

Design of Efficient Energy Storage System to Integrate Renewable Energy Source to Support in Grid

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Abstract

The trend toward green energy systems requires the integration of renewable energy (RE) into modern power grids; however, their intermittency and unpredictability pose significant challenges to reliability. An efficient energy storage system (ESS) provides a viable solution via storage excess energy when production is high and releasing it when output is low or demand is at its highest. This study proposes a novel ESS design that enhances storage efficiency and minimizes degradation by optimizing advanced battery systems through intelligent control algorithms and advanced power electronics. Real-time Internet of Things (IoT) - based monitoring enables dynamic responses to fluctuating grid conditions, while predictive artificial intelligence-driven analytics improve the scheduling of energy storage and distribution by forecasting demand and renewable generation patterns. The proposed system not only facilitates peak shaving and load leveling but also ensures stable voltage and frequency regulation, reduces dependence on fossil-fuel-based backup systems, and enhances grid fortitude by offering reliable backup energy during strikes. The operating principle and steady-state behavior of the system are presented and validated through MATLAB/Simulink simulations, demonstrating its effectiveness in enabling reliable, efficient, and stable embedding renewable energy into future smart grids.

Keywords

Artificial intelligence (AI), Energy storage system (ESS), Intelligent control, Internet of things (IoT), Renewable energy integration

Introduction

ESSs are anticipated execution an increasingly vital function with the growing adoption of renewable energy (RE). The shift toward RE is driven by the depletion of fossil resources, yet most sources remain intermittent-apart from hydropower, which is still affected by rainfall

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variability. Without ESSs, renewable energy cannot be stored and must be used immediately, leading to potential energy losses (Park, 2024). The conventional power sector also requires energy storage systems (ESSs) as well as to its intermittency function (Helwig and Bell, 2024). In order to reduce reliance on fossil fuels in both large- and small-scale applications, ESSs facilitate grid extension in remote locations, ensure dependable load supply, and enable integration of RE (Rahman et al., 2024). As seen in Figure 1, a hierarchy chart listing the various energy storage technologies that have been identified is displayed. This is because power generated by RE is frequently at its lowest or almost nonexistent at rush hours and at its highest in off-peak times (Gür, 2018).

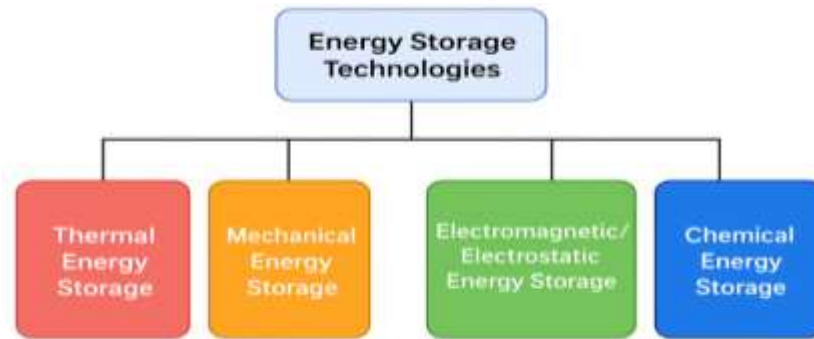


Figure 1. Energy storage types according to their manner of storage

In addition to increasing grid stability and efficiency and preserving load-generation balance, energy storage also lowers carbon emissions and enhances generating economics (Amir et al., 2023). Hydro power development frequently requires extensive soil excavation, altering local geology and potentially triggering micro-seismic activity.

Moreover, inadequate planning can disrupt river and stream flows, limiting the availability of freshwater for agriculture and domestic use in surrounding areas (Yao et al., 2016). It is predicted that by 2030, nearly half of the heat energy in Europe might be satisfied with the right policies and actions (Zalosh et al., 2021). The super capacitors (SCs) utilizes factors such as electrode surface area and the spacing between electrodes, resulting in their typically high specific capacitance (Gao et al., 2020). A ESSs and RE must be integrated for grid efficiency and stability, and their interaction must be managed by sophisticated control systems. A novel approach to energy management approach for a micro grid that combines solar, wind, and battery storage is presented in (Khan et al., 2024). Lithium-ion battery research has concentrated on enhancing energy density, longevity, and safety. Lithium-sulfur and silicon anodes could increase capacity, while solid-state electrolytes improve safety and voltage. Predictive health diagnoses are being created using AI-based battery management systems (Madani et al., 2025).

Supercapacitors and superconductors are both developing technologies. As a result, the system's complexity and cooling needs will decrease (Oladele et al., 2025). A controller design has been proposed for grid-connected hybrid systems (Gulzar et al., 2023). This PV–Wind–FC hybrid system incorporates BESS with minimal control loops and converters. Utilizing used LiFePO₄ batteries, an additional storage mechanism model will be transformed into an energy storage device (Sebasthirani et al., 2023). A new grid-forming DFIG control parameter design

technique is put forth (Zhang et al., 2024) based on the requirement for the effective transfer of oscillation energy across generators. Grid adaptability and predictability are improved when RE is integrated with ESSs. Technology such as compressed air, pumped hydro and batteries enable real-time balancing of supply and demand, manage fluctuations, and reduce the need for additional infrastructure. Advances in battery technology, managing energy, and AI-based analytics will further make battery packs essential to cost-effective and seamless renewable integration.

Proposed System

To ensure that a smooth and sustainable energy solution, the proposal technique to create an effective energy storage architecture that integrates renewable energy sources with grid assistance. Utilizing renewable resources to their fullest potential, it integrates solar and wind power with a clever storage system. Using a Maximum Power Point Tracking (MPPT), wind and solar are used as essential to maximize energy capture in a variety of situations. By reducing dependency on traditional power plants, this integration guarantees a consistent energy supply.

To fulfill the systems requirement, the MPPT makes sure that the power extracted from wind turbines and solar is optimum. The DC-to-DC converter improves the efficiency of energy transfer by adjusting the voltage levels to guarantee battery compatibility. To stabilize the grid's energy supply, by holding excess energy during periods of high generation and releasing it during moments of low RE output or high demand, the battery operates as an essential power storage device.

To ensure the safe and effective operation of connected components, to ensure steady voltages, the system incorporates voltage regulators. By controlling the energy flow between the sources, storage devices, and grid, the controller plays a vital role. It allows for precise energy distribution control by tracking data from voltage sensors. Additionally, the controller keeps the battery from being overcharged or deeply discharged, extending its life and guaranteeing system dependability. Additionally, bidirectional power flow is enabled by the controller, which enables the system to take energy when needed or feed excess energy back into the grid.

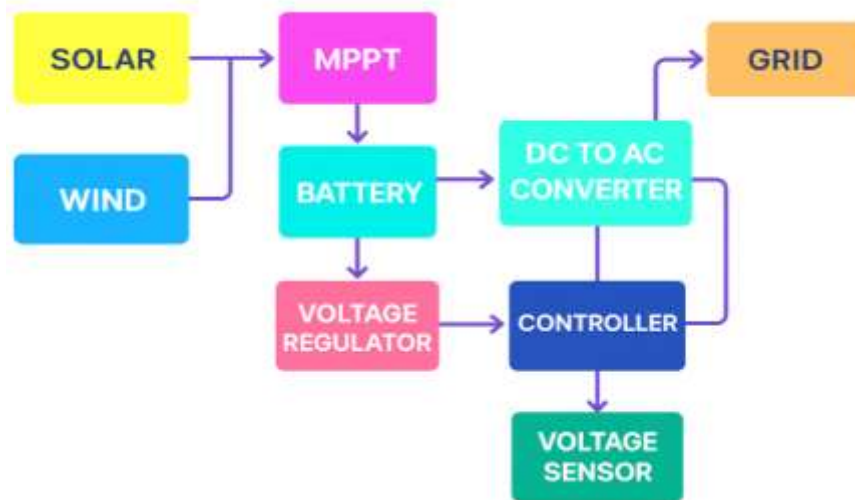


Figure 2. Block diagram of proposed system

A crucial component of the proposed system is grid integration, which allows battery storage and renewable energy sources to support the grid when consumption is high. To balance load requirements and avoid grid instability, the system constantly modifies its operation dependent on grid circumstances. The controller modifies the output to stay in sync with a grid while the voltage sensor continuously checks the grid voltage. This capability contributes to more intelligent and RE ecosystem by improving grid resilience and enabling efficient demand response.

By effectively integrating with the grid, the proposed approach is a step toward attaining energy sustainability. From compact residences to large industrial applications, its modular architecture guarantees adaptability to a range of operational scales. Utilizing cutting-edge parts like intelligent controllers, voltage regulators, and MPPT, the system minimizes energy losses while optimizing the use of RE. This technology is essential in the shift to a more robust and environmentally friendly power system since energy storage is integrated to further guarantee dependability and flexibility. Figure 2 illustrates the proposed system's block diagram.

Imperatives of ESSs in power sector RE integration

Figure 3 shows the various uses of ESSs in the electricity generation sector. The figure indicates off-grid electricity supply with an ESS, power quality, distribution deferral, transmission assistance, DG support, commodity arbitrage, and RE exploitation. The diverse roles of ESSs in power systems are amply demonstrated by this illustration.



Figure 3 Applications of different energy storage systems

Load Management Applications

Wind turbines or RE solar PV arrays can supply most of the energy required. Additionally, when power generation is abundant, the output energy can be stored in an electro-chemical energy storage device and then delivered through occasion of maximum energy demand. The

sustainability of the energy demand and supply for end users is balanced throughout the energy management system. Currently, the generation energy storage might be necessary, particularly during the night as wind and other solar and wind energy consumption is lower. Nonetheless, in the event of abrupt changes in customer load demand, provisions can be made for the discharge of most of the stored energy. Customers can use energy that has been saved for off-peak or inexpensive times to control the demand for power from utilities (Sajjad et al., 2024). When there is a strong demand for energy, the backup energy supply systems (ESSs) help to preserve supply and demand symmetry while preventing some technical limitations on the generating equipment. By using efficient energy management systems that include storage facilities, consumers can respond to utility attempts to minimize power consumption and modify their electricity purchases to lower peak demand, this reduces the price of electricity (Genç et al., 2025).

RE Intermittent Prevention and Grid Assistance

Because of their sporadic character, REs are susceptible to changes in the production of electricity and their inclination toward energy dispatchability. As a result, ESSs are necessary to lessen this issue. To offer qualitative power and address the reliability issues posed by RE systems, the current, rapidly expanding pace of RE use has also raised significant concerns about the intentional suppression of their intermittency. The significance of RE storage applications in this regard (Dodo et al., 2024). Grid-connected scenarios have been identified as a means of guaranteeing grid stability. Power delivery in distant areas (RAPS) as well (Amirkhalili et al., 2025). The requirements of ESSs like BESS have been carefully considered. Due to their modest electric power capacity, RE power systems are primarily run on the grid in rural locations. There was a proposal for a non-isolated interleaved high gain DC-DC converter (Bharathidasan, et al., 2022), to provide a high voltage gain without a massive turn ratio. When one or two supplies are unavailable, the converter can still provide the load with the necessary power. In such remote locations, load demand does follow the conventional load profile, which indicates that ESSs are a desirable energy planning technique to support local DG.

Emerging Smart-Grid Development

Power systems' progress has advanced significantly with the introduction of smart ESS. Their influence has been most noticeable thus far in electric vehicles (EV) and plug-in hybrid electric vehicles (PHEVs), and as grid-to-vehicle (G2V) systems expand, their usage is anticipated to increase even more. SESS's ongoing technological advancements will expand the range of storage system applications that use renewable energy sources, making it easier to integrate EVs and energy storage in microgrid (MG) designs, as seen in Figure 4. ESSs must operate effectively to integrate more sophisticated equipment into the power grid. Incorporating ESSs into a smart grid further lessens network volatility and dependency on expensive generating facilities at times when demand is substantial.



Figure 4. The possible application of MG

The need to incorporate storage systems into the future generation of "smart grids" (Hatami et al., 2024) is therefore being emphasized by governments worldwide. Future infrastructure development is anticipated using ESSs with massive and moderate sized energy potential. Because of the complexity of smart-grid systems, some recommended capabilities must be maintained by a dependable alternate method of power supply to ensure energy supply regularity for sustainable operation. In this sense, NaS and flow batteries are the ESSs that receive the most attention.

Predictive Maintenance

AI-based predictive maintenance methods conventional reactive infrastructure for RE experiences costly downtime and inefficiency because of maintenance programs. AI-powered forecasting opposes tradition and anticipates elements failures before they occur by utilizing data from sensors, past data, and climate trends (Chidolue and Iqbal, 2023). By taking a proactive stance, specific interventions can be made, reducing downtime, increasing equipment longevity, and maximizing maintenance expenses. AI-powered predicted upkeep for RE assets proactively foresees possible equipment breakdowns and meteorological patterns (Jose, 2018). The objective of this strategy is to reduce downtime, increase equipment lifespan, and optimize maintenance costs by utilizing cutting-edge techniques.

Numerous sensor data sets gathered from renewable energy sources are processed by machine learning algorithms. By examining past performance data and seeing trends, these algorithms can anticipate possible issues prior to them becoming critical malfunctions (Qiu et al., 2019). Utilizing a proactive approach, care personnel may deal with issues early on, avoiding unplanned outages and interruptions in the generation of energy. Deep Learning, a branch of machine learning, explores large data sets to improve predictive maintenance capabilities. Image data from drones is one of the many sources from which Deep Learning algorithms may extract insightful information in the context of RE (Capra et al., 2020). By incorporating sensor data, these digital replicas provide AI system with an accurate representation of the equipment's aspect. This broad knowledge facilitates the accurate identification of likely malfunctions and aids in the development of repair plans adapted to specific assets (Okunade et al., 2023).

When these strategies are used together, the likelihood of unplanned malfunctions is reduced, and the lifespan of renewable energy infrastructure is increased. This is accomplished by making timely and focused interventions based on knowledge gained via AI analysis. Furthermore, sensor data, historical records, and weather patterns are all easily integrated into AI-powered predictive maintenance in renewable energy. In the end, this strategy contributes to improved dependability, longer component longevity, and reduced servicing expenses in the RE industry by providing a proactive response to equipment failures with digital twins, deep learning and machine learning (Lu et al., 2019).

Modelling of RE Sources

Solar PV Model

A photovoltaic cell triggers the photovoltaic effect when sunlight reaches it (Rathore et al., 2021). Solar cell manufacturing uses semiconductor materials, such as silicon, which is often treated to enable interaction with the photons that comprise sunlight (Li et al., 2021). For photovoltaic technology, an electric field is produced by correctly doping two layers of silicon, for one side of silicon to be positively charged and the opposite side to be negatively charged. When released electrons are forced to travel through this electric field in a single direction, it functions as a diode and generates an electrical current (Mehta et al., 2019). The PV module is expressed mathematically using the Equation 1 – 4 (Bangura et al., 2023). Figure 5 illustrates the simulation setup for the solar PV system.

For the PV cell's current (I_{ph}) produced by sunlight incidentally

$$I_{ph} = \left[I_{SCR} + k_i (T - T_r) \frac{s}{100} \right] \quad \text{Eq. 1}$$

For the Inverse Saturation Current, I_{is} (A)

$$I_{is} = \frac{I_{SC}}{\left[\exp\left(\frac{qV_{OC}}{N_s K A T}\right) - 1 \right]} \quad \text{Eq. 2}$$

For the Saturation Current, I_0 (A)

$$I_0 = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp \left[\frac{qE_{go}}{BK} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad \text{Eq. 3}$$

For the PV Output Current, I_{pv} (A) module

$$I_{pv} = N_p \times I_{ph} - N_p \times I_0 \left[\exp \left(\frac{q(V_{pv} + I_{pv} R_s)}{N_s K A T} \right) - 1 \right] \quad \text{Eq. 4}$$

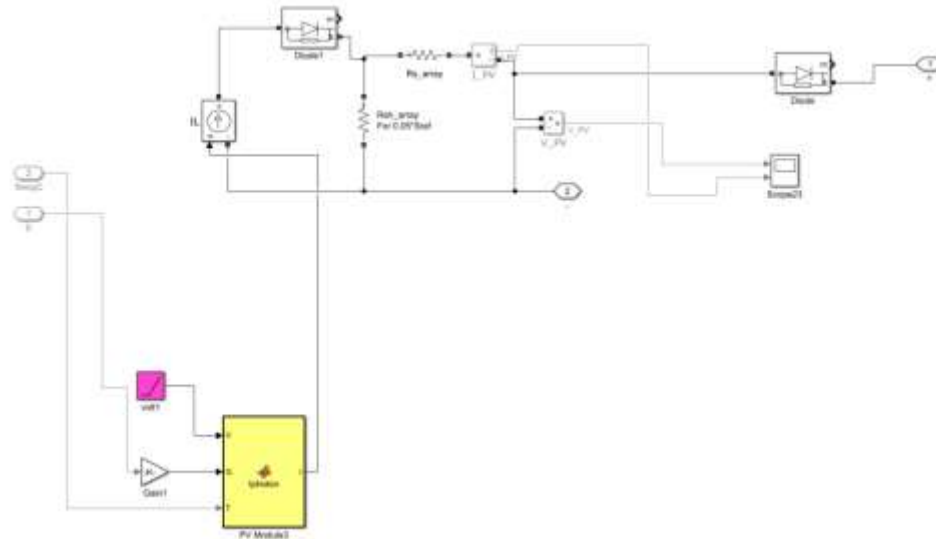


Figure 5 Simulation setup for a solar PV system

Modeling of Wind Turbine

Energy is generated by wind movement, which powers the PMSG. A lift force is produced by the air passing over the blades. The gearbox enables faster spinning, making the generator suitable. Furthermore, magnetic fields are utilized to convert the rotating energy into electrical energy (Bangura et al., 2023). Wind's kinetic energy is indicated by Equation 5. The interpretation of time-derivative wind power, or P_w , as kinetic energy is shown in Equation 6. The wind power generated by using functional wind turbines is shown as C_p (Coefficient of Performance). Betz's hypothesis states that the mechanical power P_w is determined by Equation 7. The value of C_p can be defined in terms of β and λ as shown in Equation 8 and Equation 9.

$$E_k = \frac{1}{2} m V_w^2 = \frac{1}{2} (\rho A X) V_w^2 - \text{Eq. 5}$$

$$P_w = \frac{dE_k}{dt} = \frac{1}{2} \rho A V_w^2 \frac{dx}{dt} = \frac{1}{2} \rho A V_w^3 - \text{Eq. 6}$$

$$P_w = C_p \left(\frac{1}{2} \rho A V_w^3 \right) - \text{Eq. 7}$$

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{\frac{-C_5}{\lambda_i} + C_6 \lambda} - \text{Eq. 8}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1} - \text{Eq. 9}$$

The connection between rotor speed and wind was used to calculate the tip ratio, which is shown by Equation 10. The relationship between rotor speed (W_w), and usable power taken from the wind (P_w), is used to calculate the amount of aerodynamic torque (T_W [N-m]) as shown in Equation 11. Figure 6 shows the results of the simulation as well as the thorough modeling of WECS.

$$\lambda = \frac{W_w R}{V_w} \quad - \text{Eq. 10}$$

$$T_w = \frac{P_w}{W_w} = \frac{1}{2} C_T \rho A R V_w^3 - \text{Eq. 11}$$

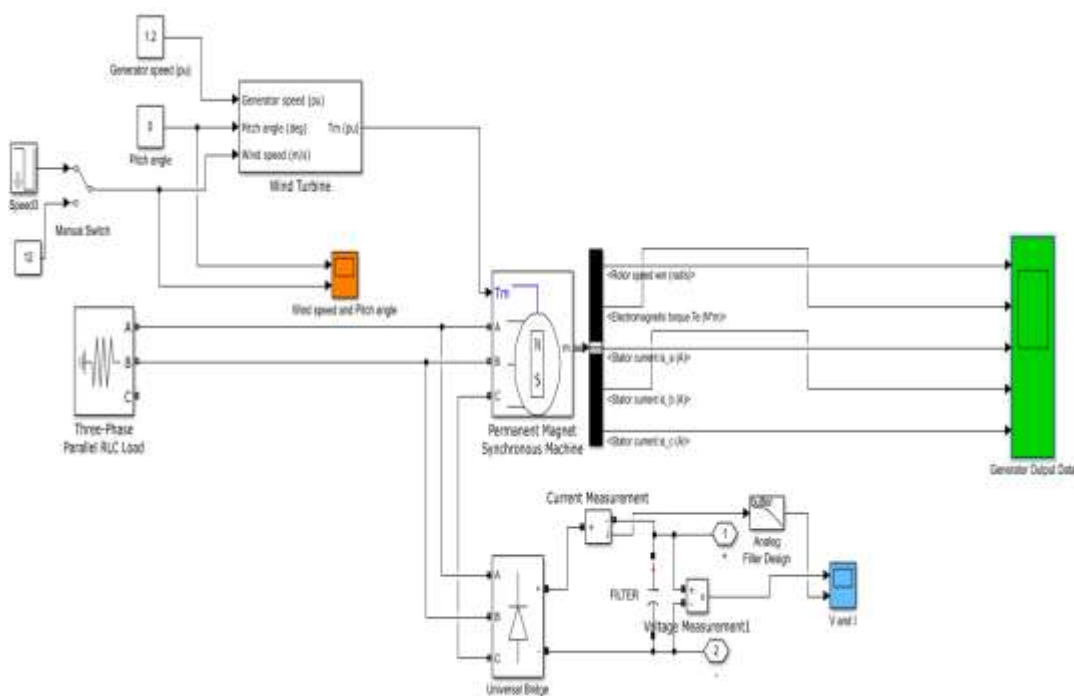


Figure 6. Simulation of the WECS module

Energy Storage System

For a reliable power source in the charging station, an ESS is required. The power generated by solar and wind is correlated with the charging and discharging states in the model. The equation can determine the system's battery count (n) (Ghenai et al., 2024).

$$\eta = \frac{\text{Energy Demand}}{\text{Battery Voltage} \times \text{Battery Ah} \times \text{Efficiency of Battery}} - \text{Eq. 12}$$

A charging controller is necessary for process control, and practically all the equations are solved by the location of the charging station's parameters. Figure 7 illustrates the simulation of battery parameters. The proposed Simulink model's hybrid generation appears in Figure 8.

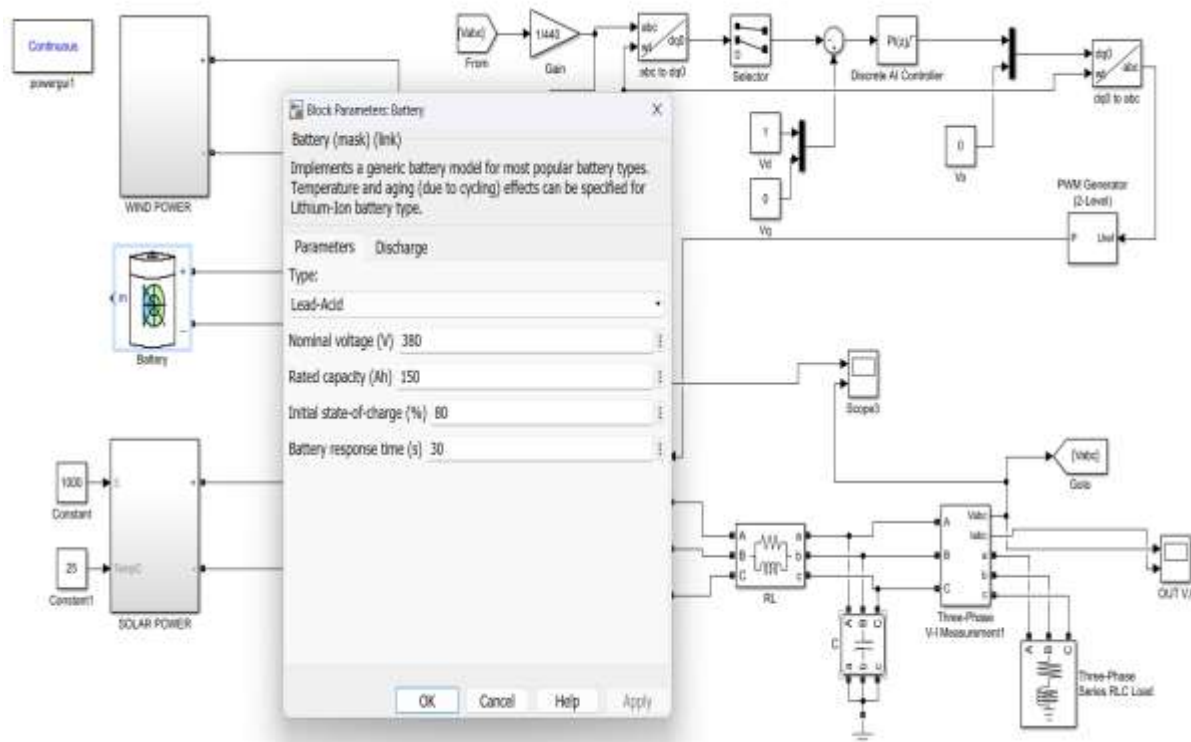


Figure 7 Simulation of battery parameter

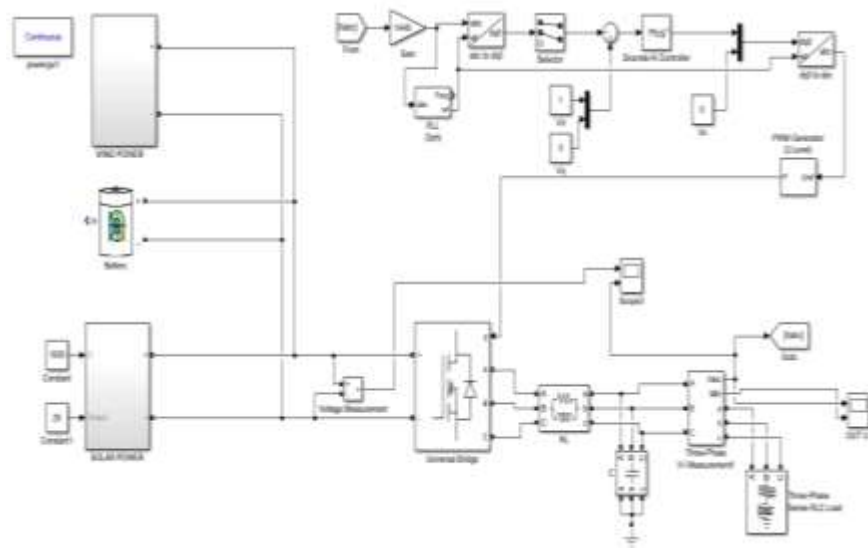


Figure 8. Simulink model of wind-PV hybrid generation integrated with battery

Results and Discussion

This section highlights a study's results on the modeling and design of an integrated hybrid generation system combining battery, wind, and photovoltaic (PV) technologies. Figure 9 illustrates the input and output voltages of the PV system, which stabilize after 0.04 seconds. The outputs of the permanent magnet synchronous motor (PMSM) are shown in Figure 10. The deployment of the wind energy conversion system (WECS) is depicted in Figure 6, with its AC output voltage and current demonstrated in Figures 11 and 12. Initially, both voltage and current are zero when wind speed is 0 m/s and gradually increase with wind speed. The WECS output reaches its maximum power of approximately 308 W at 0.05 seconds when integrated with a variable pitch angle.

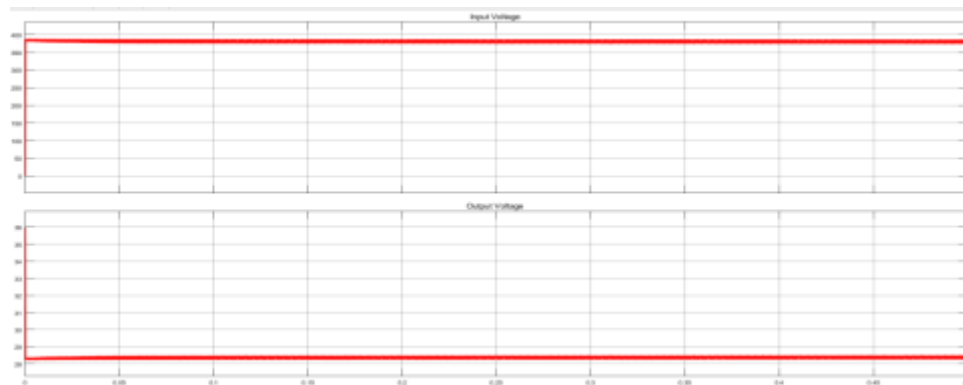


Figure 9. Solar PV input and output voltage

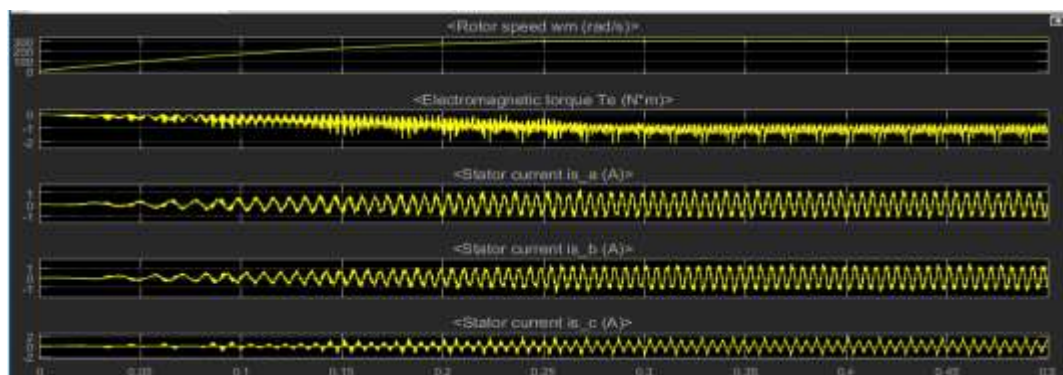


Figure 10. Outputs of the permanent magnet synchronous motor (PMSM)

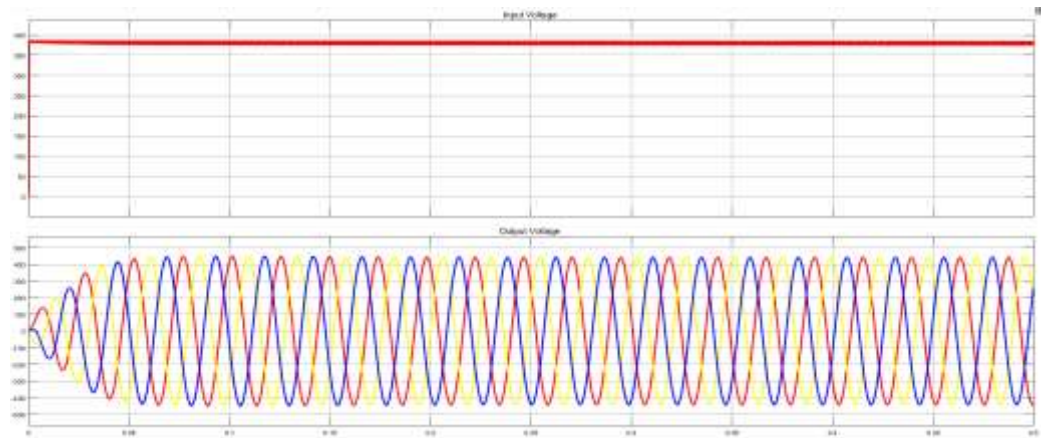


Figure 11. Input and output voltage of WECS

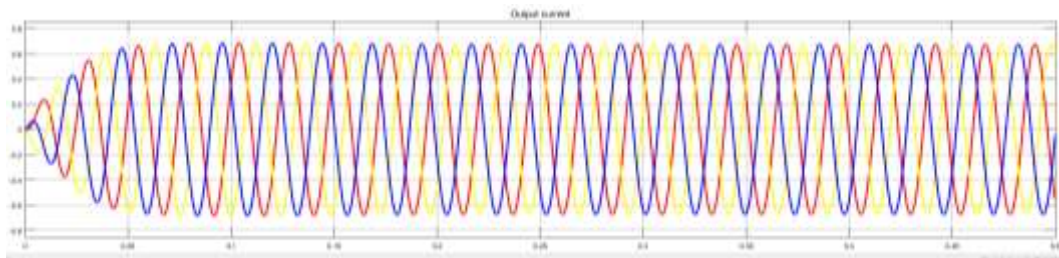


Figure 12. Output current of WECS

Conclusions

The design of an effective ESS is crucial to tackling the issues of reliability and variability in RE generation when integrating RES into the grid. An effective energy storage system is essential for lowering carbon emissions and reliance on non-RES in addition to guaranteeing the best possible use of RE. To establish an improved robust and RES, it is imperative that RES be integrated into the grid using effective energy storage devices. By addressing both operational and technical issues, these solutions guarantee a smooth transition to cleaner energy. More advancements in storage technologies, like better battery chemistry, AI-driven optimization and power electronics, will lead to more scalability and efficiency as technology develops. This development will enable enterprises and communities to depend increasingly on RE, promoting a brighter, cleaner future and guaranteeing everyone's access to energy.

Conflict of Interest

The authors declare no conflicts of interest.

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