AI-Controlled Wind Turbine Systems: Integrating IoT and Machine Learning for Smart Grids

Madeswaran. A[1], Deepa Bisht [2], Dr. S. Yuvaraj[3], M. Udayapal Reedy[4], Kassem AL-Attabi[5], and Anishkumar Dhablia[6]

[*]*Associate Professor, Scool of Business and Management, Christ university, Yeshwanthpur Campus, Bengaluru.*
[†]*Department of Management*
Uttaranchal Institute of Management, Uttaranchal University, Dehradun-248007, India
[‡]*Assistant Professor,Department of ECE,Prince Shri Venkateshwara Padmavathy Engineering College, Chennai - 127*
[§]*Department of Computer Science & Engineering, IES College of Technology,IES University, Bhopal, Madhya Pradesh 462044 India.*
[**]*The Islamic university, Najaf, Iraq*
[6]*Engineering Manager, Altimetrik India Pvt Ltd, Pune, Maharashtra, India*
anishdhablia@gmail.com

Abstract. Advances in renewable energy technologies are pivotal in addressing the challenges posed by the depletion of traditional energy sources and their associated environmental impacts. Among these, wind energy stands out as a promising avenue, with wind turbine farms proliferating globally. However, the unpredictable nature of wind and intricate interplay between turbines necessitate innovative solutions for efficient operation and maintenance. This paper reviews advancements in intelligent control systems, notably those proposed by Smart Wind technologies. These systems leverage a network of sensors and IoT devices to gather real-time data, such as wind speed, temperature, and humidity, to optimize turbine performance. A significant focus is on turbines employing doubly-fed induction generators, which offer benefits like adjustable speed and consistent frequency operation. Their integration into smart grids

[*]Corresponding Authour *:madeswaran.a@christ university.in*

[†]*Deepabisht.bisht28@gmail.com*

[‡]*S.Yuvaraj_ece@psvpec.in*

[§]*research@iesbpl.ac.in*
[**]*kassem.alattabi@iunajaf.edu.iq*

introduces challenges concerning power system dynamics' security and reliability. This review delves into the dynamics, characteristics, and potential instabilities of such integrations, emphasizing the uncertainties in wind and nonlinear load predictions. A noteworthy finding is the rising prominence of artificial intelligence, particularly machine and deep learning, in predictive diagnostics. These methodologies offer cost-effective, accurate, and efficient solutions, holding potential for enhancing power system stability and accuracy in the smart grid context.

1 Introduction

The global energy landscape is undergoing a significant transformation, driven by the pressing need for sustainable and clean energy solutions. As traditional energy sources deplete and environmental concerns mount, the focus has shifted towards harnessing renewable energy sources, with wind power emerging as a frontrunner. Wind turbine farms, established worldwide, symbolize humanity's endeavor to tap into the immense potential of wind as a renewable energy source. However, the very nature of wind, characterized by its unpredictability, coupled with the intricate dynamics between turbines in a farm, presents multifaceted operational and maintenance challenges.

To navigate these challenges, the integration of advanced technologies, particularly the Internet of Things (IoT) and machine learning (ML), has been proposed. These intelligent control systems, equipped with a network of sensors and IoT devices, are designed to collect real-time data on various parameters, such as wind speed, temperature, and humidity. By processing this data through ML algorithms, these systems can forecast wind conditions, predict potential turbine failures, and optimize turbine operations. Such advancements not only enhance the efficiency and reliability of wind energy generation but also promise reduced maintenance costs and minimized environmental impacts.

Furthermore, the global energy statistics highlight a paradigm shift in energy consumption patterns. The decline in coal-generated power and the optimistic rise in green energy generation underscore the world's commitment to a sustainable future. With wind energy's increasing integration into the smart grid, there arises a need to understand its influence on the stability of electrical systems, especially in industrial applications. The use of doubly-fed induction generators (DFIGs) in wind turbines, for instance, brings forth unique challenges and opportunities. While DFIGs offer several advantages, their increasing presence in the smart power grid necessitates further exploration into their potential contributions to stabilization and overall system reliability.

Machine and deep learning methodologies present promising solutions to address the challenges associated with smart grid-integrated wind power systems. By leveraging artificial intelligence, it becomes possible to develop diagnostic tools that are not only cost-effective and accurate but also capable of handling complex optimization challenges. As this review will elucidate, the integration of AI methodologies in wind energy systems can lead to enhanced power tracking and reduced discrepancies in anticipated datasets. As we delve deeper into the intricacies of wind energy and its integration into smart grids, this paper aims to provide a comprehensive assessment of the current state of the art and chart a path forward for future advancements in the field.

2 Review and discussions

The research by Radhakrishnan et al. (2023) underscores the pivotal role of integrating IoT and machine learning in enhancing the efficiency and reliability of wind turbine farms [1].Their comprehensive literature review highlights various methodologies and their respective merits and demerits. As we delve deeper into the realm of renewable energy, it becomes imperative to harness the power of technology to address the challenges posed by the unpredictable nature of wind. The insights from this study provide a solid foundation for our review article, emphasizing the importance of intelligent control systems in the future of wind energy. Below are the key findings of the study in table 1:

Table 1. Key findings of the study by Radhakrishnan et al. (2023) [3-5]

Method/Technique	Key Findings	Challenges/Technology Gaps	Advantages
Intelligent Fault Diagnosis for Wind Turbine Generators	Utilizes multi-feature fusion to improve accuracy.	Requires significant data to train the ML models.	Gradient boosting decision tree improves learning ability.
Wind Turbine Fault Diagnosis Method	Highly accurate in detecting faults.	Requires significant computational resources to train the ML models.	Use of Deep Belief Network (DBN) improves learning ability.
Wind Power Forecasting Method	Highly accurate in forecasting wind power.	Requires significant data to train the ML models.	Use of Deep Residual Networks (DRN) improves learning ability.
Intelligent Control Techniques for Wind Turbine Systems	Comprehensive review of control approaches.	Not focused on IoT, limiting its relevance to this literature survey.	Provides insight into the use of ML techniques.
IoT-based Monitoring and Control System for Wind Turbine Farm	Use of a cloud-based IoT platform enables remote monitoring and control.	Does not discuss specific ML techniques used for control.	Enables efficient remote monitoring and control of wind turbine farms.

While our primary focus revolves around fuel cells and green hydrogen production, the integration and optimization of renewable energy sources, such as wind power, play a crucial role in the broader context of sustainable energy solutions. Radhakrishnan's exploration into the intelligent control systems for wind turbine farms, leveraging IoT and machine learning, provides valuable insights into the technological advancements and challenges in harnessing renewable energy efficiently.

Furthermore, as the global energy landscape shifts towards more sustainable solutions, the integration of wind energy with other renewable sources becomes essential. The methodologies and findings from Radhakrishnan's study can offer a blueprint for similar advancements in other renewable energy sectors, including solid oxide fuel cells. The emphasis on machine learning and IoT in optimizing wind turbine operations parallels the potential applications of these technologies in enhancing the efficiency and reliability of fuel cells and hydrogen production systems.

In essence, while Radhakrishnan's study is centred on wind energy, the underlying themes of technological integration, optimization, and addressing challenges resonate deeply with our review's objective. The convergence of these technologies and methodologies can pave the way for a holistic and integrated approach to green energy solutions in the future.

In another study by Behara et al. (2022) the research delves into the application of Artificial Intelligence (AI) control systems in smart grids, particularly focusing on Doubly Fed Induction Generator (DFIG)-based wind turbines [2]. Wind-driven turbines, especially those utilizing doubly-fed induction generators in line with the IEC 61400 series standards, have garnered attention due to their numerous advantages. These include adjustable speed, consistent frequency mode of operation, independent capabilities for voltage and frequency control, and maximum power point tracking at the point of connection. However, integrating such resources into the existing smart grid system presents challenges related to the security and reliability of power system dynamics. The study emphasizes the potential of enhancing DFIG control systems, especially in the context of smart grid-integrated power systems. The findings of the review highlight the prominence of AI-based machine and deep learning predictive diagnosis in this domain, primarily due to their cost-effectiveness, reduced infrastructure needs, swift diagnostic time, and high accuracy levels. These methodologies can be extended to the smart grid-integrated power context, paving the way for the development of practical diagnostic tools that can bolster the accuracy and stability of the power system [6-10]. Key findings are tabulated below in table 2:

Table 2. Key findings of the study by Behara et al. (2022) [6-10]

Methodologies	Key Findings	Challenges/Technology Gaps	Advantages
Wind-driven turbines with DFIG	Gained attention due to benefits like adjustable speed, consistent frequency mode, and maximum power point tracking.	Integration into the smart grid system can lead to security and reliability issues.	Enhanced control, active and reactive power controls, and self-governing capabilities for voltage and frequency.
AI in DFIG control systems	AI-based machine and deep learning predictive diagnosis fields are gaining prominence.	Need for advancements in wind turbine-operated DFIG control systems.	Low cost, reduced infrastructure, swift diagnostic time, and high accuracy.
Smart grid-integrated power system	Assesses dynamics, characteristics, and causes of instabilities.	Instabilities arise from unclear wind and nonlinear load predictions.	Potential for creating a framework for practical and ac

The insights from Behara et al. (2022) offer a comprehensive understanding of the potential and challenges of integrating AI control systems in smart grids, especially concerning DFIG-based wind turbines. Their research underscores the transformative power of AI in enhancing the efficiency, reliability, and stability of modern power systems. As we delve deeper into our review article, it becomes evident that the fusion of AI methodologies with traditional power systems is not just a trend but a necessity. The advancements and solutions proposed in their study can serve as a foundation for future research and applications in the realm of smart grids and renewable energy sources. Their emphasis on the importance of AI-based predictive diagnosis and the potential of machine and deep learning methodologies resonates with the broader themes of our review, highlighting the pivotal role of AI in shaping the future of energy systems.

The intricate interplay between AI methodologies and DFIG-based wind turbines, as elucidated by Beharaet al. (2022), underscores a broader narrative of technological convergence in the renewable energy sector. As the global push towards sustainable energy solutions intensifies, the integration of intelligent systems becomes paramount in addressing the multifaceted challenges of energy production, distribution, and consumption. The study serves as a testament to the transformative potential of AI in redefining the paradigms of energy systems. Drawing parallels from their research, our review article emphasizes the need for continuous innovation and interdisciplinary collaboration. By harnessing the insights from such pioneering studies, we can chart a roadmap for a future where energy systems are not only efficient and reliable but also adaptive and resilient, catering to the dynamic needs of a rapidly evolving global landscape.

3 Future Scope of Research

The realm of renewable energy, particularly focusing on solid oxide fuel cells, electrolyzes, and green hydrogen production, is burgeoning with potential. As the global community pivots towards sustainable energy solutions, the need for innovative research in this domain becomes paramount. The following pointers elucidate potential avenues for future exploration, building upon the foundation laid by existing studies.

- **Integration of Multiple Renewable Sources:** Investigate the feasibility and efficiency of integrating wind energy with other renewable sources, such as solar and hydro, to create a more robust and resilient energy grid.
- **Advanced AI Algorithms:** Delve deeper into the development of sophisticated AI algorithms that can further enhance the predictive accuracy and operational efficiency of renewable energy systems.
- **Material Innovations:** Research on novel materials for solid oxide fuel cells that can operate at lower temperatures, thereby increasing efficiency and lifespan.
- **Green Hydrogen Storage:** Explore advanced storage solutions for green hydrogen to address challenges related to its low energy density and high flammability.
- **Decentralized Energy Systems:** Study the potential of microgrids and decentralized energy systems that harness renewable sources, ensuring energy security even in remote regions.

The integration of digital twin technology with renewable energy systems presents a promising avenue for future research. Digital twins, essentially virtual replicas of physical systems, can offer real-time monitoring, predictive analysis, and advanced simulations for renewable energy infrastructures. By harnessing the power of digital twins, researchers can simulate various scenarios, test new innovations in a risk-free environment, and optimize operations based on real-time data. This convergence of digitalization and renewable energy can revolutionize the way we design, implement, and manage sustainable energy solutions, ensuring that they are not only efficient but also adaptable to the ever-evolving global energy demands.

4 Knowledge Gaps

While the strides made in the domain of renewable energy are commendable, there remain certain knowledge gaps that need addressing. These gaps, if bridged, can pave the way for more holistic and comprehensive solutions in the future. Herein, we highlight some of these areas of potential exploration.

- **Real-time Data Processing:** Despite advancements in IoT and machine learning, real-time data processing and instantaneous decision-making in dynamic environments remain a challenge.
- **Interdisciplinary Collaboration:** There's a noticeable gap in collaborative research that merges the expertise of material scientists, AI experts, and energy engineers to create integrated solutions.
- **Economic Viability:** While technological solutions exist, their economic viability, especially in developing regions, needs further exploration.
- **Environmental Impact:** The long-term environmental impact of large-scale adoption of solid oxide fuel cells and green hydrogen production is not yet fully understood.
- **Regulatory Frameworks:** As the energy landscape evolves, there's a need for updated regulatory frameworks that can accommodate and promote the adoption of these advanced renewable energy solutions.

By addressing these future scopes and knowledge gaps, the research community can propel the renewable energy sector into a new era of sustainability, efficiency, and innovation.

5 Conclusion

The exploration into the realm of renewable energy, with a specific emphasis on AI-Controlled Wind Turbine Systems integrating IoT and Machine Learning for Smart Grids, has unveiled a plethora of insights and potential avenues for future research. As we culminate our review, it's imperative to encapsulate the key findings that have emerged from our comprehensive study:

- **Integration Imperative:** The seamless integration of renewable energy sources, especially wind energy with other forms, is crucial for a robust and resilient energy grid. This integration is pivotal for addressing the challenges posed by the unpredictable nature of renewable sources.
- **AI's Transformative Role:** Advanced AI algorithms, especially in the context of wind energy systems, have the potential to revolutionize predictive accuracy and operational efficiency, underscoring the importance of intelligent control systems in the future of renewable energy.
- **Material Innovations:** The quest for novel materials for solid oxide fuel cells can lead to breakthroughs in efficiency and longevity, offering sustainable energy solutions that are both effective and durable.

- **Green Hydrogen's Potential:** The production and storage of green hydrogen emerge as a promising frontier, with its potential to serve as a clean and efficient energy carrier, bridging the gap between energy production and consumption.
- **Economic and Environmental Balance:** While technological advancements are paramount, their economic viability and long-term environmental impact need to be at the forefront of research considerations, ensuring a balance between innovation and sustainability.
- **Regulatory Evolution:** The dynamic nature of the renewable energy landscape necessitates evolving regulatory frameworks that promote and accommodate the rapid advancements in the sector.

In essence, our review underscores the transformative potential of integrating AI, IoT, and machine learning with wind turbine systems for smart grids. As highlighted in our abstract, this paper reviews the pioneering work in the areas of AI-controlled wind turbine systems, intelligent control systems, and the challenges and solutions therein. The future of smart grid solutions hinges on continuous innovation, interdisciplinary collaboration, and a holistic approach that encompasses technological, economic, and environmental considerations.

References

1. Radhakrishnan, S., Jasmin, M., Senthilkumar, K. K., & Vanitha, M. (2023). Intelligent Control System for Wind Turbine Farms Using IoT and Machine Learning. In E3S Web of Conferences (Vol. 387, p. 04004). EDP Sciences.
2. Behara, R. K., & Saha, A. K. (2022). artificial intelligence control system applied in smart grid integrated doubly fed induction generator-based wind turbine: A review. Energies, 15(17), 6488.
3. Muthuvel, K., & Vijayakumar, M. (2020). Solar PV sustained quasi Z-source network-based unified power quality conditioner for enhancement of power quality. Energies, 13(10), 2657.
4. Park, J. S., Lee, K., Lee, K., Lee, J., Lee, J. Y., &Yoo, H. J. (2019). J of Electrical Eng and Technology, 14(6), 2696-2705. https://doi.org/10.1007/s42835-019-00036-z
5. Wei, Y., Xu, C., Zhang, Q., & Tang, Y. (2019). App Energy, 252, 113486. doi: 10.1016/j.apenergy.2019.113486
6. Aurangzeb, M., Ai, X., Hanan, M., Jan, M. U., Rehman, H. U., & Iqbal, S. (2019, November). Single algorithm mpso depend solar and wind mppt control and integrated with fuzzy controller for grid integration. In 2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2) (pp. 583-588). IEEE.
7. Kim, C., & Kim, W. (2020). Coordinated fuzzy-based low-voltage ride-through control for PMSG wind turbines and energy storage systems. IEEE Access, 8, 105874-105885.
8. Xu, H., Zhang, Y., Li, Z., Zhao, R., & Hu, J. (2020). Reactive current constraints and coordinated control of dfig'srsc and gsc during asymmetric grid condition. IEEE Access, 8, 184339-184349.
9. Qiao, W., Liang, J., Venayagamoorthy, G. K., & Harley, R. (2011, July). Computational intelligence for control of wind turbine generators. In 2011 IEEE power and energy society general meeting (pp. 1-6). IEEE.

10. Zhou, D., Blaabjerg, F., Lau, M., & Tønnes, M. (2014). Optimized reactive power flow of DFIG power converters for better reliability performance considering grid codes. IEEE Transactions on Industrial Electronics, 62(3), 1552-1562.
11. Brearley B.J., Bose K.R., Senthil K., Ayyappan G.,(2022),"KNN APPROACHES BY USING BALL TREE SEARCHING ALGORITHM WITH MINKOWSKI DISTANCE FUNCTION ON SMART GRID DATA",Indian Journal of Computer Science and Engineering,Vol.13,no.4,pp.1210-1226.doi:10.21817/indjcse/2022/v13i4/221304179
12. Sunder Selwyn T., Hemalatha S.,(2020),"Condition monitoring and vibration analysis of asynchronous generator of the wind turbine at high uncertain windy regions in India",Materials Today: Proceedings,Vol.46,pp.3639-3643.doi:10.1016/j.matpr.2021.01.656