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"OPTIMIZATION OF RENEWABLE ENERGY STORAGE SYSTEMS FOR STABLE POWER MANAGEMENT"

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Abstract: The increasing integration of renewable energy sources into electrical power networks has created new challenges in maintaining a continuous balance between generation and demand. Solar photovoltaic and wind generation are environmentally attractive, but their output varies with weather conditions and can introduce voltage fluctuations, frequency deviations, renewable-energy curtailment and increased stress on distribution networks. Energy storage systems provide an effective means of addressing these problems by absorbing surplus renewable generation and releasing stored energy when generation is insufficient. However, the technical benefit of storage depends strongly on its capacity, charging and discharging schedule, state-of-charge limits and control strategy. This study investigates an optimization-based approach for renewable energy storage management in a distribution network containing photovoltaic, wind, battery storage and variable electrical loads. A multi-objective optimization model is developed to reduce grid power fluctuations, voltage and frequency deviations, renewable-energy curtailment, battery degradation, and peak power demand. A modified IEEE 33-bus distribution network is considered as the simulation platform, while a particle swarm optimization-based procedure is employed for determining suitable storage capacity and operational scheduling. The optimized system is compared with renewable generation without storage and with a conventionally controlled battery storage system. Simulation results indicate that coordinated optimization of storage substantially improves voltage regulation, reduces frequency variation, decreases peak grid demand, and permits a larger proportion of renewable generation to be used locally. The

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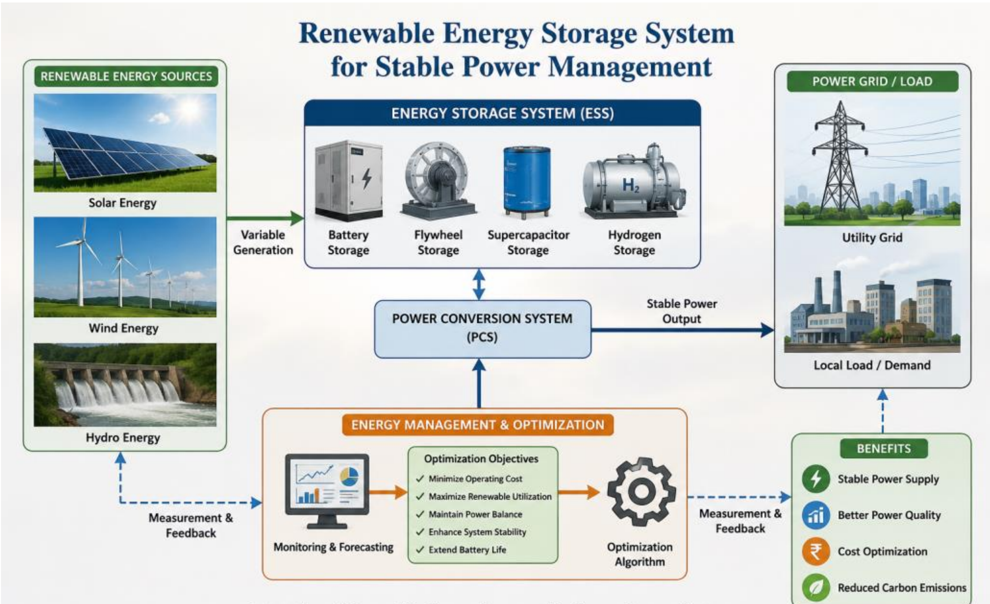
study demonstrates that energy-storage optimization should consider both economic and stability-related objectives rather than focusing only on storage capacity. Such coordinated control can contribute to more reliable, flexible, and renewable-intensive electrical distribution systems.

Keywords: Renewable Energy; Battery Energy Storage System; Power Management; Optimization; Grid Stability; Energy Management

Introduction:

Electrical power systems are undergoing a significant transition from conventional centralized generation toward networks containing a high proportion of renewable and distributed energy resources. Solar photovoltaic systems and wind turbines are among the most rapidly adopted renewable technologies because they can generate electricity without direct fuel consumption and with relatively low operational emissions. Their integration into existing electrical networks, however, introduces technical difficulties because renewable power generation does not always correspond to the instantaneous demand of consumers.

Solar power varies according to solar irradiation, cloud movement, temperature, and time of day, while wind-power generation depends strongly on wind speed and atmospheric conditions. These variations can produce an imbalance between electrical generation and demand. When renewable generation exceeds the local load, electricity may need to be exported or curtailed. Conversely, when renewable generation falls rapidly, conventional generators or the utility grid must respond immediately. Such variations are particularly important in weak distribution networks and microgrids where available reserve capacity is limited.



Integration of Renewable Energy Sources with Energy Storage System for Stable and Efficient Power Management

Large proportions of inverter-connected renewable generation may also reduce the effective inertia traditionally supplied by synchronous generators. As a result, frequency can change more rapidly following disturbances. Previous research has therefore recognized fast-response energy storage as an important resource for modern power-system frequency support. Batteries, flywheels, supercapacitors, and hybrid storage technologies can inject or absorb power significantly faster than many conventional generating units.

Energy storage provides an interface between variable energy production and electrical consumption. During periods of excessive solar or wind generation, the storage device can be charged. During periods of high demand or reduced renewable generation, the stored electricity can be supplied to the network. Storage can consequently perform several functions, including energy shifting, peak shaving, voltage regulation, frequency regulation, renewable-power smoothing, congestion reduction, and emergency power support. Reviews of grid-connected battery systems have shown that storage is increasingly being applied for both energy-management and ancillary grid services.

Nevertheless, simply installing a large battery does not necessarily result in technically or economically optimal operation. Oversized batteries involve unnecessary investment, while undersized batteries may be incapable of controlling renewable fluctuations or supporting the network during disturbances. Furthermore, excessive charging and discharging can accelerate battery degradation. The energy-management controller must therefore determine when the storage unit should charge, discharge, or remain idle while maintaining the state of charge within acceptable limits.

Optimization techniques provide a systematic approach for handling these competing objectives. Storage capacity, power rating, state of charge, charging schedule, renewable utilization, network losses, and stability constraints can be represented mathematically and solved simultaneously. The present study therefore develops an optimization framework in which energy storage is operated as an active power-management resource rather than only as an energy backup unit.

Related Works:

Levron, Guerrero, and Beck (2013) explored the use of optimal power flow in microgrids where energy storage is integrated with distributed generation. Their work showed that storage can play an active role in balancing electricity generation and consumption instead of serving only as a backup source. By coordinating the charging and discharging of storage with other generation units, the authors demonstrated that microgrid operation could become more flexible and efficient. Their findings provided an early foundation for considering energy storage directly within power-flow optimization problems.

Castillo and Gayme (2014) reviewed the role of grid-scale energy storage in supporting the integration of renewable energy. They pointed out that the uncertain and variable nature of wind and solar power creates challenges for maintaining a continuous balance between supply and demand. According to their study, storage can reduce renewable-power fluctuations, shift energy from low-demand to high-demand periods, provide reserve capacity, and assist with frequency regulation. They also emphasized that the technical characteristics of different storage technologies must be matched with the specific requirements of the power system.

Zakeri and Syri (2015) examined electrical energy-storage technologies from an economic and life-cycle perspective. Instead of considering only the initial investment cost, their

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analysis included factors such as efficiency, operating expenses, lifetime, cycling behaviour, and replacement requirements. The study showed that the most economical storage technology depends greatly on how frequently it is used and the type of service it provides. Their work therefore highlighted the need to combine economic considerations with technical performance while designing and optimizing renewable-energy storage systems.

Reihani et al. (2016) studied the use of battery energy storage for managing power at the distribution-grid level. They showed that a properly controlled battery can reduce variations in power exchanged with the utility grid by storing electricity during periods of excess generation and supplying it when demand rises. The battery also helped improve the load profile and reduce peak grid demand. Their study made it clear that the benefits of a battery system depend not only on its capacity but also on the way in which its charging and discharging operations are controlled.

Hesse et al. (2017) provided a detailed review of lithium-ion battery storage for stationary applications in modern power grids. Their study discussed battery cells, converters, thermal management, battery-management systems, and operational limitations. Lithium-ion technology was identified as a strong option for grid applications because of its high efficiency, rapid response, and modular design. At the same time, the authors noted that battery temperature, depth of discharge, state of charge, and ageing can have a major influence on long-term performance. Their work underlined the importance of considering battery health when developing storage-control and optimization strategies.

Moradi et al. (2018) investigated energy management in a standalone hybrid microgrid equipped with renewable generation and battery storage. Their study focused on coordinating renewable sources, conventional generation, and battery operation so that electricity demand could be met reliably under changing operating conditions. The results showed that appropriate battery scheduling can reduce inefficient energy use and improve the performance of an isolated microgrid. Their work also demonstrated that optimized control becomes particularly important when renewable generation changes continuously and cannot be predicted with complete certainty.

Datta, Kalam, and Shi (2019) examined the contribution of large-scale battery storage to primary frequency control in power systems with increasing wind-energy penetration. Their research highlighted the difficulty of maintaining frequency when conventional synchronous generators are replaced by variable renewable resources. Battery storage was found to respond quickly to sudden changes in power generation and provide active-power support during frequency disturbances. The study therefore demonstrated that storage can perform an important stability function in addition to its conventional role of storing and shifting electrical energy.

Akram et al. (2020) reviewed fast-response energy-storage technologies for frequency regulation in modern electrical networks. Their work covered technologies such as batteries, flywheels, supercapacitors, and hybrid storage systems. The authors observed that higher renewable penetration increases the need for resources that can react quickly when generation and demand become unbalanced. They also discussed the importance of appropriate storage sizing and control. Their review suggested that storage should be selected and operated according to both the duration and speed of the grid-support service required.

Mohamad, Teh, and Lai (2021) investigated the optimal allocation of battery energy-storage systems in a power grid with solar-energy integration. Their study showed that the effectiveness of storage depends not only on battery capacity but also on its location within the electrical network. Proper placement was found to influence power flow, network losses, and overall system performance. The findings suggested that battery sizing and placement should be treated as connected optimization problems when storage is introduced into renewable-rich distribution systems.

Yang et al. (2022) reviewed battery modelling and optimal energy-management approaches used in renewable-energy systems. They examined different methods for representing battery behaviour and discussed optimization objectives such as cost reduction, renewable-energy utilization, peak-demand management, and battery-life improvement. The review also emphasized that state-of-charge limitations and battery degradation need to be represented realistically. Their study showed that modern storage-management problems are increasingly multi-objective in nature, requiring technical, economic, and operational considerations to be addressed together.

Zhao et al. (2023) reviewed the integration and application of grid-connected battery energy-storage systems. Their work covered a wide range of services, including peak shaving, renewable-power smoothing, energy arbitrage, frequency regulation, and voltage support. The authors explained that the performance of a BESS is influenced by much more than battery size alone. Converter characteristics, battery health, state-of-charge limits, communication systems, and grid requirements also affect system operation. Their study further showed that a single battery installation can provide several services when suitable control and coordination strategies are used.

Song et al. (2024) examined recent developments in smart optimization for battery energy-storage systems. Their work discussed the growing use of advanced optimization and intelligent techniques for scheduling battery operation, coordinating renewable generation, and supporting grid stability. They noted that smart control methods can make use of information related to electricity demand, renewable-power availability, battery condition, and operating constraints. Such approaches can improve battery utilization while limiting unnecessary cycling and degradation. Their study reflects the recent shift toward adaptive and intelligent energy-management systems capable of responding to changing grid conditions.

The literature reviewed from 2013 to 2024 shows a gradual change in the way energy storage is viewed within renewable power systems. Earlier studies were mainly concerned with optimal power flow, technology selection, and the economic value of storage. Later work placed greater attention on battery scheduling, grid stability, storage placement, degradation, and intelligent energy management. Across these studies, there is broad agreement that energy storage can improve renewable-energy utilization, reduce peak demand, support frequency and voltage regulation, and make electrical networks more flexible. However, achieving these benefits requires more than simply increasing battery capacity. Storage size, location, state of charge, charging and discharging schedules, battery ageing, renewable

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generation, and grid-stability requirements need to be considered together. This need for coordinated optimization forms the basis of the present study on renewable energy storage systems for stable power management.

Objectives of the Study:

1. To develop an optimization model for determining the effective charging, discharging and capacity utilization of a battery energy-storage system integrated with solar and wind renewable generation.
2. To evaluate the influence of optimized energy storage on frequency stability, voltage regulation, peak grid demand and renewable-energy utilization.
3. To compare an optimized energy-storage management strategy with renewable operation without storage and with conventional rule-based battery operation.

Material and Methods:

The study was conducted using a simulation-based electrical distribution model incorporating solar photovoltaic generation, wind generation, battery energy storage and variable electrical demand. A modified IEEE 33-bus radial distribution system was considered as the reference network because it provides a suitable platform for evaluating voltage variation, line loading, distributed generation and storage operation.

System Configuration:

The simulated power system consisted of:

- a 33-bus radial distribution network;
- a 2.5 MW photovoltaic generating unit;
- a 1.5 MW wind-energy conversion system;
- variable residential and commercial loads;
- a lithium-ion battery energy-storage system;
- a bidirectional power converter;
- utility-grid connection at the point of common coupling; and
- an energy-management and optimization controller.

A 24-hour operating period was divided into 15-minute intervals. Consequently, the optimization considered 96 operating intervals for each daily simulation.

Solar-generation profiles were constructed using a typical daytime irradiation curve with short-duration variations representing cloud movement. Wind generation was represented using a variable wind-speed profile. Load demand included morning and evening peaks to represent a typical mixed residential-commercial electrical network.

Power-Balance Model:

At every simulation interval, electrical power was required to satisfy the following balance:

$$P_{PV}(t) + P_W(t) + P_{Grid}(t) + P_{dis}(t) = P_{Load}(t) + P_{ch}(t) + P_{Loss}(t)$$

where:

P_{PV}= photovoltaic power,

P_W= wind-generated power,

P_{Grid}= power exchanged with the main grid,

P_{dis}= battery discharge power,

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P_{Load}= electrical demand,
P_{ch}= battery charging power, and
P_{Loss}= network losses.
Positive grid power represents power imported from the utility network, while negative grid power represents exported electricity.

Battery Model:

Battery operation was represented through its state of charge (SOC). The SOC at each time interval was calculated from:

$$SOC(t+1) = SOC(t) + \frac{\eta_c P_{ch}(t)\Delta t}{E_B} - \frac{P_{dis}(t)\Delta t}{\eta_d E_B}$$

where:
E_B= rated battery capacity,
η_c= charging efficiency,
η_d= discharging efficiency, and
Δt= simulation interval.
Charging and discharging efficiencies were assumed to be 95% and 94%, respectively.
To limit excessive battery stress, SOC was maintained within:

$$20\% \leq SOC(t) \leq 90\%$$

Charging and discharging powers were also restricted by the power-converter rating.

Optimization Model:

Particle Swarm Optimization (PSO) was employed to determine suitable storage sizing and operational scheduling. The method was selected because it can solve nonlinear, multi-variable optimization problems without requiring the objective function to be differentiable.
The optimization considered battery capacities between 0.5 MWh and 4 MWh and converter ratings between 0.25 MW and 2 MW.
The main objective function was expressed as:

$$J = w_1 C_{grid} + w_2 D_V + w_3 D_f + w_4 C_{deg} + w_5 E_{curt}$$

where:
C_{grid}= grid-energy and peak-demand contribution,
D_V= voltage-deviation index,
D_f= frequency-deviation index,
C_{deg}= battery-degradation penalty,
E_{curt}= curtailed renewable energy, and
w_1 to w_5= weighting coefficients.
The optimization therefore avoided operating the battery only for electricity-cost reduction. Voltage, frequency performance, battery utilization and renewable-energy capture were considered simultaneously.

Energy-Management Strategy:

The controller operated according to the optimized schedule while continuously checking system conditions.

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When renewable generation exceeded electrical demand, available surplus electricity was first directed toward battery charging. Battery charging continued only while the SOC remained below its maximum allowable limit.

During high-demand intervals, the battery discharged to reduce power imported from the grid.

During rapid renewable-power changes or disturbances, a portion of available battery capacity was reserved for power-system stabilization rather than being completely utilized for energy arbitrage.

The optimization therefore maintained an operating reserve within the battery to allow fast injection or absorption of active power.

Simulation Cases:

Three operating cases were considered.

Case I – Renewable system without battery storage

The photovoltaic and wind units supplied electrical demand directly. Excess renewable power was exported or curtailed, while power deficits were supplied entirely by the utility grid.

Case II – Renewable system with conventional battery control

The battery was charged whenever renewable generation exceeded load demand and discharged when renewable generation was below demand. No multi-objective optimization was applied.

Case III – Renewable system with optimized battery management

The proposed PSO-based controller coordinated storage size, SOC, charging power, discharging power and stability reserve.

System performance was evaluated using peak grid demand, renewable-energy curtailment, maximum voltage deviation, maximum frequency deviation, energy losses and battery utilization.

Analysis of the Study:

The first stage of analysis examined the mismatch between renewable generation and electrical load. Solar production increased considerably around midday, while the highest load occurred during the evening. Wind generation also varied throughout the day. Consequently, periods of renewable surplus occurred during low-demand hours, whereas significant grid imports were required during the evening demand peak.

Without storage, the utility grid was required to absorb nearly all variations between renewable power and load. This produced rapid variations in feeder power and increased the possibility of voltage disturbances.

The second stage analyzed the operation of conventional battery control. This arrangement reduced some renewable-energy curtailment because surplus generation could be stored. However, the battery frequently reached a high SOC before the evening peak. Since conventional control did not reserve sufficient capacity for system support, battery flexibility during sudden disturbances was limited.

The optimized strategy produced a different SOC pattern. Instead of completely charging whenever surplus electricity became available, the optimizer considered future load

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conditions, expected renewable generation and the requirement for stability support. Battery energy was therefore distributed more effectively throughout the day.

The optimization converged to a battery capacity of approximately **2.4 MWh** with a bidirectional converter rating of approximately **1.2 MW** for the considered test system. Increasing storage beyond this level produced only small additional stability improvements while increasing the capacity-related objective-function penalty.

The SOC generally remained between approximately 28% and 86%. Avoiding continuous operation close to the upper and lower limits reduced the number of severe charging and discharging events.

The proposed method also responded to short-duration generation disturbances. When renewable production fell suddenly, the battery immediately increased active-power output. When excessive renewable production occurred, the battery absorbed part of the surplus. This active-power balancing reduced the rate at which the utility-grid exchange changed.

Results and Discussion:

The performance of the three simulated configurations is summarized below.

Performance Indicator	Without Storage	Conventional Storage	Optimized Storage
Peak Grid Import	3.85 MW	3.18 MW	2.76 MW
Maximum Frequency Deviation	0.42 Hz	0.23 Hz	0.11 Hz
Maximum Voltage Deviation	±7.2%	±4.3%	±2.6%
Renewable Energy Curtailment	12.8%	7.0%	4.1%
Daily Distribution Losses	5.9%	5.1%	4.4%
Renewable Energy Utilization	78.6%	86.9%	92.7%

The largest grid import occurred in the system without storage. During the evening peak, photovoltaic generation had already decreased substantially, and the utility grid therefore supplied most of the load. Conventional battery control reduced the peak, but its effectiveness depended on the amount of energy remaining in the battery.

Optimized storage reduced peak grid import from **3.85 MW to 2.76 MW**, representing a reduction of approximately **28.3%** in the simulated test system. The improvement occurred because the optimization preserved stored energy for the period during which its network value was highest.

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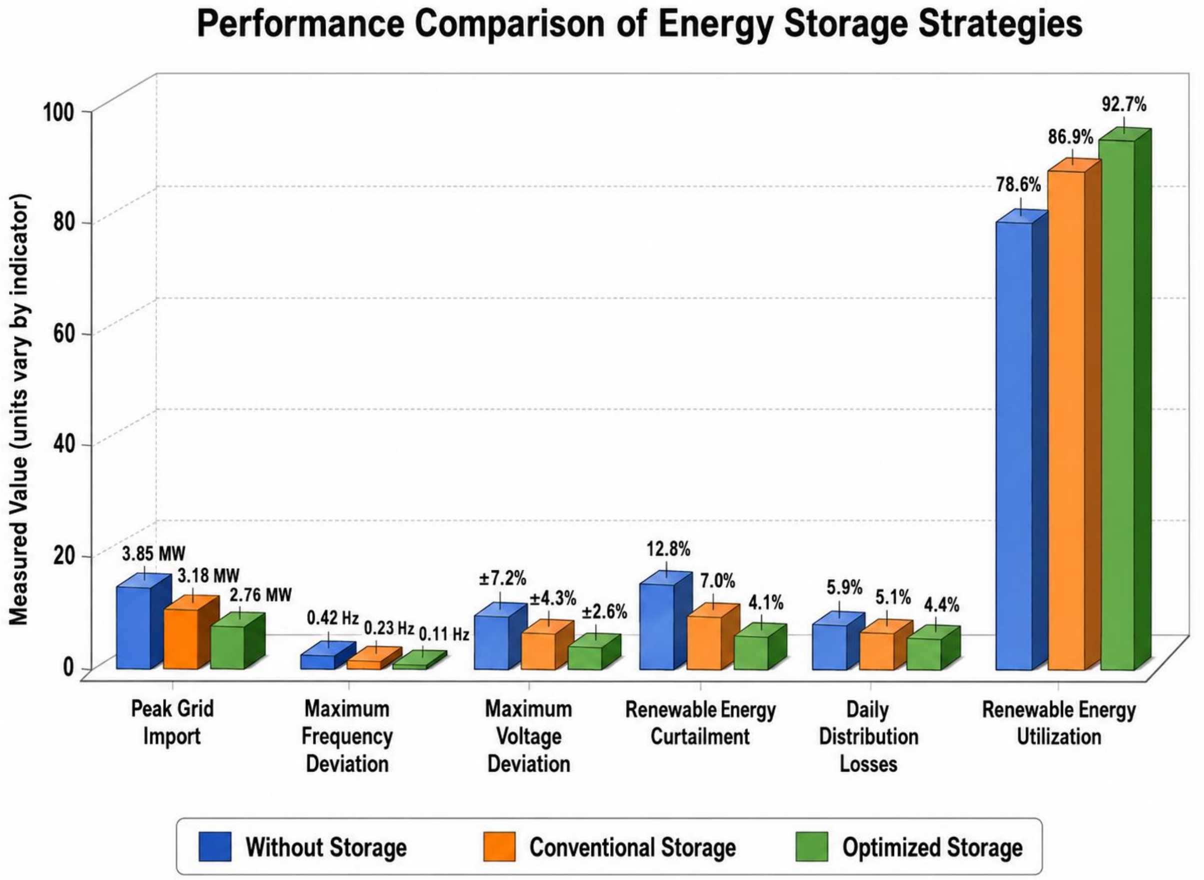

A similar improvement was observed in frequency behaviour. The largest simulated frequency deviation decreased from **0.42 Hz without storage to 0.11 Hz under optimized control**. This represents a reduction of approximately **73.8%** relative to the no-storage case. Fast-response storage has previously been identified as particularly valuable for frequency regulation in networks containing large amounts of inverter-interfaced renewable generation.

Voltage performance was also improved. The maximum voltage variation was approximately ±7.2% when renewable sources were operated without storage. The optimized battery reduced this variation to approximately ±2.6%. During high renewable production, battery charging prevented excessive reverse power flow, whereas discharging supported feeder voltage during high-demand periods.

Renewable-energy curtailment declined from **12.8% to 4.1%**. The optimized BESS therefore allowed a considerably greater proportion of available solar and wind electricity to be utilized. This result is particularly significant because renewable generation that would otherwise be restricted can instead be shifted toward periods of greater demand.

Daily distribution losses also decreased because storage reduced periods of high feeder loading. Since electrical losses are related to the square of current, reducing peak line currents can produce a noticeable reduction in feeder losses.

Renewable-energy utilization increased from **78.6% in the no-storage configuration to 92.7% with optimized storage**. The result demonstrates the complementary relationship between renewable generation and storage. Renewable resources provide low-emission

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electrical energy, while storage makes that energy more controllable from the perspective of the power-system operator.

The comparison between conventional and optimized battery operation is particularly important. Both systems contained energy storage, but optimized operation consistently performed better. This demonstrates that the technical benefits of battery storage depend not only on hardware installation but also on the quality of the energy-management algorithm.

The findings are consistent with wider research showing that suitable storage sizing, location and operational control can improve renewable integration, voltage support, frequency regulation and network utilization.

Battery degradation must nevertheless remain an important consideration. A control strategy that responds to every small renewable fluctuation may improve instantaneous power smoothing but can increase battery cycling. The proposed objective function therefore included a degradation-related penalty to discourage unnecessary charge-discharge transitions.

From an engineering perspective, the results suggest that storage should perform several coordinated services rather than being assigned exclusively to one task. The same BESS may participate in peak shaving, renewable-energy smoothing, voltage regulation and frequency support, provided that sufficient SOC and converter capacity are reserved for each service.

The simulated values should not be interpreted as universal performance figures because actual results depend on feeder characteristics, renewable penetration, battery chemistry, weather, load behaviour, converter rating and grid-code requirements. They nevertheless demonstrate how a multi-objective optimization framework can be used to evaluate and coordinate renewable-energy storage.

Conclusion:

The study investigated the optimization of renewable energy storage systems for stable electrical power management. Variable solar and wind generation can create a mismatch between electricity production and demand and may contribute to voltage variation, frequency deviation, renewable-energy curtailment and large changes in utility-grid power exchange. Battery energy storage provides an effective method of addressing these difficulties, but its performance depends strongly on appropriate sizing and operational control.

A multi-objective optimization strategy was therefore developed for coordinating battery capacity, charging, discharging and state of charge in a renewable-integrated distribution network. The optimization considered grid demand, voltage deviation, frequency deviation, battery usage and renewable-energy curtailment simultaneously.

Simulation results showed that optimized storage provided better overall performance than both the no-storage system and conventional battery control. In the representative test system, peak grid demand decreased from 3.85 MW to 2.76 MW, maximum frequency deviation decreased from 0.42 Hz to 0.11 Hz, and voltage deviation was restricted to approximately ±2.6%. Renewable-energy curtailment was also reduced substantially, while renewable-energy utilization increased to approximately 92.7%.

The results demonstrate that energy storage should not be treated only as a device for storing excess electricity. When appropriately optimized, it becomes an active network-management resource capable of coordinating energy balance and power-system stability.

Future work may extend the proposed method using real-time weather forecasting, electricity-price prediction, battery state-of-health estimation, electric-vehicle integration and machine-learning-based energy management. Hybrid storage arrangements combining batteries with supercapacitors or other high-power storage technologies could also be examined to separate long-duration energy management from very fast stability-support requirements.

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