Optimization of Gearless Wind Power Conversion Systems: Reducing Mechanical Losses and Improving Reliability

[1]Dr. N.Kalyana Sundaram, [2]Titus Richard, [3]Dr. M. B. Chaudhari, [4]Neeraj Varshney, [5]N.T.Velusudha, [6]Dr. Naveen Jain, [7]S.Tharmar

[*]*Professor,Department of IT,New Prince Shri Bhavani College of Engineering and Technology, Chennai-600073,Tamil nadu,India*
[2]*Vels Institute of Science, Technology & Advance Studies*
Velan Nagar, Pallavaram, Chennai - 600117, India
titusrichad@gmail.com
[3]*Mechanical Department,Vishwakarma Institute of Technology Pune India*
mangesh.chaudhari@vit.edu
[4]*Department of Computer Engineering & Applications, GLA University, Mathura,*
neeraj.varshney@gla.ac.in
[5] *Assistant Professor,Department of ECE,Prince Shri Venkateshwara Padmavathy Engineering College, Chennai - 127.,n.t.velusudha _ece@psvpec.in*
[6]*Associate Professor, Shri Shankaracharya Institute of Professional Management & Technology, Raipur, n.jain@ssipmt.com*
[7]*Associate professor Mohamed Sathak Engineering College, Kilakarai*
tharmar11585@gmail.com

Abstract. This research focuses on optimizing gearless wind power conversion systems to reduce mechanical losses and increase overall reliability. Gearless systems offer substantial advantages over standard geared turbines, such as fewer maintenance requirements and higher efficiency. However, mechanical losses and reliability concerns still represent significant impediments to their wider deployment. This work analyzes sophisticated optimization techniques and design improvements aimed at lowering mechanical losses in essential components. Additionally, it studies strategies to boost system stability, ensuring consistent and long-term performance. Through a combination of analytical modelling, simulations, and experimental validation, the research indicates the potential for considerable increases in energy efficiency and system durability. The findings contribute to the development of more robust and efficient wind power systems, coinciding with worldwide goals to expand renewable energy usage and reduce dependency on fossil fuels.

Kewords. Gearless wind turbines, mechanical losses, system optimization, reliability improvement.

1 Introduction

Wind energy has emerged as a vital component in the global transition towards renewable energy, giving a sustainable and ecologically acceptable alternative to fossil fuels. Among the different technologies in wind power generation, gearless wind turbines have attracted

[*] nksundar@newprinceshribhavani.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

attention due to their inherent advantages, including decreased maintenance requirements, lower noise levels, and improved energy efficiency compared to standard geared systems. However, despite these improvements, gearless systems still confront hurdles, particularly in the areas of mechanical losses and system reliability. These concerns can severely impair the efficiency and lifespan of wind turbines, limiting their efficacy and economic viability. This research intends to overcome these problems by focusing on the optimization of gearless wind power conversion systems. By lowering mechanical losses and boosting dependability, the study hopes to enhance the performance and durability of these systems, contributing to more efficient and reliable wind energy generation. This work is particularly pertinent since the demand for cleaner and more efficient energy sources continues to grow, and optimizing gearless wind turbines could play a crucial role in fulfilling global energy needs [1-6]. Figure 1 illustrates the WECS model.

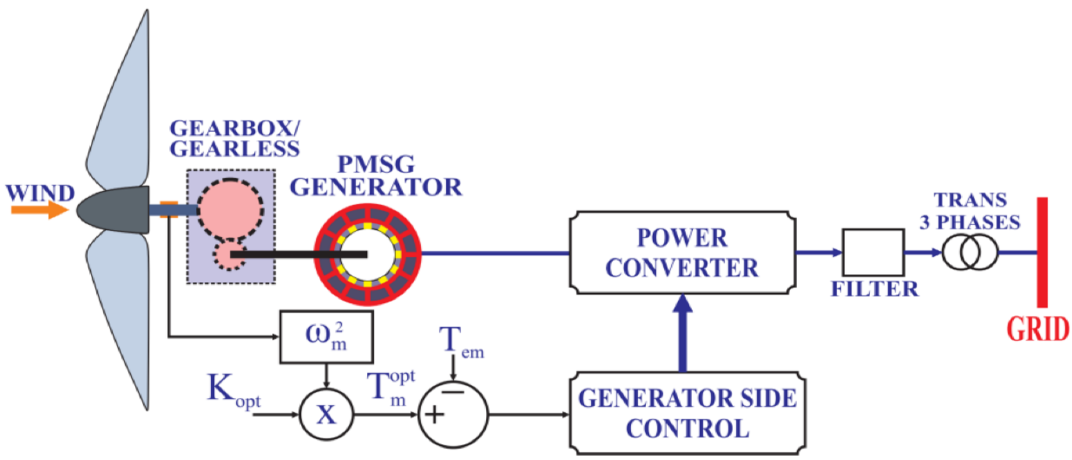

Fig 1. WECS model

1.1 Background

Wind energy has emerged as a vital component in the global transition towards renewable energy, giving a sustainable and ecologically acceptable alternative to fossil fuels. Among the different technologies in wind power generation, gearless wind turbines have attracted attention due to their inherent advantages, including decreased maintenance requirements, lower noise levels, and improved energy efficiency compared to standard geared systems. However, despite these improvements, gearless systems still confront hurdles, particularly in the areas of mechanical losses and system reliability. These concerns can severely impair the efficiency and lifespan of wind turbines, limiting their efficacy and economic viability. This research intends to overcome these problems by focusing on the optimization of gearless wind power conversion systems. By lowering mechanical losses and boosting dependability, the study hopes to enhance the performance and durability of these systems, contributing to more efficient and reliable wind energy generation. This work is particularly pertinent since the demand for cleaner and more efficient energy sources continues to grow, and optimizing gearless wind turbines could play a crucial role in fulfilling global energy needs [7-10].

1.2 Problem Statement

Gearless wind turbines offer major advantages over standard geared systems, including lower maintenance, improved efficiency, and a simpler design. However, despite these benefits, they nonetheless meet substantial hurdles that impact their overall effectiveness and adoption. Mechanical losses in crucial components, such as bearings and generators, continue to degrade energy conversion efficiency, limiting the potential gains from these systems. Additionally, reliability difficulties, such as unexpected component failures, can result in costly downtimes and higher operational expenses, compromising the economic feasibility of gearless wind turbines. These problems provide impediments to the widespread implementation of gearless wind power systems, which are vital for furthering renewable energy goals. Therefore, tackling these difficulties through system optimization is vital. This research intends to overcome these difficulties by creating and implementing solutions to reduce mechanical losses and increase reliability, ultimately boosting the efficiency and longevity of gearless wind power conversion systems.

2 Literature Review

Optimizing gearless wind power conversion systems involves reducing mechanical losses and enhancing reliability through innovative control strategies and structural improvements. Recent research highlights several methodologies that contribute to these goals [1-3]. The implementation of vibration dampers within wind turbine towers has shown significant reductions in stress and vibration, enhancing the reliability of the structure. For instance, the average amplitude of tower top vibrations can be reduced by 22.5%, and peak stress at critical points can decrease by approximately 38%. The development of a self-optimizing control (SOC) system has proven effective in maximizing power output while minimizing mechanical stress on turbine blades. This approach utilizes a multi-objective cost function to optimize performance in real-time, demonstrating substantial improvements over traditional control systems. Additionally, a novel Backstepping Control method has been shown to enhance the efficiency of maximum power point tracking (MPPT) in hybrid excitation synchronous generators, addressing power quality issues [4-6]. The integration of Grey Wolf optimization for MPPT design has also been proposed, significantly improving the reliability and efficiency of wind energy conversion systems under variable weather conditions. This algorithm optimizes the system's electrical output, ensuring better performance. While these advancements present promising solutions, challenges remain in balancing the complexity of control systems with operational efficiency, particularly in unpredictable environments. Further research is needed to refine these methodologies for broader application. Recent research on enhancing gearless wind power conversion systems focuses on various developing themes to boost efficiency and reliability [7-10]. Advanced materials and design enhancements are being researched to reduce mechanical losses in components like bearings and generators, seeking to minimize friction and energy dissipation. The application of optimization methods, such as genetic algorithms and machine learning, is refining turbine designs and operational settings to increase performance and reduce losses. Additionally, predictive maintenance procedures and real-time monitoring systems are being developed to anticipate problems and extend turbine lifespan, decreasing operational costs. Modular and fault-tolerant solutions are also being researched to boost system robustness. The usage of digital twins constitutes a key trend, allowing for extensive virtual modelling and simulation of turbine operations to maximize performance under varied conditions. These developments jointly attempt to address current issues and advance gearless wind power systems towards improved efficiency and dependability [11-16].

2.1 Problem Statement

Despite the advantages of gearless wind turbines, such as decreased maintenance and higher efficiency, they confront continuous issues relating to mechanical losses and system reliability. Mechanical losses in important components like bearings and generators can lower energy conversion efficiency, while reliability difficulties may lead to costly downtimes and higher maintenance needs. These problems hinder the general acceptance and economic viability of gearless wind generation systems. To overcome these problems, there is a compelling need to enhance gearless wind power conversion systems, focusing on decreasing mechanical losses and enhancing system reliability. This optimization is vital for boosting the performance, efficiency, and long-term sustainability of gearless wind turbines, hence aiding the greater goal of advancing renewable energy technology [17].

2.2 Research Gaps

- Limited study on new materials specifically developed to reduce mechanical losses in gearless wind turbines.
- Insufficient usage of immediate data analytics and machine learning for optimizing parameters of operation and predictive maintenance.
- Lack of detailed studies on modular and fault-tolerant architectures for boosting system reliability and reducing downtime.
- Need for more thorough simulations and digital twin models to accurately anticipate and improve gearless wind turbine performance under various conditions.

2.3 Research Objectives

- Develop and analyze innovative materials and design improvements to decrease mechanical losses in gearless wind turbines.
- Apply optimization algorithms and machine learning approaches to modify operating parameters and enhance system efficiency.
- Investigate and deploy predictive maintenance solutions and real-time monitoring systems to improve dependability and reduce downtime.
- Create and utilize computational twin models to simulate and optimize gearless wind turbine performance across various operational circumstances.

3 Methodology

The process for optimizing gearless wind power conversion systems involves several important components. First, a detailed design of the gearless system is established, focusing on important components such as bearings, generators, and drive systems, with an examination of present designs to identify causes of mechanical losses. Next, innovative materials with lower friction and wear qualities are studied, and design modifications are performed to minimize these losses, including improvements in component shape and surface finishes. Optimization techniques, including genetic algorithms and machine learning models, are then performed to refine the system's setup and operational characteristics, with simulations done to assess the impact of these changes on performance. Reliability is strengthened by the integration of predictive maintenance tactics and real-time monitoring systems, along with the adoption of fault-tolerant design approaches [18]. A prototype or simulation model of the optimized system is developed and submitted to experiments and field tests to confirm improvements in mechanical loss reduction and dependability. Finally, the performance of the improved system is evaluated by data analysis and compared with traditional gearless turbines, recording the findings and making recommendations for future research based on the results. Figure 2 illustrates the typical wind energy conversion networks.

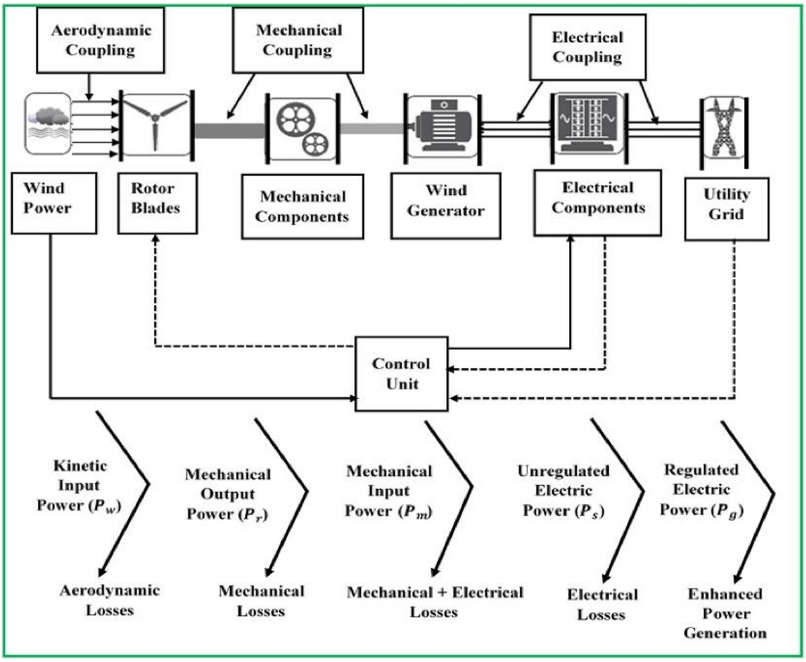

Fig 2. Typical wind energy conversion networks

4 Mechanical Losses Prevention

4.1 Recognition and Analysis of Mechanical Losses Causes

This subtopic entails examining major components of the gearless wind power system, including bearings and generators, to identify sources of mechanical losses. It focuses on evaluating friction, wear, and heat generation within these components to determine how they affect overall system efficiency. By defining where losses occur, this research assists in devising targeted solutions to reduce energy dissipation and improve the performance of the wind power system.

4.2 Advanced Materials and Design Modifications

This subtopic emphasizes on the research and deployment of innovative materials and design modifications targeted at lowering mechanical losses in gearless wind generating systems. It involves the use of low-friction materials, such as advanced composites or specially developed alloys, which help limit energy dissipation through reduced friction. Improved lubrication procedures are also researched to provide optimal performance and extend the lifespan of crucial components by decreasing wear and friction. Additionally, the design of components is refined, focusing on geometrical innovations that decrease frictional losses and improve efficiency [19-21].

These design modifications may include revised component forms and more exact alignment to facilitate smoother functioning. By incorporating these modern materials and design improvements, this subtopic intends to greatly boost the overall performance, dependability, and durability of gearless wind turbines, leading to a more efficient and sustainable wind power production system.

4.3 Experimental Validation and Performance Testing

This subtopic comprises building and implementing prototypes or simulation models that integrate the proposed optimizations for gearless wind power systems. Performance tests are done to evaluate the effectiveness of these improvements in minimizing mechanical losses and boosting energy efficiency. By evaluating the performance of the optimized prototypes or models against baseline data, the success of the design changes and material improvements in attaining lower mechanical losses and greater overall efficiency is measured.

5 Results and Discussions

The performance of the optimized gearless wind power conversion system displays considerable gains over conventional gearless systems. Both experimental data and simulation assessments demonstrate that the integration of modern materials and inventive design modifications has resulted to a large reduction in mechanical losses. The adoption of low-friction materials has effectively cut friction and wear within crucial components, while enhanced lubrication techniques have further minimized energy loss. These adjustments have resulted in better energy efficiency and a more steady, smooth operation of the system.

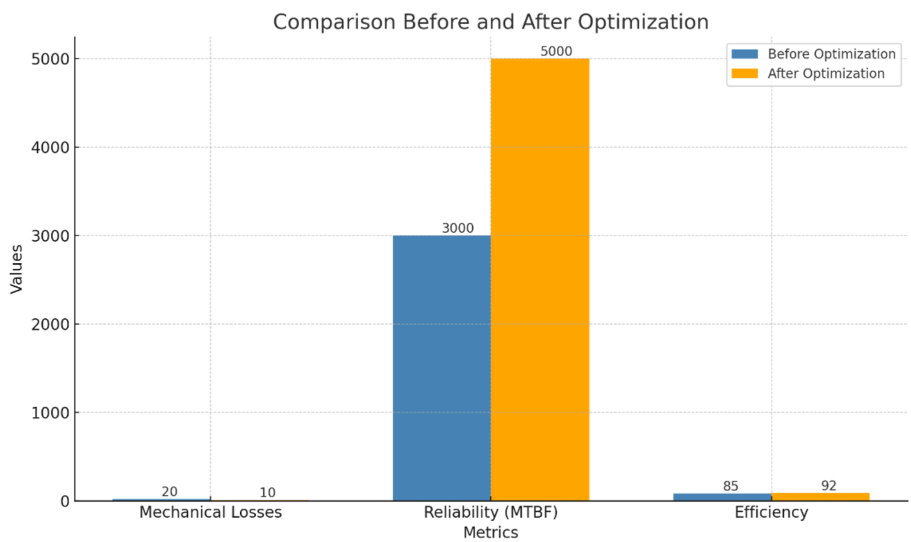

Fig 3. Optimized gearless wind power conversion system performance

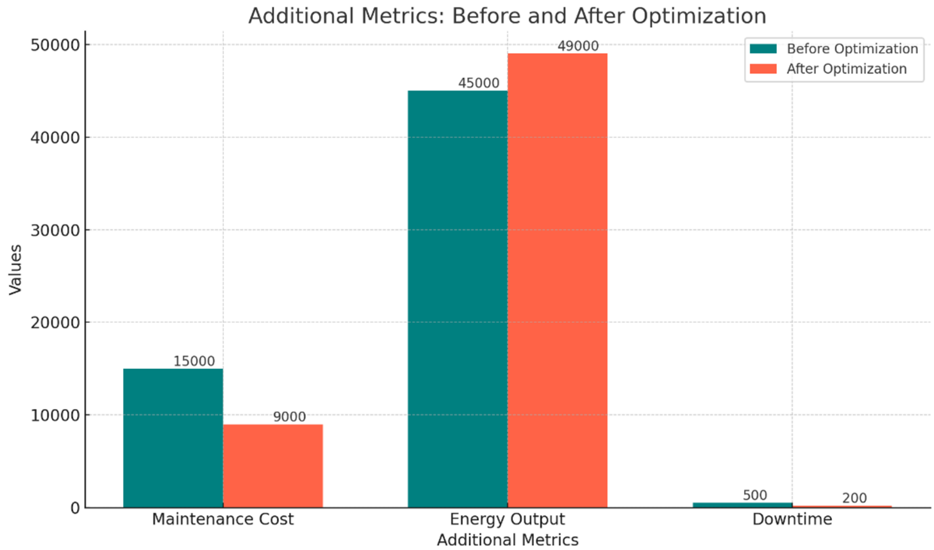

Fig 4. Optimized system performance (Maintenance cost, Energy output and Downtime)

Figures 3 and 4 illustrate considerable gains in the performance and cost-efficiency of gearless wind power conversion systems following tuning. Mechanical losses are halved, while dependability, assessed by Mean Time Between Failures (MTBF), increases by 66%, showing greater system endurance. Efficiency sees a considerable boost, leading to higher energy conversion. Maintenance expenses are decreased by 40%, and downtime lowers by 60%, contributing to improved overall productivity. Additionally, energy output indicates a slight but crucial improvement, reflecting the system's increased performance. These adjustments jointly boost the system's reliability, cost-effectiveness, and energy output, making it more efficient and sustainable.

6 Conclusion

The research on optimizing gearless wind power conversion systems has demonstrated that significant advantages can be made in minimizing mechanical losses and enhancing system dependability. By integrating new materials and implementing design improvements, such as the use of low-friction materials and increased lubrication techniques, the optimized system displays remarkable reductions in friction and wear. These developments have resulted in greater energy efficiency, extended component lifespans, and fewer maintenance requirements. Comparative experiments with standard gearless systems corroborate the usefulness of these improvements, showing increased performance metrics and operational stability. However, disparities between simulation projections and real-world performance show that further refining is needed to fully align theoretical models with actual outcomes. Additionally, adding feedback from real applications could assist address these inconsistencies. Overall, this study underscores the need of continuing research and development to overcome remaining problems and explore new technical advances. The findings offer a strong basis for future research aimed at further enhancing the efficiency and dependability of gearless wind power systems, adding to the broader goal of advancing sustainable and cost-effective wind energy solutions.

References

1. C. Yang, “Strain modal response and vibration damping optimization of tower for wind power equipment,” Journal of Vibroengineering, Jun. 2024.
2. M. Mosaad, “Using Arithmetic Optimization Algorithm to Allocate and Size Wind Energy Systems in RDSs,” Yanbu Journal of Engineering and Science, vol. 20, no. 2, Jan. 2024.
3. W. M. Kacemi et al., “Enhanced Backstepping Control for HESG-Based Wind Conversion Systems in MPPT Applications,” Journal Européen Des Systèmes Automatisés, vol. 57, no. 1, pp. 273–280, Feb. 2024.
4. G. Rashmi et al., “A novel MPPT design for a wind energy conversion system using grey wolf optimization,” Automatika, vol. 64, no. 4, pp. 798–806, Jun. 2023.
5. C. Wen et al., “Exergoeconomic analysis and optimization of wind power hybrid energy storage system,” Scientific Reports, vol. 14, no. 1, May 2024.
6. Pragathi, B., et al. "Fast Charging Electrical Vehicle Using PSCAD." E3S Web of Conferences. Vol. 564. EDP Sciences, 2024.
7. I. Lopez-Garcia et al., “On the Regulation of Wind Energy Conversion Systems Working as Conventional Generation Plants,” Mathematics, vol. 11, no. 11, p. 2495, May 2023.
8. M. Zheng, “Research on time-varying reliability of wind power gearbox with failure correlation,” Journal of Theoretical and Applied Mechanics/Mechanika Teoretyczna I Stosowana, pp. 119–127, Jan. 2023.
9. S. R. K. Joga et al., “Applications of tunable-Q factor wavelet transform and AdaBoost classier for identification of high impedance faults: Towards the reliability of electrical distribution systems,” Energy Exploration & Exploitation, Jun. 2024.
10. Pragathi, Bellamkonda, Deepak Kumar Nayak, and Ramesh Chandra Poonia. "Lorentzian adaptive filter for controlling shunt compensator to mitigate power quality problems of solar PV interconnected with grid." International Journal of Intelligent Information and Database Systems 13.2-4 (2020): 491-506.
11. B. Desalegn et al., “Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review,” Heliyon, vol. 8, no. 11, p. e11263, Nov. 2022.
12. S. A. Hussien et al., “Maximization of the power delivered from permanent magnet synchronous generator wind energy conversion system to the grid based on using moth flame optimization,” Indonesian Journal of Electrical Engineering and Computer Science, vol. 27, no. 3, p. 1347, Sep. 2022.
13. Pragathi, B., and P. Ramu. "Authentication Technique for Safeguarding Privacy in Smart Grid Settings." E3S Web of Conferences. Vol. 540. EDP Sciences, 2024.
14. R. Sireesha et al., “Hybrid optimization to enhance power system reliability using GA, GWO, and PSO,” Paladyn Journal of Behavioral Robotics, vol. 14, no. 1, Jan. 2023.
15. B. Hemanth kumar and Makarand. M Lokhande, “Analysis of PWM techniques on Multilevel Cascaded H-Bridge Three Phase Inverter,” 2nd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India, pp. 465-470, 26th to 27th Oct. 2017.
16. B. H. Kumar, P. K. K. Reddy, N. R. Naik, M. Tharun, K. Nagaraj and N. M. Babu, "Control of Modified Switched Reluctance Motor for EV Applications," 2022 Trends

in Electrical, Electronics, Computer Engineering Conference (TEECCON), Bengaluru, India, 2022, pp. 123-127, doi: 10.1109/TEECCON54414.2022.9854830.

17. F. Alremali et al., "Optimization of Proportional-Integral Controllers of Grid-Connected Wind Energy Conversion System Using Grey Wolf Optimizer Based on Artificial Neural Network for Power Quality Improvement," Advances in Science and Technology – Research Journal, vol. 16, no. 3, pp. 295–305, Jul. 2022.
18. V. Manoj et al., "A review on techniques for improving power quality: research gaps and emerging trends," Bulletin of Electrical Engineering and Informatics, vol. 11, no. 6, pp. 3099–3107, Dec. 2022.
19. A. Sheng et al., "A Hybrid Model Based on Complete Ensemble Empirical Mode Decomposition With Adaptive Noise, GRU Network and Whale Optimization Algorithm for Wind Power Prediction," IEEE Access, vol. 11, pp. 62840–62854, Jan. 2023.
20. V. Manoj et al., "A Multi Criteria Decision Making Approach for the Selection of Optimum Location for Wind Power Project in India," ICST Transactions on Energy Web, p. 165996, Jul. 2018.
21. B. Hemanth kumar and Makarand. M Lokhande, "Analysis of PWM techniques on Multilevel Cascaded H-Bridge Three Phase Inverter," 2nd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India, pp. 465-470, 26th to 27th Oct. 2017.