International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Hybrid Wind–Solar Energy Systems with Battery Storage: A Comprehensive Review

JAISAIN[1], Suneel Baboo[2]
[1] Research Scholar, Department of Electrical Engineering, A.N.A College of Engineering & Management, Bareilly
2 Assistant Professor, Department of Electrical Engineering, A.N.A College of Engineering & Management, Bareilly

Abstract: - The rapid growth in energy demand and the environmental impact of fossil fuels have driven significant interest in hybrid renewable energy systems, particularly the integration of wind and solar power. These sources are inherently intermittent and weather-dependent, leading to fluctuations in power generation. To address this challenge, battery energy storage systems (BESS) are increasingly incorporated to enhance system reliability, stability, and efficiency. This review paper presents a comprehensive analysis of hybrid wind–solar energy systems integrated with battery storage. It examines various system architectures, including grid-connected and standalone configurations, and evaluates different battery technologies such as lithium-ion, lead-acid, sodium-sulfur, and flow batteries in terms of performance, cost, lifecycle, and environmental impact. The study also highlights key energy management strategies used to balance generation and load demand, ensuring optimal utilization of renewable resources. Furthermore, the review discusses advanced control techniques and optimization methods, including artificial intelligence and heuristic algorithms, for improving system performance and reducing operational costs. Critical challenges such as battery degradation, high initial investment, and scalability issues are also addressed. Recent advancements in smart grids, IoT-based monitoring, and next-generation storage technologies are explored to provide insights into future developments.
The findings indicate that hybrid wind–solar systems with battery storage offer a reliable, sustainable, and cost-effective solution for modern energy needs, particularly in remote and off-grid areas. This integration plays a crucial role in enhancing energy security, reducing carbon emissions, and supporting the global transition toward clean and resilient energy systems.
Keywords: Hybrid Renewable Energy System, Wind Energy, Solar Energy, Battery Energy Storage System (BESS)

I. INTRODUCTION

The global energy landscape is undergoing a significant transformation driven by the rapid increase in energy demand, depletion of fossil fuel resources, and growing concerns over environmental sustainability. Conventional energy generation methods, primarily based on coal, oil, and natural gas, contribute heavily to greenhouse gas emissions and climate change. In response, renewable energy sources such as wind and solar power have emerged as clean, sustainable, and widely available alternatives. These resources are abundant, environmentally friendly, and capable of supporting long-term energy security. However, their integration into existing power systems presents several technical and operational challenges due to their intermittent and unpredictable nature [1, 2].

Wind energy depends on atmospheric conditions and varies with wind speed, while solar energy generation is influenced by solar irradiance, time of day, and weather conditions. As a result, standalone utilization of either source often leads to fluctuations in power output, making it difficult to ensure a continuous and reliable energy supply. To overcome these limitations, hybrid renewable energy systems that combine wind and solar power have gained considerable attention. The complementary characteristics of wind and solar energy—where solar power is typically available during the day and wind energy can be stronger at night or during different seasons—help in balancing overall energy generation and improving system reliability [3].

Despite the advantages of hybrid systems, the mismatch between energy generation and load demand remains a critical issue. This is where battery energy storage systems (BESS) play a vital role. Battery storage allows excess energy generated during peak production periods to be stored and utilized during periods of low generation or high demand. By acting as a buffer, batteries enhance the stability, reliability, and efficiency of hybrid renewable energy systems. Moreover, they contribute to voltage and frequency regulation, reduce power fluctuations, and improve overall power quality in both grid-connected and standalone systems [4, 5].

Various types of batteries are employed in renewable energy applications, including lithium-ion, lead-acid, sodium-sulfur, and flow batteries. Among these, lithium-ion batteries are widely preferred due to their high energy density, longer lifecycle, and fast charging capabilities. However, factors such as cost, safety, environmental impact, and degradation over time must be carefully considered when selecting appropriate storage technology. In addition to hardware advancements, effective energy management strategies are essential to optimize the performance of hybrid systems. Techniques such as load forecasting, demand-side management, and intelligent control algorithms help in efficiently coordinating power generation, storage, and consumption [6].

Recent developments in advanced technologies, including artificial intelligence, machine learning, and heuristic optimization methods, have further enhanced the capabilities of hybrid renewable systems. These approaches enable accurate prediction of energy generation and demand, optimal sizing of system components, and real-time decision-making for efficient energy utilization. Furthermore, the integration of smart grid technologies and Internet of Things (IoT)-based monitoring systems has improved system automation, reliability, and scalability [7, 8].

In this context, hybrid wind–solar energy systems integrated with battery storage represent a promising solution for addressing modern energy challenges. They offer a reliable, cost-effective, and environmentally sustainable approach for power generation, particularly in remote and off-grid regions where conventional grid infrastructure is limited or unavailable. This review aims to provide a comprehensive analysis of such systems, covering their design, technologies, control strategies, challenges, and future prospects, thereby contributing to the advancement of clean energy solutions [9].

II. LITERATURE REVIEW

M. M. Gulzar et al. (2023) presented an innovative converter-less control strategy for a grid-connected hybrid renewable energy system integrating solar photovoltaic (PV), wind energy, and fuel cells with battery energy storage. The primary contribution of this work lies in eliminating the need for conventional DC–DC and DC–AC converters, which are typically associated with increased system complexity, switching losses, and cost. By employing a direct control mechanism, the proposed system enhances overall efficiency and reduces power conversion stages. Additionally, the integration of battery storage ensures continuous power supply during fluctuations in renewable generation. The authors demonstrated improved dynamic response and system stability under varying environmental conditions, making the approach highly suitable for modern hybrid renewable energy applications.

S. Bhattacharyya et al. (2022) investigated the operation of a grid-connected hybrid system comprising PV, wind energy, and battery storage using a Doubly Fed Induction Generator (DFIG). The study focused on developing a coordinated control strategy to manage power flow between different sources and the grid efficiently. The proposed system effectively balances active and reactive power, enhances voltage regulation, and ensures stable operation during transient conditions. The inclusion of battery storage improves load leveling and mitigates intermittency issues associated with renewable sources. The results highlight the suitability of DFIG-based systems for large-scale renewable integration and their potential role in smart grid applications.

N. K. Kulkarni et al. (2022) explored passive islanding detection techniques in distributed generation systems involving renewable energy sources. The study analyzed various inverter configurations, including single-point single-inverter, single-point multi-inverter, and multi-point multi-inverter scenarios. The authors identified key performance indicators such as voltage, frequency deviation, and harmonic distortion to detect islanding conditions effectively. Their findings contribute significantly to improving the safety and reliability of grid-connected hybrid systems, as undetected islanding can lead to equipment damage and safety hazards. This work is particularly relevant for hybrid wind–solar systems where multiple distributed sources are connected to the grid.

M. Li et al. (2022) proposed a wind speed correction method based on a modified Hidden Markov Model (HMM) to enhance the accuracy of wind power forecasting. Accurate prediction of wind speed is critical for optimizing energy generation and scheduling battery storage usage in hybrid systems. The proposed model effectively captures the stochastic nature of wind behavior and reduces forecasting errors compared to traditional models. Improved prediction accuracy enables better energy management, reduces uncertainty, and enhances the overall efficiency of wind–solar hybrid systems integrated with battery storage.

Z. Tang et al. (2022) provided an in-depth discussion on the role of power electronics as a key enabling technology for renewable energy integration. The paper highlights advancements in converter and inverter technologies, control strategies, and switching techniques that facilitate efficient energy conversion and grid synchronization. The authors emphasized that modern power electronic systems are essential for handling the variability and intermittency of renewable sources such as wind and solar. Their work underscores the importance of robust and efficient power electronic interfaces in ensuring the reliable operation of hybrid renewable systems with battery storage.

P. Roy et al. (2022) presented a comprehensive review of wind–solar hybrid renewable energy systems, covering system configurations, design methodologies, performance analysis, and optimization techniques. The study discussed the advantages of hybridization in reducing intermittency and improving overall energy reliability. It also examined various energy storage options, including batteries, and their role in enhancing system performance. The authors highlighted key challenges such as cost, sizing, and control complexity, while also identifying future research directions. This work serves as a foundational reference for understanding the integration of battery storage in hybrid renewable systems.

G. An et al. (2021) developed a hybrid forecasting model combining Particle Swarm Optimization (PSO), Extreme Learning Machine (ELM), and AdaBoost algorithm for short-term wind power prediction. The integration of multiple machine learning techniques significantly improves prediction accuracy and reduces computational complexity. Accurate forecasting is essential for efficient energy scheduling and battery management in hybrid systems. The proposed approach demonstrates superior performance compared to traditional methods, making it a valuable contribution to renewable energy forecasting and optimization.

R. B. Bollipo et al. (2021) conducted a detailed review of Maximum Power Point Tracking (MPPT) techniques used in photovoltaic systems. The study compared classical methods such as Perturb and Observe (P&O) with advanced intelligent techniques including fuzzy logic, neural networks, and hybrid approaches. The authors evaluated these methods based on tracking efficiency, response time, and implementation complexity. Efficient MPPT is crucial for maximizing solar energy extraction, which directly impacts the performance of hybrid wind–solar systems integrated with battery storage.

T. Hong et al. (2021) introduced a relaxed PV bus model for linear power flow analysis in power systems. The proposed model simplifies the mathematical representation of PV buses, reducing computational complexity while maintaining acceptable accuracy. This approach is particularly useful for large-scale power systems with high penetration of renewable energy sources. The model facilitates efficient planning and operation of hybrid renewable systems, contributing to improved grid stability and performance.

S. Xu et al. (2021) proposed a single-phase grid-connected photovoltaic system using a Golden Section Search-based MPPT algorithm. The method enhances tracking accuracy and speed, enabling optimal power extraction under varying environmental conditions. The study demonstrated improved system efficiency and reduced power losses compared to conventional MPPT techniques. This work is significant for hybrid renewable systems, as efficient solar energy utilization directly influences battery storage performance and overall system reliability.

III. KEY POWER CONVERTER FEATURES FOR EV CHARGING SYSTEMS

In order to effectively accomodate the specifications/battery voltages of the commercially available EVs and available power source (single- and/or three-phase), while efficiently charging the EV battery and supporting the utility grid, some essential features of the power converters are summarized herewith:

1. Power factor: A high power factor near unity is essential for EV charging to maximize energy efficiency, minimize power losses, optimize power grid utilization, and reduce overall electricity consumption and cost.
2. Single and three-phase power converters: Single-phase PFC rectifiers are commonly used for onboard EV charging due to their compactness and lightweight design, making them suitable for charging from a standard household outlet. On the other hand, three-phase PFC rectifiers are used for off-board EV charging, as they provide higher power output, making them suitable for fast charging stations with high charging demands.
3. Bidirectional power flow: A bidirectional power converter is crucial for both G2V charging and V2G discharging processes in EVs. It includes components such as an AC-to-DC converter, DC-to-DC converter, and DC-to-AC inverter. It efficiently manages the bidirectional flow of electricity, complies with safety standards, and incorporates advanced control algorithms for seamless communication between the EV, the grid, and the converter.
4. Wide voltage range: EV chargers must provide a wide range of output DC voltage to accommodate different nominal battery voltage levels. To meet this requirement, EV chargers must be designed with efficient and reliable voltage regulation and current control mechanisms, ensuring safe and optimal charging performance for different EVs and batteries.

IV. BATTERY MODEL

Simple battery models are composed of the ideal voltage source (open circuit voltage (OCV)) Voc connected in series with the constant internal resistance R0 as shown in Figure 1. Simple battery model parameters are constant and do not depend on the SOC [13]. This model is not capable of describing the voltage profile for the charging and discharging process [14]. Hence, this model work appropriate when the dependency on SOC is not essential energy released from the battery is supposed to be infinite [15]. In practical conditions, internal resistance changes concerning the change in load. The advanced simple battery model is obtained by adding dependency of internal resistance on the SOC and temperature. These models represent the static behavior of the battery. Many researchers have utilized this model for monitoring of battery, but this model did not explain the capacitance effect for representing transient current conditions. Modeling of the lead-acid battery used in various application such as uninterpretable power supply is performed by using this battery model.

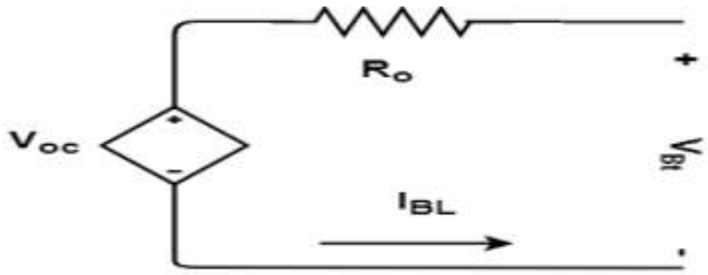

Figure 1: Simple battery model

V. PV ARRAY

The photovoltaic cell converts the light energy into electrical energy depending on the irradiation of the sun and temperature in the atmosphere. Basically PVC is a PN junction diode. But in PN junction diode DCI AC source is needed to work, but here light energy is used as a source to produce DC output. PVC is a current control source not a voltage control source. The equivalent electrical circuit diagram of PVC is shown in the Figure 2.

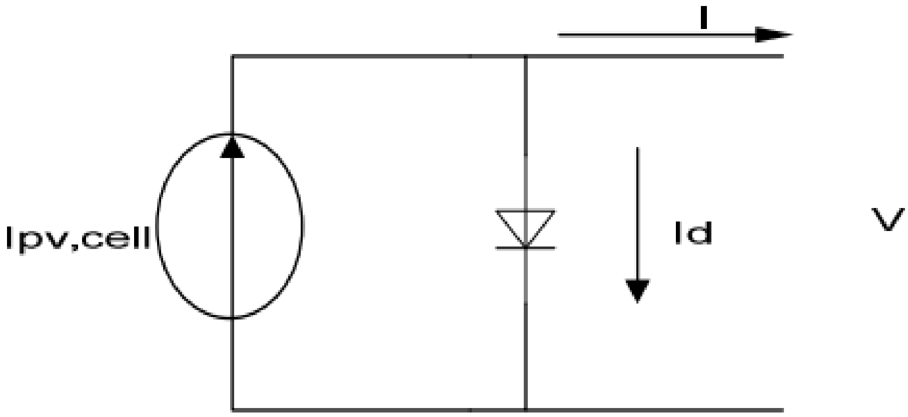

Figure 2: Show ideal photovoltaic cell equivalent circuit

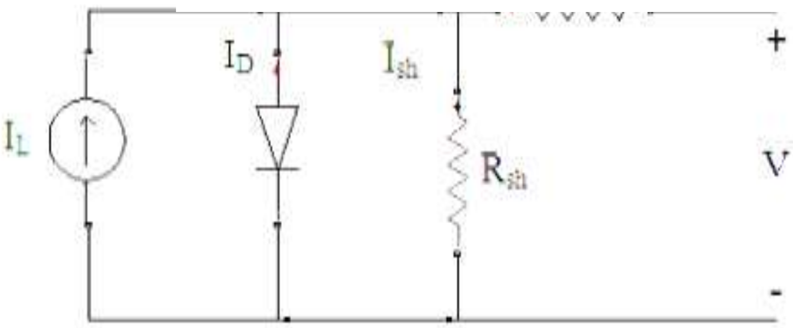

Figure 3: Equivalent Electrical Circuit of PVC

$I_D = I_0[\exp(V + IR_S)/KT - 1]$ (1)

Therefore PVC output current is given in equation 2.

$I = I_L - I_D - I_{Sh}$ (2)

$$I = I_L - I_0[\exp(q(V + IR_S)) / KT - 1] - (V + IR_S) / R_{Sh} \quad (3)$$

Where I_D the diode is current, R_{sh} is the shunt resistance, I_L is the light generated current of solar array. Solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted electricity through photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor are absorbed and create some electron-hole pairs proportional to the incident irradiation. Under the influence of the internal electric fields of the p-n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar insolation. PV system naturally exhibits a nonlinear I-V and P-V characteristics which vary with the radiant intensity and cell temperature.

WIND ENERGY

Wind energy has emerged as one of the most reliable and rapidly growing renewable energy sources, offering a clean and sustainable alternative to conventional fossil fuels. It plays a crucial role in reducing greenhouse gas emissions, minimizing environmental impact, and supporting global efforts toward energy transition. Modern wind turbine technologies, improved aerodynamic designs, and advanced control systems have significantly enhanced energy conversion efficiency and power output.

Moreover, wind energy systems are highly scalable and can be deployed in both onshore and offshore environments, making them suitable for diverse geographical conditions. Integration with hybrid systems, such as wind–solar combinations and battery storage, further improves energy reliability and addresses intermittency issues. However, challenges such as variability in wind speed, high installation costs, noise, and land usage constraints still need to be addressed.

VI. CONCLUSION

Hybrid wind–solar energy systems integrated with battery storage represent a highly promising solution for achieving reliable, efficient, and sustainable power generation. This review highlights that combining wind and solar resources effectively mitigates the intermittency associated with individual renewable sources, while battery storage enhances energy reliability, stability, and grid independence. Various system configurations, control strategies, and optimization techniques discussed in the literature demonstrate significant improvements in power quality, load balancing, and overall system efficiency.

Furthermore, advancements in power electronics, energy management systems, and intelligent control algorithms—particularly those based on machine learning—have contributed to more adaptive and cost-effective hybrid systems. Despite these advantages, challenges such as high initial investment, battery degradation, and complex system design remain critical concerns that require further research and innovation.

Overall, hybrid wind–solar systems with battery storage play a vital role in the transition toward clean and decentralized energy systems, especially in remote and off-grid areas. Future research should focus on improving battery technologies, developing advanced predictive control models, reducing system costs, and enhancing scalability to support widespread adoption and integration into smart grid infrastructures.

REFERENCES

[1] M. M. Gulzar, A. Iqbal, D. Sibtain, and M. Khalid, "An innovative converterless solar PV control strategy for a grid connected hybrid PV/Wind/Fuel-Cell system coupled with battery energy storage," *IEEE Access*, vol. 11, pp. 23245–23259, 2023.

[2] S. Bhattacharyya, S. Puchalapalli, and B. Singh, "Operation of grid-connected PV-battery-wind driven DFIG based system," *IEEE Transactions on Industry Applications*, vol. 58, no. 5, pp. 6448–6458, 2022.

[3] N. K. Kulkarni and M. Khedkar, "Determining potential passive islanding detection indicators for single-point single inverter, single-point multi-inverter and multi-point multi-inverter scenarios," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 3, pp. 696–709, 2022.

[4] M. Li, M. Yang, Y. Yu, and W. J. Lee, "A wind speed correction method based on modified hidden Markov model for enhancing wind power forecast," *IEEE Transactions on Industry Applications*, vol. 58, no. 1, pp. 656–666, 2022.

[5] Z. Tang, Y. Yang, and F. Blaabjerg, "Power electronics: The enabling technology for renewable energy integration," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 1, pp. 39–52, 2022.

[6] P. Roy, J. He, T. Zhao, and Y. V. Singh, "Recent advances of wind-solar hybrid renewable energy systems for power generation: A review," *IEEE Open Journal of the Industrial Electronics Society*, vol. 3, no. 4, pp. 81–104, 2022.

[7] G. An, Z. Jiang, X. Cao, Y. Liang, Y. Zhao, Z. Li, W. Dong, and H. Sun, "Short-term wind power prediction based on particle swarm optimization-extreme learning machine model combined with Adaboost algorithm," *IEEE Access*, vol. 9, pp. 94040–94052, 2021.

[8] R. B. Bollipo, S. Mikkili, and P. K. Bonthagorla, "Hybrid, optimal, intelligent and classical PV MPPT techniques: A review," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 1, pp. 9–33, 2021.

[9] T. Hong, D. Zhao, and Y. Zhang, "A relaxed PV bus model in linear power flow," *IEEE Transactions on Power Delivery*, vol. 36, no. 2, pp. 1249–1252, 2021.

[10] S. Xu, R. Shao, B. Cao, and L. Chang, "Single-phase grid-connected PV system with golden section search-based MPPT algorithm," *Chinese Journal of Electrical Engineering*, vol. 7, no. 4, pp. 25–36, 2021.

[11] J. Pahasa and I. Ngamroo, "Two-stage optimization based on SOC control of SMES installed in hybrid wind/PV system for stabilizing voltage and power fluctuations," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 8, 2021.

[12] L. E. Mathew and A. K. Panchal, "A complete numerical investigation on implicit and explicit PV single-diode-models using I- and V-approaches," *IEEE Journal of Photovoltaics*, vol. 11, no. 3, pp. 827–837, 2021.

[13] A. Zahedmanesh, K. M. Muttaqi, and D. Sutanto, "A sequential decision-making process for optimal technoeconomic operation of a grid-connected electrical traction substation integrated with solar PV and BESS," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 2, pp. 1353–1364, 2021.

[14] Y. Jin, D. Wu, P. Ju, C. Rehtanz, F. Wu, and X. Pan, "Modeling of wind speeds inside a wind farm with application to wind farm aggregate modeling considering LVRT characteristic," *IEEE Transactions on Energy Conversion*, vol. 35, no. 1, 2020.

[15] Z. Kan, Z. Li, S. Li, T. Zhang, D. Zhu, M. Yi, and Y. Huang, "Research on grid-connected/islanded control strategy of PV and battery storage systems as emergency power supply of pumping storage power station," in *Proc. IEEE 3rd Int. Conf. Electronics Technology (ICET)*, pp. 457–462, 2020.