ghosh et al., 2023).Energy storage technology is an essential component of the modern energy system.

It allows for the efficient capture and use of energy, enabling a more reliable, sustainable, and cost-effective energy supply (Sayed et al., 2023). Data is gathered from a variety of sources in a smart grid, including electrical plants, transmission lines, and consumer electronics. The grid's performance is then optimized, waste is eliminated, and expenses are decreased by analysis of this data. By controlling their erratic nature and assuring their effective and dependable integration into the grid, smart grids also make it easier to include renewable energy sources like solar and wind power (Bhattarai et al., 2023) & (Kabeyi and Olanrewaju, 2022).

To stabilize the erratic output of renewable energy sources, energy storage is crucial for the future Smart Grid (SG). Despite the fact that there are many excellent storage solutions, they are either too expensive or too inefficient. Numerous studies have examined the use of energy storage for a variety of purposes, including voltage support, peak shaving, frequency stability, renewable firming, transmission upgrade deferral, and a lot of others (Salkuti, 2023). A lot of academics are now working on hot subjects related to energy storage materials and applications for electricity and heat storage procedures to combat peak demand-supply discrepancy. In terms of hot water and space heating needs, heat accounts for the largest part of the overall energy demand in a person's daily life (Sadeghi,2022)Energy storage systems can help balance the supply and demand of electricity on the grid by storing excess energy during times of low demand and releasing it when demand is high. This can help reduce the need for peaker plants, which are typically more expensive and emit more pollutants than base-load power plants. (Streicher et al., 2019).The rest of the paper is as follows related works presents in section 2, the proposed method describes in section 3, and the result and discussion are present in sections 4 and section 5 conclusion of the paper.

2. RELATED WORKS

(Worighiet al., 2019) suggested architecture for a smart grid that includes both the primary grid and several embedded microgrids. Moreover, a Micro-grid Key Elements Model (MKEM) has been proposed, which focuses on micro-grid systems. Virtualization is used to test and evaluate the suggested model and architecture. Modernization of Internet of Things (IoT) grids with capabilities will show a peer-to-peer decentralized architecture with a huge degree of across the board autonomy for the whole system as the old techniques of energy management are rendered obsolete by the usage of IoT (Bagherzadeh et al., 2020).

(Rath and Tomar, 2021) explored whether IoT may be used in smart grids. Consequently, a brief overview of the need for IoT adoption in smart grids is given first. After then, three tiers of power generation, transmission, and dissemination are proposed for IoT applications. (Shahinzadeh et al., 2019) & (Shan et al., 2022)compared the modularity, capacity for long-term energy storage, and average capital cost across a range of periods. To take into consideration new long-duration storage applications and use scenarios, additional metrics of comparison are established. These include a land-use footprint and comparable efficiency based on idle losses. Based on land availability and duration needs, which may vary by region, the technological landscape may enable a wide variety of storage applications. (Sepulvedaet al., 2021) proposed a compared energy administration analysis of a single “Direct Current Micro-Grid (DCMG)”. This system is made up of two main sources: wind turbines and solar panels generators operating at the MPP to extract the most energy possible, followed by a lead-acid ESS battery to assure the van's durability.

(Song, 2021)& (Hafsi, et al., 2022) provided a technical viewpoint to aid comprehend the function of digitalization in the advancement of energy storage. Based on a patent co-classification study, they map out the landscape of energy storage and digital convergence, and a firm-level empirical analysis allows us to look at how the digital revolution has affected energy storage innovation. (Wang et al., 2023) & (Stamatellos et al., 2022)brand-new Pumped Thermal-Liquid Air Energy Storage (PTLAES) system is put forward that uses electricity to create heat and liquid air, then returns those energies to electricity when it's required. Because low-density cold storage devices are not necessary, the PTLAES system provides a very dense storage for energy. (Pamucar et al., 2020) & (Gandhi et al., 2022)used the UK as a case study to assess the investment appeal of rooftop PV installations and the effects of energy storage systems (ESS). The assessment takes into account the installation's location, the temporal development of the supporting policies, the local power consumption, the price of the investment over time, and the price of electricity. (Kuttyet al.,

2023) & (Hadian et al., 2022) objective is to assess and rank several energy storage technology options (methods) based on technical, financial, environmental, and social factors. They provide a hybrid Dombi weighted geometric averaging operator and Multi Atributive Ideal-Real Comparative Analysis (MAIRCA) model for trapezoidal neutrosophic fuzzy numbers.

3. EXPERIMENTAL PROCEDURE

In this section, we discuss in detail about the Technology and uses for energy storage's incorporation into smart grids. Energy storage systems can store excess energy generated by renewable energy sources like solar and wind power, which can then be used during periods of high demand or when renewable energy sources are not generating electricity. Selection and extraction are in the third section. The most significant material is provided in the fourth section, which discusses the effort made to develop the suggested model and compile the essential experiences. The fifth step compares the related parameters to assess the performance of each existing and new model.

3.1 Hybrid system for energy storage

In this part, an experimental examination of an intelligent microgrid design is made into a photovoltaic (PV) system connected to the boosted by HESS made up of batteries with an ultra-capacitor unit in a 4-wire3-phase 4-leg inverters architecture. With a HESS powered by PV energy and various operational scenarios, experimental experiments are conducted. In the experimenting lab setting, renewable energy is provided via 5 kW-capable PV modules. To compensate for PV power output fluctuations and to satisfy energy demand when solar power is scarce, the HESS is employed as storage for energy. Figure 1 provides the suggested system's block diagram.

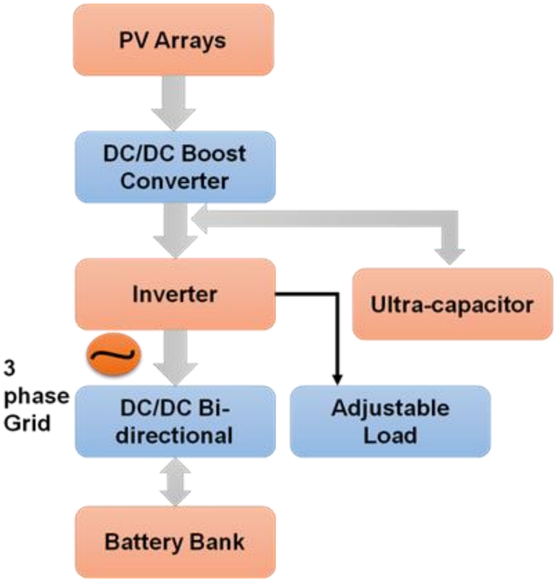

Figure 1. Proposed method's block diagram

To accomplish the following objectives, the SECT among the battery, ultra condenser, and PV power is suggested and developed:

- Keeping the system's overall power balance,
- Using the "Maximum Power Point Tracking (MPPT)" approach to regulate the PV energy produced.
- To extend the battery's lifespan, prohibit excessively frequent ripple flows moreover, the battery is being subjected to high rates of depth of discharge.

In the proposed HESS, ultra-storage units and the battery is combined. Although they have a lower electrical density, ultra-capacitors have a greater power density. Batteries, on the other hand, have a greater energy density. In order to get more power and the amount of energy, battery, and ultra-condenser storage devices for energy are employed in tandem. PV panels function as current sources to provide the grid with the necessary energy.

3.2 Structures for a bi-directional converter and boost controls

Considering the flow of power from RES is continually variable and is dependent on climatic conditions, energy management among the various kinds of power sources and the infrastructure for energy storage in HESS is an intriguing topic. To accomplish this operation, the control system analyzes PV panel characteristics and modifies the power converter's standard value to deliver power to attain the MPP. There are several ways to determine MPP in the research, including the constant current, Pilot cell, constant voltage, perturb and observe gradually implemented conductivity, and cycle controls approaches. Figure 2 displays a Simulink block illustration of a control unit for a bidirectional DC/DC converter. Switch S2 is a switch, while switch S1 remains off to guarantee that the bi-directional transformer is operating in buck mode. The control technique relies on the energy administration algorithm to function. When the third mode's incoming information is 1, the management algorithm switches the system to buck mode. Information from the battery's solid state relay (SSR), input 5 which connects the battery to the direct current DC bus through a DC-DC converter with bi-directions.

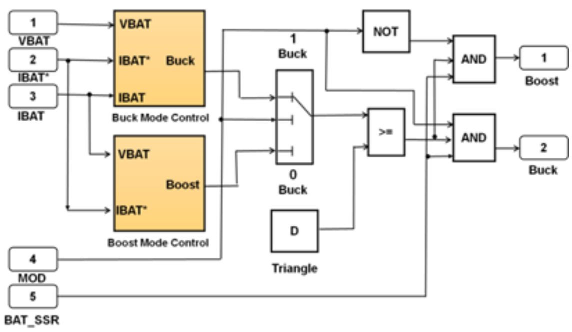

Figure 2. Bi-directional transformer manage unit block diagram

The initial task of the PI controller is to maintain the 235V battery bank's voltage. The power source charging current is managed by another PI controller. Only information about the power bank's current of discharge is provided through the bus control module in boost mode. The obtained measurements and reference current values are compared by the PI controller to provide an output. A switching signal is produced when the PI output is contrasted with the triangle wave at a frequency of 10 kHz. In this device, the SECT also determines the reference current.

3.3 The whale optimization-based Smart Energy Control Technique (SECT)

The generation of power from RES fluctuates continually and is dependent on weather conditions, making energy management between each energy source and the energy storage structures in HESS an intriguing problem. The most critical management component of the suggested HESS is SECT depicted in Figure 3. The SECT is designed to improve power flow and regulates energy flows in the system based on operating scenarios. For the system to function correctly and securely, several restrictions and bandwidths must be established. The total amount of electricity taken from the battery affects how long it will last or provide backup power. Whether the specified discharge current is sufficient to extract the battery bank's 20% SOC. When the battery is charged to more than 95% SOC, the charging current is reduced to protect the power supply from overcharging. The SECT will disable the PV panel if its output power is less than 50W.

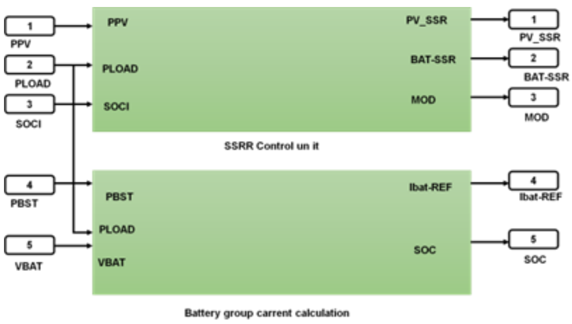

Figure 3. SECT of HESS

The suggested SECT, which differs from other algorithms in that it includes all potential working instances and the flexible reaction of modifications, among each functioning scenario in a single day, is the study's most significant and distinctive approach. The suggested SECT evaluates SOC and discharge or charge references electricity of the power source taking into account all potential working circumstances and evaluates the system characteristics using established in advance system constraints, indicating PV, battery, and energy load in a frequency band. With the suggested SECT, both the converter and inverter's efficiency will be increased without often activating the battery, and transitioning between all operational instances would be seamless.

I_{BAT_REF} determines the charging and draining of the power source bank based on the measured data. Two formulae are used to compute the I_{BAT_REF} current while the power source is being discharged and charged. Equation (3) is used to compute the battery bank's charging and discharging current.

$$P_{BAT\_C} = P_{BST} - P_{LOAD} \tag{1}$$

$$P_{BAT\_D} = P_{LOAD} - P_{BST} \tag{2}$$

$$I_{BAT\_REF} = \frac{P_{BAT}}{P_{LOAD}} \tag{3}$$

$$SOC = \left(1 - \frac{\frac{1}{1800} \times \int I_{BAT}}{Ah}\right) \times 100 \tag{4}$$

The battery bank determines its operating environment before calculating the charge/discharge value at the moment. The control circuit of the bi-directional DC/DC transformer receives the calculated charge/discharge current measurement. In the battery discharge or charge current computation block, the differentiation among the PV current and the load is computed, and the switch current is established. PV panel power computed minus estimated current equals discharge power. When the batteries are charged, the power differential between the PV panels and the loads is equal to the power that the inverter supplies. By comparing estimated current readings to PV panel current readings, one may determine the battery charge current.

3.4 Wheal Optimization Algorithm (WOA)

The A swarm intelligence method called WOA has been presented for continuous optimization issues. It has been shown that this algorithm performs as well as or better than some of the other algorithmic strategies now in use. WOA has drawn inspiration from the humpback whales' hunting techniques. The whales employ two different techniques to both attack and locate their prey. In the first, the prey is enclosed, while in the second, bubble nets are made. Whales seek prey in an optimized manner by exploring their environment, and they utilize their environment when they attack. In other words, we are different from other organisms because of our spindle cells.

The key factor contributing to whales' intelligence is the fact that they have twice as many of these cells as an adult human. The metaheuristic optimization process known as whale optimization was influenced by humpback whales' propensity for hunting. A based on populations method is used to look for the best answers in a multidimensional search space by simulating the social behavior of whales. This method may be used with smart grid technologies to monitor and regulate energy storage more effectively.

A control technique known as the whale optimization-based Smart Energy Control Technique makes use of whale optimization to improve the dispatch and scheduling of energy storage devices in smart grids. In order to create the best energy storage control strategy, the approach takes into account variables including energy demand, renewable energy output, energy storage capacity, and grid restrictions. This method may be included into smart grid systems to increase grid stability, cut energy costs, and manage energy efficiently. By making sure that extra energy is stored and accessible for use during times of low production, it may help boost the dependability of renewable energy sources. A method for integrating energy storage onto smart grids is the whale optimization-based Smart Energy Control Method. Optimizing energy storage control and management can improve the efficiency, reliability, and sustainability of smart grid systems.

A metaheuristic optimization method called GWO was developed after studying grey wolves' social interactions and hunting techniques. In GWO, a population of possible answers is repeatedly updated to look for the best one. A pack of grey wolves symbolizes this population. The program mimics how wolves work together to find and catch their prey in a cooperative hunting strategy. Each wolf in the initial population of the GWO algorithm serves as a solution to the optimization issue. Each wolf's location correlates to a specific place in the search space. The wolves' social hierarchy and hunting habits are then considered as the algorithm repeatedly develops their placements. The alpha, beta, and delta wolves, three critical members of the pack, are used to update the wolves' locations during the iteration. The beta and delta wolves indicate the second and third-best answers, respectively, while the alpha wolf represents the finest solution. The wolves' placements have an impact on how the whole pack explores and makes use of their surroundings. Equations in mathematics are used in the updating procedure to establish the new locations of the wolves. The wolves' final sites show the best or nearly the best answers to the given optimization issue. Numerous optimization issues, such as those involving mathematical functions, engineering design, data mining, and neural network training, have been tackled with Grey Wolf Optimization. It is a competitive optimization algorithm for convergence speed and solution quality because it strikes a balance between exploring uncharted territory and capitalizing on promising ones.

4. RESULTS AND DISCUSSION

The real-time management platform is used to implement the suggested control method. A thermoelectric generator (TEG) and transducers are used to measure currents and voltages. Using the Chroma Solar simulator gadget, PV panels are simulated in the experiment. The DC-DC boost transformer makes use of the MPPT algorithm, which powers the DC bus. The battery is powered by a bi-directional DC-DC transformer so that the DC bus may charge and discharge it. The circuit specifications employed in the setup of the experiment are shown in Table 1.

Table 1. Test parameters of HESS.

Parameters		Values
Grid	Voltage (V_{gabc})	112Vrms/phase–neutral
	Frequency (f)	52 Hz
	Impedance (R_g, L_g)	11 m, 1 mH
PV panels	Open circuit voltage(VOC)	460V
	Short circuit current	1–10A
	Energy at MPP	250–370V
	MPP Current	0–8,5A
Battery bank	Normative voltage	213V
	Certified capacity	150Ah
Ultra-capacitor unit	Nominal voltage	410 v
	Certified capacity	3.89 F
Load	Symmetrical resistance load	0–4 kW
	Full-wave diode rectification for one phase	0–3 kW
	Full-wave diode rectifier with three phases	0–5 kW

In order to regulate the system's components, solid-state relays (SSR) are linked to the battery bank, PV modules, and ultra-storage unit in the DC and inverter, grid and loaded in the AC bus. To reduce surge currents and restrict the inverter the AC side of a flash power, pre-charge resistors are utilized. The SECT management panel is developed to regulate system connections and control in the test experiment configuration control signals used on this board are sent to the testing platform so that all of the components may be controlled quickly and securely. The achieved experimental results demonstrate that the suggested SECT's performances are adequate in both dynamic and steady-state loading circumstances. The outcomes of the field experiments attest to the viability and efficacy of the suggested SECT. In this part, the findings from the experimental design are given and discussed. Fig. 4 depicts the DC/DC boost converter's inputs and outputs of power and voltage for scenario 3. The maximum operating voltage and power for PVs are 370V and 7,9A, respectively. The DC by DC boost transformer output is 400V, and its power is 6.8A.

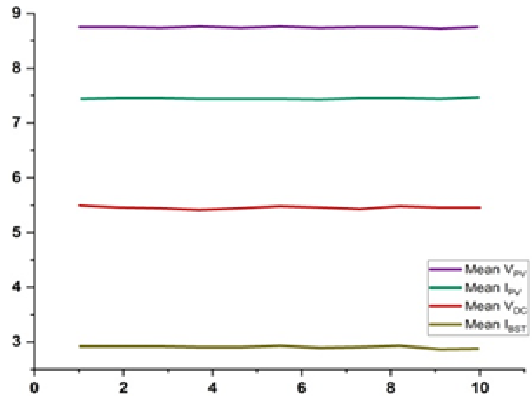

Figure 4. Bi-directional transformer input/output voltage results and proposed methods

Table 2. Bi-directional transformer input/output voltage results.

		Value	Mean	Min	Max	StdDev
1	Mean V_{PV}	372.7 V	371.2	369.2	373.2	8.240
2	Mean I_{PV}	9.905 A	9.685	9.685	9.912	61.24m
3	Mean V_{DC}	403.0 V	398.1	398.1	410.9	4.857
4	Mean I_{BST}	8.816 A	8.784	8.786	8.822	45.50m

Figure 5 displays the results of measurements made of the bi-directional converter's input as well as the output current. In this instance, 5.61A is used to charge the power source. In this scenario, the bidirectional converter runs in buck mode. A battery bank is charged by the converter at a beforehand established present value set by SECT.

The previously mentioned clarification of the experimental findings supports the suggested SECT for distributing power across sources, energy storage, and loads. When the battery's "State of Charge (SOC)" reaches 95%, the SECT diverts the excess solar energy onto the grid to prevent overcharging. By restricting the energy taken from the sources to meet the load requirement, the SECT control technique also does away with the necessity for a dump load. The supply of batteries and ultra-capacitor unit for the HESS is used to test the planned SECT. The testing findings showed that by maximizing battery SOC and improving battery lifespan, the suggested SECT is capable of appropriately supplying dynamic load needs in a variety of operational scenarios.

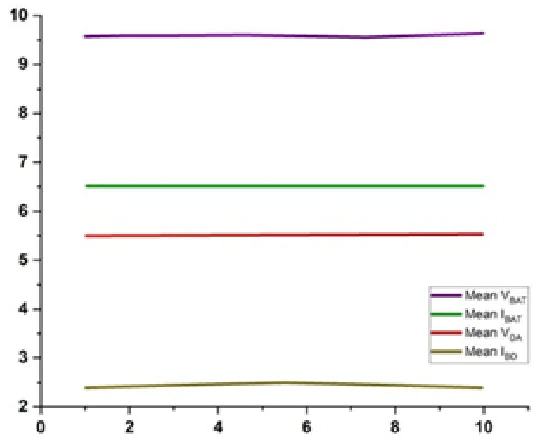

Figure 5. Bi-directional transformer input/output voltage results

Table 3. Bi-directional transformer input/output voltage results.

		Value	Mean	Min	Max	StdDev
1	Mean V_{BAT}	237.2 V	236.9	232.2	239.2	7.830
2	Mean I_{BAT}	-7.610 A	-7.582	-7.507	-7.788	63.24m
3	Mean V_{DA}	403.5 V	401.8	398.1	410.9	5.461
4	Mean I_{BD}	5.479 A	-5.458	-5.384	-5.642	52.13m

5. CONCLUSION

The This Energy storage technology is a crucial component of smart grid development and opens up new possibilities for all stakeholders. By enhancing the safety, dependability, and adaptability of the electrical grid, technique for storing energy is a key component of smart grid programs for effective use of power sources, supporting the integration of sustainable power into the grid, increasing power production where energy is consumed, and increasing energy access. The next generation of RES will include complementing energy storage technologies. The power quality of the energy generated by RES may now be improved using HESS. In this paper, a brand-new, distinctive SECT is suggested for HESS powered by a grid-connected solar power system. This study proposes an innovative adaptive making decisions technique using SECT for the HESS-aided PV application. The SECT can decide how to optimally manage the energy flows in this system by using two storage mechanisms for energy, a power source and an ultra-capacitor, as well as solar panels. The suggested the goal of the control algorithm is to generate the necessary load electricity at whenever possible by lowering the energy storage system's running expenditures, boosting system performance, and lowering power consumptions. The suggested approach provides a choice for the best control strategy to create hybrid systems for grid-connected systems that provide electricity at a reasonable cost. Future research will use a bi-directional DC by DC transformer to discharge and charge an ultra-capacitor group to regulate the flow of energy.

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