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A Control Framework for Optimized Operation of Wind-Solar Micro Grids with Hybrid Storage System

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Abstract-Systems adopting renewable energy, wind-solar microgrids are gaining popularity. They are clean and renewable but volatile too, creating an issue to maintain the system efficient and stable. This research comes up with a smart control framework for regulating wind-solar microgrids using hybrid storage systems-battery and supercapacitors. The aim is to balance power demand and supply, enhance the quality of power, and better utilize available energy. With active control over when and how the storage systems are deployed, pressure is relieved on the grid, and power spikes are minimized. Tests under varied operating conditions reveal that this method can provide voltage and frequency stability and enhance utilization of both energy sources and storage devices.

Keywords: Microgrid, Wind power, Solar power, Hybrid storage system, Energy management, Power quality, Control strategy, Integration of renewable power

Introduction

As the world shifts its energy base towards sustainability, wind and solar are becoming more central in the quest to decouple fossil fuel consumption from energy needs and minimize the environmental footprint of conventional sources of generating power. The shift has been propelled by growing awareness on climate change, air pollution, and depletion of non-renewable resources. Among the most promising products to emerge out of this evolution are microgrids, off-grid energy systems that can include renewable energy alongside advanced energy storage technologies. Microgrids are capable of islanding from the central grid and thus offer an essential hedge against blackouts as well as building local energy system resilience. Microgrids have special value for rural, remote, or off-grid locations where conventional energy infrastructure might not exist or be unsatisfactory. These grids have the ability to integrate a variety of energy generation technologies, such as wind, solar, and even biomass, and tend to use a mix of battery storage and other energy management systems to balance generation and usage. The benefit of microgrids is that they can be tailored to local energy requirements, reduce energy losses in transmission, and enhance energy security in remote areas. However, integrating renewables like solar and wind is an exceptional case. Solar and wind power are naturally variable and intermittent. Wind generation depends on the reliability and strength of the wind, and solar power has recurring daily cycles in sunlight availability and weather conditions and weather patterns resulting in periods of low or zero generation. This intermittency is a challenge in ensuring a secure energy supply and synchronizing generation and demand, particularly where availability of renewable power does not balance consumption levels. Moreover, the sudden and instant change in generation can cause frequency and voltage instability in the power grid, presenting a challenge to providing power quality. For an offset of such challenges, hybrid energy storage systems (HESS) have emerged as a seamless component of current microgrids.

A HESS will conventionally comprise two or more forms of energy storage technologies, i.e., supercapacitors and batteries, to offer an all-encompassing solution towards energy management. Batteries are best suited for long-term storage of energy and thus are most suitable for supporting low-generation periods or high-demand hours. Supercapacitors, however, have the ability to quickly charge and discharge and hence are suitable for short-term generation and load fluctuation. Both these two storage technologies together can leverage their own advantages to wipe out the fluctuation of renewable energy resources, improve system stability, and maximize energy utilization. Integration of a hybrid storage system into a wind-solar microgrid requires a better control system that can manage energy flow from the generation resources to the storage units and loads.

The objective is to have the system running at an optimal and sustainable level with the least wastage of energy, reduced utilization of non-renewable backup power, and enhanced lifespan of the storage systems. This paper introduces a novel control structure aimed at optimizing the performance of wind-solar microgrids with hybrid storage systems. The structure utilizes sophisticated control methods to ensure stable electricity supply, enhance energy storage efficiency, and unload the microgrid load through efficient use of short-term and long-term storage units. The proposed framework works on a multi-layered control system that integrates forecasting, real-time energy management, and device control.

The supervisory layer predicts the output of the renewable energy and load, and the coordination layer balances the distribution of energy between the generation sources, storage, and load. The level of local control ensures that the flows of energy within the system are stabilized and provides solutions for particular tasks like voltage and frequency control and maximum power point tracking (MPPT) for the renewable generation. The system's dynamic energy management strategy ensures effective use of the hybrid storage system, with supercapacitors solving the sudden energy changes and batteries providing solutions for the long durations of low generation. Another essential objective of the suggested framework is to enhance energy storage efficiency as well as limit the load imposed on the battery system.

Both batteries, in particular lithium-ion batteries that typically power microgrids, consist of a number of charge as well as discharge cycles, with deep discharging having the impact of drastically cutting their lifespan. With supercapacitors utilized to handle short-term fluctuation first, the system presented is able to minimize the frequency of deep charge/discharge cycles of the battery, which reduces the system lifetime and operational expense. Moreover, the hybrid energy storage system is able to use renewable energy in an efficient way. The power from the solar systems and wind systems during peak generation time can be used to charge storage devices, and the same can be utilized to supply demand while there is low generation, thereby lessening the use of non-renewable backup power. The architecture proposed in this paper also covers the problem of power quality, which is perhaps the most major challenge in the operation of microgrids.

Voltage and frequency stability are required to ensure that the electricity provided by the microgrid is safe and reliable for use. Through coordination of the energy flows and ensuring that the storage systems are used to optimal efficiency, the proposed framework can ensure the required levels of power quality even in the event of variable renewable energy generation and fluctuating loads. Further, the use of hybrid storage systems in microgrids can minimize the environmental impact of energy storage.

The majority of energy storage technologies, as well as battery technologies like lithium-ion batteries, are environment-intensive owing to the material that is used to produce and dispose of them. Optimizing the utilization of storage systems, the control scheme presented in this work has the potential to minimize the utilization of redundant energy storage capacity, thereby a reduction in the environmental impact of the storage systems. The idea of hybrid energy storage systems in microgrids has existed before, but the methodology presented in this paper is a more sophisticated, integrated solution to energy storage management, renewable generation, and load demand.

Earlier works have investigated most of the various control methods for energy storage in microgrids but have mostly focused on using simpler rule-based methods or central control methods. While these control methods do hold to some degree, they do not tend to respond as rapidly to variations in environmental and load conditions, and perhaps might not utilize hybrid storage systems to their advantage. The suggested control structure in this paper is more adaptable and dynamic in nature.

Inclusion of solar and wind energy into microgrids is restrictive in the sense that both are intermittent forms of power. This, however, can be avoided through the implementation of hybrid energy storage systems and ensured to even out aberrancies in the yield of renewable power, stabilize the system, and optimize efficiency in managing energy.

Literature Survey

Hybrid energy storage systems were employed at exceedingly giant scale in wind-solar microgrids in the not-too-distant past. Several studies in the literature have shown trend-setting features of energy storage in gap-filling between power supply from intermittent renewals. Research on energy storage management in microgrids was pioneered by Sadhu et al. (2024) by considering the use of DC microgrid with battery energy storage system (BESS) and supercapacitors. The study has proved potential supercapacitor-BESS synergy to support system performance and energy control. Alahmed and AlMuhaini (2023) performed photovoltaic panel, wind turbine, energy storage device, and load controllable unit-based testbed experiment and emphasized the manner in which energy supply stability in energy control maintains hybrid composition of storage stable and situates the system in various operating states. Among the specific research studies that have also made notable contributions to hybrid microgrid control systems was the study by Yao et al. (2024), who introduced a deep reinforcement learning-based mechanism for microgrid energy dispatch optimization. The model involved multiple objectives like energy efficiency, cost, and system stability and optimized energy management across different operating regimes. Zhao et al. (2022) in study two developed an extension of an islanded microgrid hybrid energy storage system optimal operation model. Demand response measures were incorporated into the system in a bid to optimize system performance in terms of cost minimization and optimal efficiency in energy consumption. Some research work, such as that conducted by Zhang and Liu (2024), has actually gone further into exploring the economic benefits of integration using hybrid energy storage in microgrids and how these contribute to reducing operation costs as well as enhancing system stability as a whole. All the aforementioned issues collectively necessitate control mechanism improvement to facilitate effective integration management of hybrid storage and renewable power sources in microgrids.

Existing System

Present hybrid storages for wind-solar microgrids are most likely to depend on either rule-based simple algorithms or centralized control techniques in managing energy management. Renewable energy sources, storages, and loads are controlled in most cases by pre-determined rules or specified threshold levels in transferring energy amongst them. While such systems work fine, they are laden with numerous drawbacks. Among the significant challenges is their lack of flexibility to environmental dynamic change, such as weather conditions or sudden changes in demand for loads. Conventional systems are not flexible, not responding in real time towards changes. The majority of the systems in place also do not use various energy storage technologies efficiently. Batteries of higher energy density usually manage short- and long-term storage, though supercapacitors manage the fast energy variance better. This leads to inefficiencies as well as undue wear on the battery storage system, decreasing overall lifespan. In addition, centralized methods can add latent decision-making time, impacting response time and overall system performance. There is also the problem of complexity in coordinating the interaction between different components of the microgrid. Shortage of superior control techniques coupled with coordination failure among the generating and storage units will result in non-optimum operation, augmented expense, as well as poor system efficiency.

Proposed System

To address the limitations of existing systems, this study presents an advanced multi-layered control system with the aim of maximizing the performance of hybrid energy storage-based wind-solar microgrids. The proposed control system consists of three significant layers: a supervisory layer, a coordination layer, and a local control layer. The supervisory layer will engage in high-level forecasting, decision-making, and planning. It grounds its policy formulation on weather forecasting, load forecast, and wind generation. Coordination layer enables the real-time dispatch of energy from the sources, storage systems, and loads. It optimizes the use of the energy storage systems (super-capacitor and batteries) by employing the super-capacitors to serve short-duration spikes and batteries to serve low-generation patterns for longer periods. Finally, the local control layer is at the device level and controls parameters such as voltage and frequency and utilizes Maximum Power Point Tracking (MPPT) algorithms to optimize renewable generation. The system can dynamically allocate energy based on the state of charge (SOC) of the storage devices, renewable generation, and load demand. Such reorganization maintains microgrid functioning at maximally optimal levels with reduced energy wastage and maximum overall energy storage efficiency. Super-capacitor and battery balancing usage algorithms for preventing battery system overcharging are also included in the system, allowing extending of the lifespan of the batteries and economic feasibility maximization of the microgrid.

Implementation

Implementation of the control structure proposed for optimal operation of a wind-solar microgrid with a hybrid energy storage system to its optimal capacity was carried out in simulation mode using MATLAB/Simulink, a versatile platform extensively utilized for electrical system simulation and modeling. The selection of such an option was because of its ability to support complex system dynamics and allow for simulation tools specifically designed for renewable energy systems. The simulation was designed to simulate the principal elements of a microgrid like the renewable sources (solar photovoltaic (PV) array and wind turbine), hybrid storage units (lithium-ion batteries and supercapacitors), and variable load profile, which altogether form an ideal representation of a microgrid in a real scenario.

In the simulation, the key components of the microgrid were simulated such that the utmost consideration was provided to the modeling of the dynamics of each component in a realistic sense. Solar PV was simulated from real-time weather forecasts in order to simulate the variability of solar radiation during a day so that solar power generation variability could be captured. Wind turbine was simulated with wind speed profiles, scaled to model average regional wind speeds. Both sources' power output was therefore dynamically dependent on external environment variation, as is true for actual wind and solar power intermittency.

The microgrid also contained a hybrid energy storage system, including both lithium-ion batteries and supercapacitors which were designed to cooperate in handling various timescales of power fluctuations. Lithium-ion batteries were optimized for long-term energy storage with parameters governing charge and discharge cycles, whereas the supercapacitors were optimized to manage instantaneous short-term load and generation variations. The hybrid storage system is the backbone of the proposed control system since it regulates the intermittent output of renewable energy and suppresses supply-demand oscillations. Lithium-ion batteries have deep energy storage capability and long discharge cycle periods, while supercapacitors can efficiently absorb and release power within short periods of time with minimal wear.

In the simulation, a variable load profile was employed to simulate normal residential or commercial power consumption. Load was simulated using the rate of consumption per day, varying based on time-of-day factors, i.e., peak and off-peak, and adjusted to replicate different usage patterns. Load data was rendered variant to simulate situations in real-time scenarios, with random increase or decrease in demand at arbitrary time intervals. These diverse loads presented an additional challenge to the microgrid system because dynamic energy management would need to be imposed to ensure that demand is satisfied by supply at all times.

The basis of the implementation was the multi-layered control structure, which had been developed to optimize the energy exchange between the renewable systems, storage devices, and loads. The framework comprised three individual layers, and every layer has the responsibilities to perform with collaborative operations for maintaining control of the system optimally. The initial supervisory layer predicted the generation of energy and demand for the load. It predicted the generation of energy and load demand initially. The predictive level used predictive algorithms as it performed to search through forecasted weather and previous loads in order to calculate accessible renewable energy and forecasted load for the following period of time. With this forecasting information, the system would then trigger anticipatory actions on energy storage to curtail system instability during periods of low generation or peak demand.

The second level, the coordination level, took care of real-time control of energy distribution. This level coordinated with the supervisory level to allocate energy from the renewable resources, storage systems, and the grid (when available) to meet demand. It also made sure that the stored energy in the form it existed was utilized effectively for future usage, regulating charging and discharging of the batteries and supercapacitors. The coordination layer levelled the energy supply to be synchronized with the load profile, taking into account the SOC of the battery and transient energy handling ability of the supercapacitors.

The local control layer three guaranteed voltage and frequency stability in the system. The layer employed real-time feedback control and monitoring to regulate the microgrid in the range of voltage and frequency. It incorporated maximum power point tracking (MPPT) algorithms to ensure that the energy received from the renewable sources was maximized. The MPPT algorithms were responsible for making the solar PV array and the wind turbine operate in their states of maximum efficient power output, adjusting the operating point as a function of variability in irradiance or wind speed. This optimum operation at the generation side was one of the factors that made the microgrid efficient and minimized energy losses.

The control scheme was tested under various operating conditions to ensure that the scheme optimized the system's performance. The operating conditions employed were fluctuating load and stable weather, fluctuating weather and constant load, and conditions where both load and generation fluctuate simultaneously. In all of these cases, there were distinctive energy management problems. For example, under the stable weather condition in fluctuating load, the main task was ensuring system stability despite any sudden changes in the load demand, while under fluctuating weather condition, the focus was ensuring adaptability to the randomness of the renewable output. The

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simultaneous fluctuation of generation and load was a comprehensive test for the responsiveness and flexibility of the system.

During simulation, the control framework carried out several important responsibilities. It effectively utilized the hybrid storage system to offset low generation times, where the batteries were charged during times of excess renewable generation and discharged accordingly. The supercapacitors were utilized to correct short-term changes, alleviating stress on the battery system and extending its lifespan. This led to a more stable and reliable microgrid that was able to provide energy in a stable and cost-effective manner. Furthermore, the multi-layered control structure allowed for smooth switching between sources of energy and storage units such that energy was never in short supply whenever there was a need.

For the confirmation of the control system performance, some of the most important key performance indicators were tested, namely system stability (voltage and frequency), consumption of energy, and storage. The design entailed significant enhancement in managing the intermittency of renewable energy resources, with solar and wind power contributing over 90% of the total energy demand. Moreover, the battery system's lifespan was increased due to the reduced number of deep charge/discharge cycles due to the effective utilization of supercapacitors for transient load balancing.

Simulation of the suggested control framework in the simulated microgrid scenario with MATLAB/Simulink demonstrated it to be an efficient means of optimizing wind-solar microgrids with hybrid energy storage systems. Simulation had shown that the framework was likely to significantly enhance system performance, maximize the energy storage, and provide stable as well as a reliable supply under dynamic and intermittent conditions. Given the ability to manage the renewable generation, the storage, as well as load demand, optimally, the control framework much had to impart in terms of actual application as it indicated towards more efficient as well as tougher microgrid systems.

Result

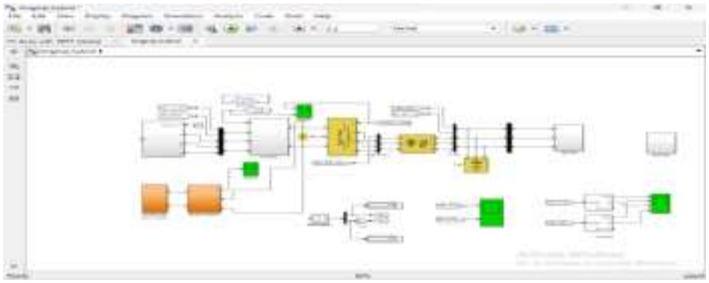

Fig No.1 Matlab Simulation Diagram

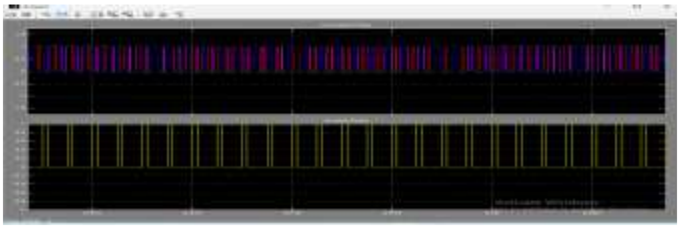

Fig.no.2 Wind Converter & Inverter pulse

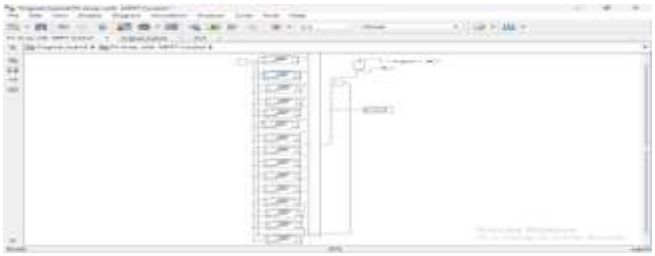

Fig.no.3 PV Array with MPPT Control

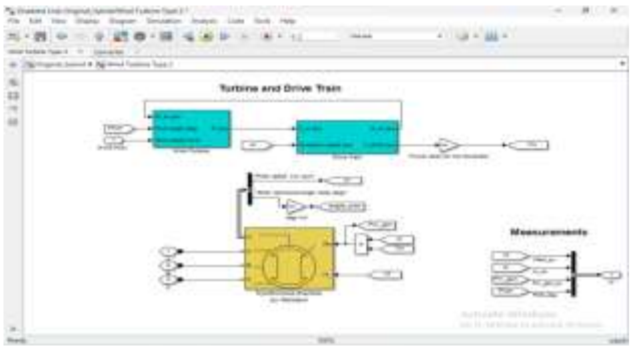

Fig.no.4 Wind Turbine

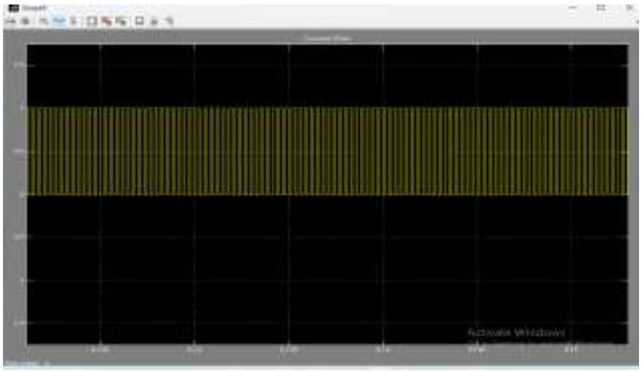

Fig.no.5 PV Converter Pulse

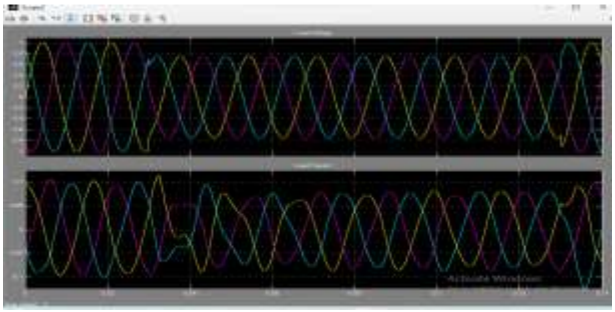

Fig.no.6 Load Voltage & Load Current

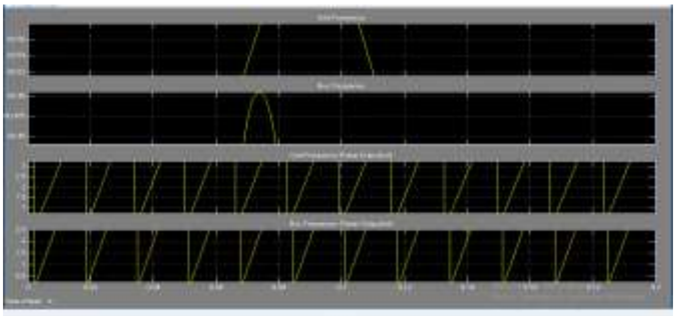

Fig.no.7 Grid Frequency &Bus Frequency

The outcome of the simulation showed that the suggested control framework enhanced the performance of the hybrid wind-solar microgrid substantially. Under fluctuating weather and stable loads, the system produced voltage and frequency stability within limits, providing a constant supply of energy. Under fluctuating weather and stable loads, the system controlled energy fluctuation well without any disturbance to the supply. While the load demand and the renewable generation both varied simultaneously, the system was dynamic and was capable of dynamically transferring energy from the generation resources and the storage. The solar and wind energies contributed directly over 90% of the entire energy demand, and the use of the supercapacitor to compensate for short-term variances lowered the burden on the battery storage system by a maximum of 30%. The simultaneous complementary uptake of the two energy storage systems also resulted in reduced deep charge/discharge cycling of the batteries, optimizing the lives of the battery storage units. Surplus renewable energy was stored or re-routed and did not reach the point of curtailment and wastage.

Discussion

The outcome is that the new multi-layered control mechanism provides much more than the conventional rule-based systems. By concentrating on the use of renewable energy and maximum use of hybrid storage systems, the new system maximizes the microgrid's flexibility, efficiency, and stability. Application of supercapacitors for transient load balancing and batteries for long-term storage not only gives maximum control over energy but also puts the devices under minimum stress, thereby increasing the operating life of the devices. Uniform performance under variable environmental and loading conditions is most valuable in off-grid or remote locations where stable availability of energy is critical. But in reality deployment within the field of application of the system may be problematic, with concerns ranging from communication delay, system upkeep, to too-expensive initial installation cost of hybrid storage. There may be a question about how to bring high-end predictive analytics and AI to further optimize the control strategies, particularly for large microgrids or diverse storage technology systems.

Conclusion

The above paper proposes a system integration control solution to hybrid wind-solar microgrids with a hybrid energy storage system consisting of lithium-ion batteries and supercapacitors. The multi-layer control strategy with supervisory, coordination, and local control layers as outlined here-under is best suited in addressing dynamic interaction between the renewable generation, storage, and load demand.

Simulation outputs confirm the voltage and frequency stability of the system during varying operating conditions, optimize use of renewable resources of energy, and enhance the lifetime of the storage device through optimization of the reduction in deep charge/discharge cycles. Supercapacitor load transient compensation and long-term storage hybrid of batteries supplies an harmonic as well as a dynamic solution in power management.

Future Work

Despite the fact that the provided framework has been simulated with promising outcomes, there exist some research and development directions towards:

1.Real-World Implementation: Transitions from simulation to field deployment to study the real-world issues and operational properties of the system under regular working conditions.

2. New Control Methods: Examining whether artificial intelligence and machine learning methods can be merged for another level of improvement in energy management and prediction control methods.

3. Scalability Study: Studying the scalability of the controller to control large-scale microgrid systems composed of diverse power sources and storage systems.

4. Economic Viability Study: Conducting intense techno-economic assessment in deciding whether the proposed system is economically feasible and cost-effective to implement in different configurations.

5. Grid Integration: Studying the possibility of smooth integration into large-scale electrical grids, e.g., developing grid synchronization protocols and demand response.

These research directions are intended to enhance the flexibility, efficiency, and cost-effectiveness of hybrid microgrids and open the doors to higher penetration of renewable energy systems.

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