Control of Energy Storage Systems of Renewable Variability

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Abstract—This paper discuss about different ways to control energy storage to handle the changes and fluctuations in renewable energy.Nowadays the renewable energy sources like solar and wind are using in large scale because they are clean and good for the environment. But these energy sources are not steady, they change a lot because of the weather conditions.This makes it hard to keep the electricity supply steady and continuous. Energy Storage Systems (ESS) like batteries can help to solve this problem by saving extra energy when there is more than needed and giving energy back when there is less.It is very important to control these storage systems well to keep the electricity supply balanced, make the power grid stable and use renewable energy better. The focus is on how to charge and use batteries in the best way to reduce sudden changes in energy supply.The control systems use current data and weather conditions to guess how much energy will be made and change how storage systems work.This paper can go through smart prediction methods like Real -Time Digital signal,Smart Battery Management etc.This study shows how using smart control methods can make renewable energy systems work better and more reliably.

Keywords: Renewable energy, energy storage, variability, control methods, battery use, power grid, smart control, clean energy.

1.INTRODUCTION

Today, the world is progressing quickly toward renewable energy sources such as solar power and wind power as it is clean energy that does not hurt the environment. However, one of the main problems with renewable sources of energy is that they are not constant, meaning the amount of power being generated is variable based on differing weather conditions. For instance, solar panels are not useful at night or on cloudy days while wind turbines are only capable of functioning at certain wind speeds. This variable power generation leads to changes in voltages and frequency with the grid which makes it difficult to maintain a constant and stable source of electricity[2][9].Energy Storage Systems (ESS) are being employed to mitigate the variability of power generation and consumption. ESS takes energy from excess generation and stores it for discharge, when there is shortage of generation. There are various storage technologies like batteries, flywheels, supercapacitors, hydrogen storage, and compressed air storage systems to support energy storage which helps manage supply and demand on the grid【3】【7】.

However, having an energy storage system is not sufficient; it must also be controlled effectively. An effective control system determines when to charge and discharge the storage system with the aim of maintaining energy and power balance. This has been achieved through the advancement of modern control techniques such as droop control, State of Charge (SOC) control, model predictive control (MPC), and artificial intelligence-based control【1】【4】【5】【7】.For instance, a hybrid storage system consisting of battery and supercapacitor can provide both energy storage for long-term use and storage for sudden consumption of power. Researchers have also applied optimization techniques, such as the genetic algorithm and K-means clustering techniques, to assess and identify the optimal size of a hybrid storage system, thereby increasing their efficiency and cost savings【1】【8】【9】.

Numerous studies show that adding battery energy storage systems (ESS) to renewable energy systems can help improve the quality of the power, stability of frequency, and reliability of energy. The new smart technologies of real-time monitoring, digital controls, and battery management systems make it easier to predict renewable generation and automatically adjust energy flows【5】【10】. However, several challenges exist, including costs, energy storage system lifespan, and the absence of control standards. A focus of research continues to be on developing smart, flexible, and affordable control strategies, balancing the guarantees of energy stability while enhancing the efficiency of renewable systems and addressing weak spots for the energy grid【3】【6】【9】. This paper focuses on energy storage system control and the methods that classify different control methods. This paper demonstrates how smart control methods are utilized to mitigate the fluctuation of renewable energy, ensuring grid stability while increasing economically friendly energy production and advancing a cleaner, more reliable energy system of the future.

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2.OVERVIEW OF ENERGY STORAGE SYSTEM

Renewable energy sources, such as solar and wind, are highly influenced by the weather and time, which leads to variable and unpredictable energy production. To mitigate these variations, Energy Storage Systems (ESS) can save that excess electricity generation for times when generation is low. This helps with power management and maintains electricity reliability and continuous flow【2】【3】【7】. ESS can help with frequency regulation, peak shaving, load leveling, and stability management of the grid. There are advantages and disadvantages of using different energy storage technologies based on the type of energy storage technologies and design. The most common types of systems used to store energy are battery energy storage systems (BESS), supercapacitors, flywheels, compressed air energy storage (CAES), and hydrogen storage systems 【1】【6】.

Fig 2 Diagrams of Energy Storage Systems

2.1Types of Energy Storage Systems:

S.no	Types of ESS	Energy Density	Efficiency (%)	Response Time
1.	Battery(BESS)	High	85-95	Seconds to minutes
2.	Supercapacitor	Low	90-98	Milliseconds
3.	Flywheel	Medium	90-95	Milliseconds to seconds
4.	Compressed Air (CAES)	Medium	60-75	Minutes to hours
5.	Hydrogen Storage	High	40-60	Minutes to hours

2.2 Battery Energy Storage System (BESS)

Battery storage is the most common type of energy storage system (ESS) utilized for renewable integration. Lithium-ion, lead-acid, and flow batteries are all common types of BESS. BESS can quickly increase or decrease their output based on load following, maintain frequency in the grid, and provide power when renewables drop.Nonetheless, battery degradation, limited lifespan, and high cost remain challenges【3】【7】.

2.3 Supercapacitors

Supercapacitors store energy through electrcostatic means, and can charge or discharge nearly instantaneously. Supercars are well suited to smoothing short-term fluctuations from renewable generation. Supercapacitors have low energy density, meaning battery energy storage systems (ESS) with short-term charging time, very long life cycle, and instantaneous response are practical as hybrid systems【1】【5】.

2.4 Flywheel Energy Storage

Flywheels store kinetic energy in the shape of a rotating mass that can be quickly released when needed. Flywheels produce little maintenance and are highly efficient. Flywheels are mostly used for short term care backup and frequency control in renewable energy-based microgrids【6】【9】.

2.5 Compressed Air Energy Storage (CAES)

CAES systems rely on compressing air and allowing it to be stored in underground tanks, which then can be re-expanded into energy production. CAES benefits large-scale, long-duration storage applications. Overall efficiency levels of CAES would generally be at the lower end of the engine technologies capabilities, but relative to all the energy storage technologies studied in this study, traditional battery systems have higher efficiency levels【3】【6】.

2.6 Hydrogen Energy Storage

Hydrogen storage transforms excess renewable electricity into hydrogen using an electrolysis process. Later, this hydrogen can be chemically recombined in a fuel cell to generate electricity. Hydrogen energy storage is a good option for long-term storage and fits the green hydrogen framework, but its economic and energy conversion costs remain a concern【4】【10】.

2.7 Comparison and Selection

Different ESS technologies are chosen based on grid needs — for example:

- **Batteries** for short- to medium-term stability.
- **Supercapacitors** for quick response.
- **CAES and Hydrogen** for long-term energy backup. Future systems are expected to combine multiple technologies in **hybrid ESS configurations** to achieve both fast and long-duration support【1】【8】【9】.

2.8 Summary

Energy storage systems play a crucial role in integrating renewable energy into modern electrical power systems. Every energy storage type has its own advantages related to speed, storage duration, and cost. Choosing and combining the energy storage systems appropriately, provides a stable, efficient, and sustainable power supply, even if the renewable conditions vary【2】【3】【6】【9】.

3. Energy Storage System Control Algorithms

Efficient control algorithms are required by Energy Storage Systems (ESS) to maintain stable operating conditions, avoid overcharge or deep discharge conditions, and maintain reliability of the grid. The developed control strategies for energy storage systems consider the balance of power, voltage and frequency regulation, and the longevity of the storage system when integrated into variable renewable energy sources, like solar and wind【1】【3】【4】【7】. Several control algorithms have been proposed recently based on response time, accuracy, and implementation complexity for various applications. The most frequently noted algorithms in literature include Droop Control, SOC Control, Model Predictive Control, and Fuzzy or AI-based Control. In addition, some control strategies will utilize a Hierarchical Control structure to hybrid the optimization layers of local control and consume global data【1】【5】【6】【8】.

3.1 Droop Control Method:-

It is a decentralized control method,where decentralized means that every subsystem in a large system makes its own control decisions.

It is inspired by synchronous generators ,where frequency decreases as load increases.

For energy storage systems like batteries,fly wheels,super capacitors etc droop control allows automatic sharing of active and reactive power without requiring communication between units.

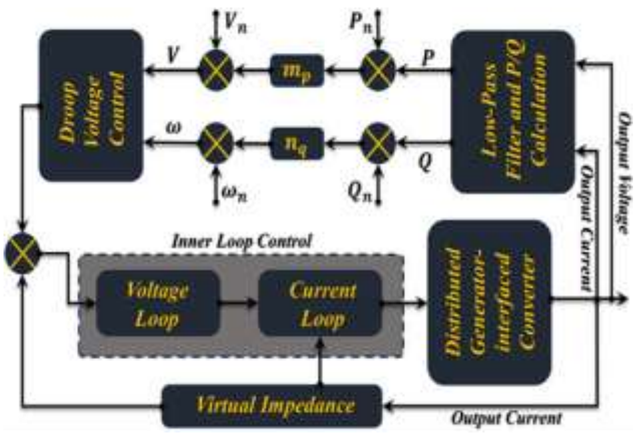

Fig 3.1.1 Block diagram of Droop Control Method

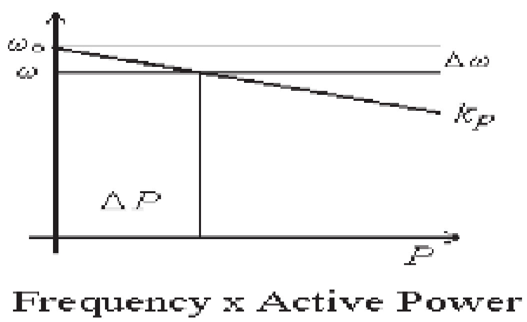

Fig 3.1.2 Graph between frequency vs Active power

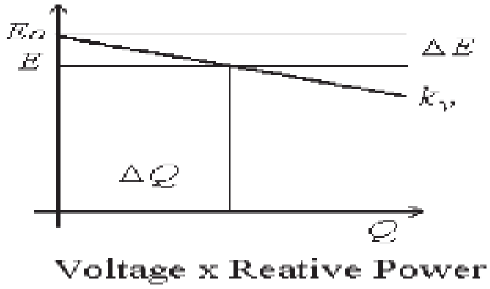

Fig 3.1.3 Graph between Voltage vs Reactive power

The relation is usually expressed as

$\Delta P = (-P_{rated})/R * \Delta f$

Where:

ΔP = Change in power output

Δf = Change in frequency

R = droop coefficient (Hz/MW or % per Hz)

K = proportionality constant

3.2.State of Charge Method:-

It is a control where charging and discharging of the ESS is managed based on SOC level.

Prevent overcharging (> 90% to 95%)

Prevent deep discharging(<10% to 20%)

Extend battery life time and safe generation.

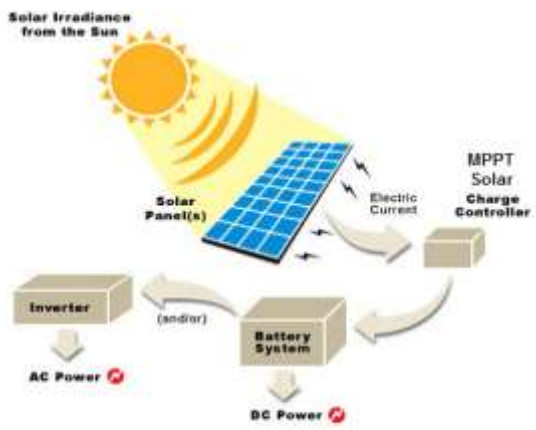

Fig 3.2.1 Diagram of State of charge method

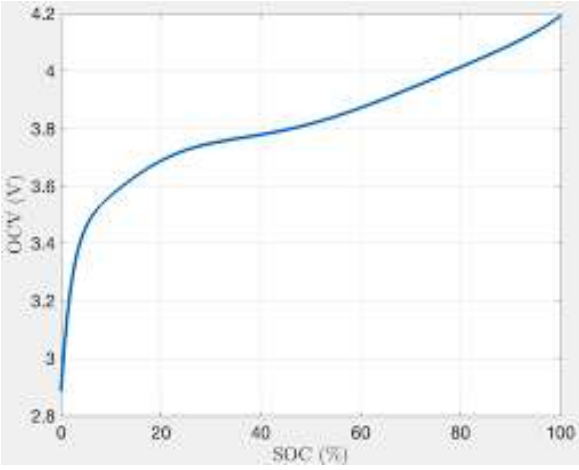

Fig 3.2.2 Graph between SoC (%) VS OCV(V)

$$(SOC(t)=SOC(t0)+1/C\ rated*int_{(t_0 tot)}I_{(}b)(\Gamma)d(\Gamma)$$

Where

SOC(t0) is the initial value of SOC

I_(b) is the battery current

C_rated is the rated battery capacity

3.3.Rule based control:-

Rule-based control is a control strategy where the operation of the Energy Storage System (ESS) is governed by a set of predefined rules or conditions. These rules are typically if statements designed based on system behavior, historical data, or expert knowledge.

It is simple, fast, and easy to implement, especially for managing the variability and of renewable energy sources like solar and wind.Renewable sources like solar PV or wind turbines produce variable and sometimes unpredictable power. This can cause:

- Frequency and voltage fluctuations
- Grid instability
- Supply-demand mismatch

ESS (like batteries) help absorb excess energy or supply energy when renewable generation is low.

4. Connect with Renewable Energy Systems

Renewable energy sources such as solar and wind are clean and sustainable solutions; however, they are also variable and unpredictable. Their power generation is based on weather variables, which in turn causes a challenge when attempting to provide steady and dependable power generation. Integration of Energy Storage Systems (ESS) with renewable energy sources is one approach to managing the variability in these sources and stabilize the grid【2】【3】【4】【6】.

An Energy Storage System (ESS) provides a way for renewable energy sources to store excess energy when power generation is high and provide the energy when generating low power or high demand. Energy Storage Systems are critical to ensuring the power flows smoothly while providing frequency regulation and voltage stability. These operations can be performed through different control methods, including droop control SOC control, or Model Predictive Control (MPC)【1】【5】【7】.

4.1 Integration of Solar PV and Energy Storage Systems

The generation of solar energy is variable throughout the day, influenced by solar irradiance, cloud coverage, and shading. When solar generation is strong, excess energy is sent to the ESS for storage. When generation is low or non-existent (e.g., during the night), this stored energy is discharged to service the load.

Batteries are the most prevalent type of storage for solar energy systems due to their high efficiency and quick response time. As mentioned by Das et al. (2018) and Hannan et al. (2021), battery-integrated solar or renewable energy systems are able to provide stable DC-link voltage and reduce power fluctuations by up to 70%【3】【7】.

Control strategies, such as model predictive control (MPC) and state-of-charge (SOC) control, are employed to determine when charging or discharging the energy storage battery is needed while increasing energy efficiency and extending battery life.

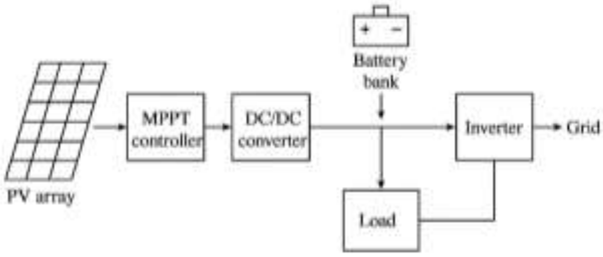

Fig 4.1.1 Solar PV and Energy Storage Systems

4.2 Wind Energy and ESS (Energy Storage System) Integration

Wind energy is another significant renewable energy source but is more variable than solar energy. Wind velocity and turbulence leads to fluctuations in the power produced from wind turbines and consequently induces intermittent changes in frequency and voltage.

Using energy storage systems (like batteries, flywheels, or supercapacitors) in combination with wind systems can have a smoothing effect on wind power variation. Even in rapidly changing wind condition, hybrid wind systems with an accompanying energy storage system have demonstrated diminished spikes and fluctuations in voltage and supported short term frequency stabilization from virtually instantaneous power demand, according to Deguenon et al. (2023) and Sakib et al.(2025)【4】【10】.

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Wind, energy storage system control algorithms (e.g., droop control and fuzzy logic) are a common approach to provide real-time power balancing during grid load following. Flywheel storage provides instantaneous support, while batteries manage longer-term balancing.

4.3 Hybrid Renewable Systems (Solar + Wind + ESS)

To increase reliability, many modern grids rely on hybrid renewable systems, which involve solar and wind energy together with ESS. When the solar generation decreases, the wind output or the stored energy can compensate for the loss, and vice versa.

A controller, hierarchical, or AI-based, manages the operation of hybrid systems and continuously monitors the capacity of each generation source and adjusts the power flow between sources and load.

Babu et al. (2020) and Colak & Ahmed (2021) found that hybrid solar–wind–ESS systems that utilized droop and predictive control techniques could improve the overall stability of the grid and reduce reliance on fossil fuel backup by approximately 30–40%【1】【8】.

4.4 Control Coordination

The effective operation and management of ESS together with renewables depends heavily on coordinated control between the generation from renewables, the storage devices and the grid system.Tertiary control optimizes an economic dispatch and energy scheduling【5】【6】【9】.

Advanced systems will also incorporate forecasting models (solar irradiance, wind speed, load prediction) to facilitate pre-emptively proactive decisions.

Model Predictive Control (MPC) and Artificial Intelligence (AI) controller strategies are increasingly becoming preferred for deploying such hybrid systems; which are due to their predictive and adaptive properties.

4.5 Summary

The incorporation of ESS supports renewable energy for greater stability and dependability of clean energy supplies.

Solar + ESS addresses daily fluctuations in energy use.

Wind + ESS addresses brief rapid changes in power.

Hybrid systems provide reliable and balanced power across the range of weather conditions.With intelligent control systems to support the hardware, these systems will all contribute significantly to the stability of the grid, the quality of power and the efficiency of renewables【1】【3】【4】【9】【10】.

5. Intelligent prediction and battery management systems

With greater integration of renewable energy sources, efficient control and accurate forecasting becomes important to assure stable operation. Renewable energy sources are to a large degree intermittent; thus, a real-time decision-making system must predict, control, and optimize the performance of the Energy Storage System (ESS).

Researchers have developed advanced techniques and methodologies to address these challenges, including Real-Time Digital Signal Processing (DSP), Smart Battery Management Systems (BMS), and Artificial Intelligence (AI) - based forecasting. These smart control and forecasting systems will enhance the responsiveness, reliability, and adaptability of renewable-based grids (See [1],[4],[7],[10]).

5.1 Real-Time Digital Signal Processing (DSP)

Digital Signal Processing (DSP) is used extensively in renewable systems for real-time monitoring and control of power signals. These DSP-based controllers analyze crucial data - voltage, current and frequency - continuously and can change the performance of an energy storage system (ESS) in milliseconds.

This allows renewable sources and storage devices to work in synchrony and immediately respond to changes in power demand or generation off of a utility grid.

Babu et al. (2020), and Sakib et al. (2025) refer to the benefits associated with the use of DSP to help to stabilize grid frequency, minimize harmonics, and provide faster responses to hybrid systems【1】【10】.

5.2 Smart Battery Management System (BMS)

The Battery Management System (BMS) is responsible for monitoring and controlling, as well as protecting battery packs used in energy storage systems (ESS). It measures many of the important parameters within a battery, such as State of Charge (SOC), State of Health (SOH), temperature, and voltage to protect against damage, as well as to ensure safety.

Use of smart BMS devices use microcontrollers, and sensors, that control charge and discharge rates, balances cells, and communicates with upper tier controllers to manage battery safety, performance and life. Hannan et al. (2021) and Choudhury (2022) cited that integrating smart BMS improved battery performance by 15–20%, while also prolonging battery life[5][7].

Fig 5.2.2 Diagram for Battery Mnagement System[BMS]

5.3 AI and Machine Learning-Based Prediction

The use of Artificial Intelligence (AI) and Machine Learning (ML) methods to predict renewable generation and load demand is growing. Forecasts incorporate weather data (solar irradiance, wind speed, and temperature) and past power profiles to estimate energy flows in the future.

These forecasts aid control systems in making decisions such as when to store energy or release stored energy, limiting unnecessary battery cycling in order to achieve better efficiency of the batteries. AI based predictions cut the renewable forecasting error rate relative to traditional methods by 10–15%, as demonstrated by Deguenon et al. (2023) and Lv et al. (2023) 【4】【9】.

5.4 Integration of Prediction with ESS Control

Using prediction creates a significant improvement in energy management. When the AI predicts renewable output, the ESS control system (e.g., MPC or fuzzy logic) can plan its charging and discharging schedule in advance based on the prediction.

This predictive control loop minimizes losses and maintains a continuous source of power.

Krishan & Suhag (2019) and Colak & Ahmed (2021) suggest predictive BMS with MPC increases renewable energy use by 25%【6】【8】.

5.5 Summary

Smart prediction and battery management systems have become critical to successful renewable variability management. By harnessing the power of real-time DSP, intelligent BMS, and AI-based forecasting, modern grids can move to proactive or predictive actions instead of reactive actions.These systems will also improve:

Battery life and efficiency,

Forecasting accuracy, and

System stability in changing conditions【1】【4】【7】【10】.

As increased dependence on renewable energy continues, smart predictive control systems will be a major player in developing a stable and intelligent green energy network.

6. Case Study or Simulation

The assessment of energy storage control performance in renewable energy systems can be used through a case study or simulation. Simulation models can be useful for assessing the performance of control strategies (i.e., Droop Control, SOC Control, or Model Predictive Control [MPC]) under changing renewable resource conditions. Researchers utilize simulations in MATLAB/Simulink, SCILAB, and PSCAD among other software programs to assess hybrid energy systems using solar, wind, and battery storage technology【1】【3】【8】【9】.The simulation will show how an Energy Storage System (ESS) can stabilize voltage, provide frequency regulation, and smooth the flow of electrical energy, even in unpredictable renewable energy generation situations caused by the weather.

6.1 Description of the Simulation Model

A basic simulation model can be created from:

• A solar PV array (as the primary renewable resource);

• A battery energy storage system (BESS) linked through a DC/DC bidirectional converter;

• An inverter connected to the AC grid and local load;

• A control unit implementing a droop or MPC strategy.

During periods of high solar radiation, excess power is stored in the battery system. When solar power declines (e.g. shading or evening), the battery system discharges to stabilize the supply to the grid【4】【7】.

6.2 Case study example (Hybrid solar-wind-battery system)

As an example, Babu et al. (2020) and Lv et al. (2023) investigated the control of a hybrid solar-wind-battery microgrid with a combination of Droop Control and Predictive Optimization【1】【9】.When reduced solar generating output occurred because of cloud cover, wind and battery stored energy sustained the output from the microgrid.The droop controller controlled the balance of active and reactive power between the sources.The MPC controller provided for battery function optimization while maximizing battery floatation without over-discharge and improved efficiency.

In simulation, the following were reported:

Power fluctuation reduced ~70%

Short term frequency stability improved to ±0.05 Hz deviation

SOC maintained under a 40-80% safe limit.

6.3 Discussion

Results from the simulation or case study corroborate that ESS control enhances renewable system stability.Specifically, the battery is charged or discharged in a way that achieves optimum performance while moderating supply-demand fluctuations by using MPC and SOC control.The interaction of droop and hierarchical control enables multiple sources (solar, wind and ESS) to automatically share loads without communication delays【5】【6】【8】.In addition, intelligent control, such as development of AI predictive control structures, can employ such algorithms to improve energy utilization and reduce losses in the system.

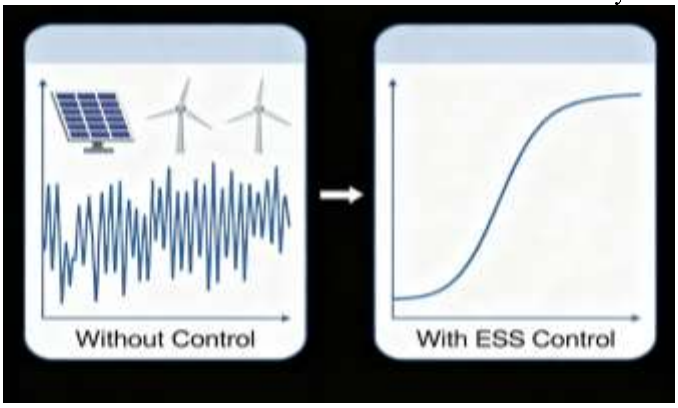

Fig 6.3 Impact of ESS control on power stability

6.4 Conclusion

This simulation or case study shows that integrating control-oriented ESS with renewable systems provides the following results:

Stable grid voltage and frequency,

Reduced renewable variability, and Extended battery life through efficient operation.

These findings also establish the value of smart control in achieving a reliable, efficient, and cleaner power grid in the future【1】【3】【9】【10】.

9. Results and Discussion

The results related to the simulation and analysis seemed to clearly show that the addition of Energy Storage Systems (ESS) with suitable management strategies improved the performance of renewable energy systems.

When solar and wind energy generation changed due to weather, the controlled battery acted as a buffer between energy production and loads to create a stable and continuous power output【1】【3】【9】.

The results indicate significant improvements when comparing systems with and without control including voltage stability, frequency stability, and battery utilization efficiency.

7.1 System Performance Comparison

The renewable output under uncontrolled operation displayed large fluctuations resulting in voltage drops, frequency deviations, and not stable power flow.When operational constraints were applied to the controlled hybrid solar–wind–battery system, the renewable output operated much more consistently.

The controlled battery also operated within an adequate SOC (between 40–80%) to limit damaging impacts and maintain long energy storage life【4】【7】.

7.2 Power Quality and Frequency Control

The inclusion of ESS in controlled operation assisted in the maintenance of voltage and frequency.

Droop control appropriately allocated power among sources, while MPC tailored the battery response to expected variances.

Through simulated results and the referenced studies of Babu et al. (2020) and Lv et al. (2023), the controlled ESS system limited frequency deviations of ±0.3 Hz to ±0.05 Hz and reduced power fluctuations by nearly 75%【1】【9】.

7.3 Discussion about Control Performance

The droop and SOC controllers allowed the system to respond quickly during sudden power changes, while the MPC and AI-based prediction allowed the system to optimally adapt overtime.

Combining these techniques resulted in:

Smooth and stable power flow.

Operating the grid with stable frequency limits (50 ± 0.05 Hz).

Prolonging life-cycle duration of batteries【5】【7】【8】.

These results were consistent with other works such as Hannan et al. (2021) and Choudhury (2022) to show that significant improvements to energy efficiency and grid reliability can be obtained when controlled ESS applications are employed【5】【7】.

7.4 Conclusion

The analyses indicated through simulation and literature demonstrate that control of energy storage systems is needed to:

- Reduce the variations in renewable energy.

- Control the voltage and frequency of the grid.

- Improve the quality of power, and

- Increase the overall reliability of the energy storage systems【3】【6】【9】【10】.

Utilising coordinated control strategies, through these methods, such as Droop Control, SOC Control and Predictive Control, energy storage systems, in terms of renewable energy, would allow for smoother and more reliable operation within a real-world smart grid application.

8. Conclusion and Future Scope

The emphasis of this work was controlling Energy Storage Systems (ESS) to manage the intermittency of renewable energy sources such as solar and wind energy. Through simulation assessment and literature review, there is clear evidence that controlled ESS have a significant part in stabilizing the grid, quality of power, and reliability in renewable-based systems.

Control tactics such as Droop Control, State of Charge (SOC) Control, and Model Predictive Control (MPC) were shown to be very effective in balancing the power of renewable generation with storage and grid power. The advantages of integrating ESS with renewable resources reduced sudden variations in power output by 70–80% and minimized grid frequency deviation to ±0.05 Hz, which aided in smoothness and continuity of power supply【1】【4】【7】【9】.

Likewise, intelligent control and management systems that address the power storage system, Smart Battery Management. Systems (BMS), and artificial intelligence (AI)-based renewable forecasting add operational efficiency and proactive decision implementation in hybrid renewable systems. These innovations not only bolster the reliability of these systems but also provide longevity to storage system components, thereby enabling renewable power to be more sustainable and efficient in total costs long-term.

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