Volume 10, Number 1, 2024

Modern Strategies for Controlling Wind Power Plants: Technologies, Challenges and Prospects

Nazarii Kurylko*, Roman Fedoryshyn

Lviv Polytechnic National University, 12 Stepana Bandery St., Lviv, 79013, Ukraine

Received: April 20, 2024. Revised: June 14, 2024. Accepted: June 21, 2024.

Abstract

This paper explores the evolution of wind power plant (WPP) control strategies, from simple approaches aimed at optimizing the operation of individual wind turbines to the development of more complex systems that manage WPPs as single integrated entities. Particular attention is paid to the key requirements for WPP control systems and the analysis of WPP structure, especially in the context of their integration into the overall power system. The main objectives of WPP control systems have been studied. The paper presents a detailed review and analysis of the control strategies that are being actively investigated. The control strategies that have successfully found commercial application are identified, and directions for further research needed to optimize and improve these strategies are outlined.

Keywords: wind power plant; wind turbine; control system; wind power; control strategy.

1. Introduction

Electricity generated from wind is gaining increasing importance in the 21st century as a clean and sustainable energy source. In various countries around the world, the share of electricity generation from wind installations can reach up to 50%. For example, in Denmark, the share of wind-generated electricity accounts for about 50% of the country's total generation, which is one of the highest rates in the world. In other countries, such as Germany and the United Kingdom, this figure is within the range of 20-30% [1]. In Ukraine, as of 2021, the share of generation from renewable energy sources was approximately 8.1%, of which 2.7% was provided by wind power plants [2]. The further development of wind energy as a distributed source of electricity generation has become particularly important in the context of Russia's military aggression. Indeed, the bombing of Ukraine's generation facilities prompts a shift away from centralized sources of electricity, which can be vulnerable to attacks, to more decentralized systems. Moreover, the use of renewable energy sources will help Ukraine reduce its dependence on imported fossil fuels, which is critically important in the context of energy security and economic stability [3].

Thus, with the growing demand for renewable energy resources, wind power plants are becoming key in meeting global energy needs. Control systems for these stations play an important role in optimizing electricity production and ensuring their efficient operation. Recent scientific research emphasizes that the use of advanced wind power plant (WPP) control strategies will enhance the productivity of WPPs, providing stable and reliable electricity supply at costs comparable to traditional sources [4].

2. Evolution of wind power plant control systems

The evolution of wind power plant control systems reflects general trends in the energy sector aimed at increasing efficiency, reliability, and the integration of renewable energy sources into the overall power system.

* Corresponding author. Email address: nazarii.v.kurylko@lpnu.ua

This paper should be cited as: N. Kurylko, R. Fedoryshyn. Modern strategies for controlling wind power plants: technologies, challenges and prospects. *Energy Engineering and Control Systems*, 2024, Vol. 10, No. 1, pp. 56 – 63. https://doi.org/10.23939/jeecs2024.01.056

Initially, control system developers focused on optimizing the operation of individual wind turbines using basic strategies that ensured stable energy production [5]. With technological advancements and the scaling up of wind power plants, control systems have become more complex and integrated. Modern systems focus on group control, where coordination of the operation of many wind turbines allows maximizing overall energy production, minimizing mutual impacts, and reducing the load on the turbine structures themselves. Within these goals, scientists are working on innovative strategies aimed at overcoming the limitations of traditional control methods. This includes independent control of wind turbine blades to reduce fatigue loads on wind turbine components, controlling vortex flows, model-predictive control to maximize WPP power and reduce mechanical loads, and the application of LiDAR systems for precise measurement of wind flow parameters. Some of these control strategies have found commercial application, while others still require further refinement.

3. Wind power plant control system structure

Let's consider the hierarchical structure of the WPP control system shown in Figure 1. It consists of a main WPP controller and individual controllers for each wind turbine (WT). The main WPP controller coordinates tasks related to active and reactive power, set by the grid operator, distributing them among the individual wind turbine controllers, which ensure the execution of these tasks. In some cases, such as when the WPP has a large number of turbines or is divided into several groups with a common connection point to the grid, a cluster controller may be applied. The weather station controller provides the main WPP controller with current meteorological data, and the grid monitoring system controller is responsible for measuring the grid parameters at the connection point. This control structure is widely used for monitoring and controlling wind power plants, making their control similar to that of traditional power plants [7].

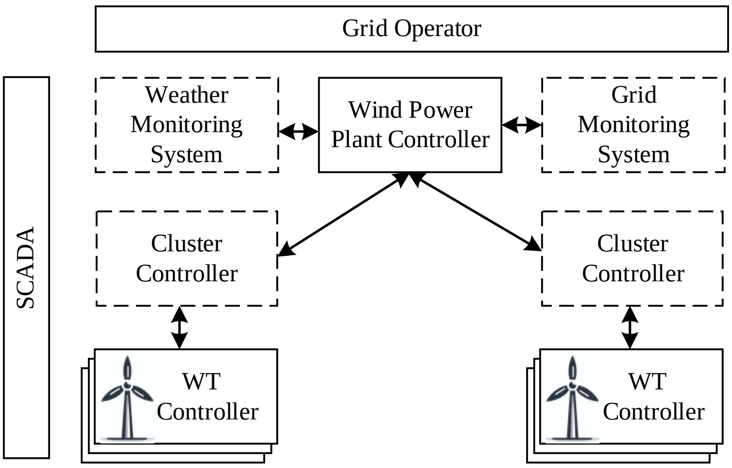

Fig. 1. Wind power plant control system structure.

Components such as the main WPP controller (or WPP cluster controller), weather and grid monitoring systems, can function on different hardware or on a single device, depending on the WPP infrastructure and electrical grid. An important requirement is that all components operate on a real-time platform, which ensures a quick and predictable response of the system to disturbances or task changes. The advantage of such a hierarchical control system is its scalability, allowing for effective control of large wind power plants with numerous wind turbines.

4. Integration into electrical grids

The primary task of the WPP control system is to ensure the technical compatibility of the generated electricity with the power system. In countries such as Germany, the United Kingdom, Ireland, the USA, China, Denmark, Spain, and others with a significant percentage of electricity generated from renewable sources, the integration of wind power plants into the electrical supply system is carried out with mandatory adherence to specific technical requirements, known as "grid codes" [8],[9]. Below is a list of the general requirements for WPP control systems for connecting wind power plants to electrical grids:

Electric power quality: The electricity generated by WPPs must meet established electric power quality standards, specifically IEC 61400-21 [10], an international standard applicable in many countries worldwide, and IEEE Std 1547-2018 [11], predominantly used in the United States but whose principles can be applied globally.

These standards cover frequency, voltage, and harmonics regulation, ensuring that the electrical parameters conform to accepted norms. Given the potential instability of wind flows, which can negatively affect the parameters of electrical networks, it is crucial for the WPP control system to be able to adequately respond to such disturbances and ensure stable energy supply.

Operation during grid faults: WPPs must be capable of supporting the network during outages and avoid immediate disconnection during grid interruptions. This functionality is critically important for preventing widespread failures and enhancing the reliability of the power supply system. The implementation of Low Voltage Ride Through (LVRT) technology, which ensures the ability of wind power plants to remain connected and continue operating during brief voltage drops, is extremely important [12]. Particularly significant is the contribution of WPPs to voltage stabilization by injecting capacitive reactive power, which helps to increase the voltage level in the network during such drops. Wind power plants can also play an active role in regulating the network frequency, providing or consuming additional power to stabilize the frequency in the power system [13].

Active power curtailment: This function is one of the main tasks in controlling a wind power plant. It is important that WPPs be able to adapt the level of generated active power according to the current needs of the electric grid, which ensures effective load balancing and maintaining grid stability (see Figure 2).

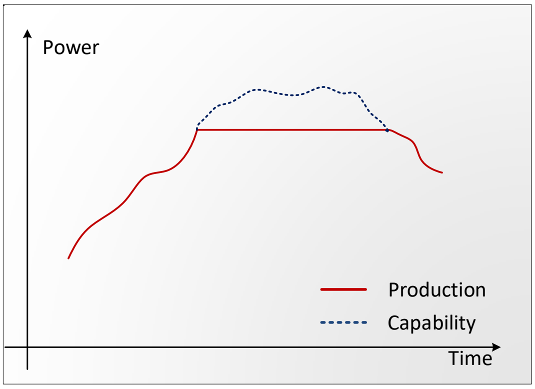

Fig. 2. Active power curtailment.

Power gradient limitation: This function is crucial for regulating the rate of increase in active power at WPPs, allowing it to adapt to the technical requirements of the electric grid operator (see Figure 3). Control over this rate is a means of smoothing the impacts of wind gusts, which is particularly significant for WPPs with a considerable number of wind turbines. Such limitation helps ensure a stable supply of electricity to the grid, minimizing the risks of imbalance that can be caused by sudden increases in power generation.

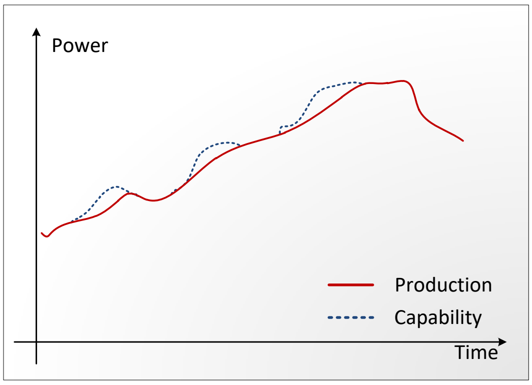

Fig. 3. Power gradient limitation.

Active power reserve: The function of reserving active power (see Figure 4) is important for controlling WPPs, as it allows grid operators to ensure a stable reserve of active power relative to the maximum possible at any given time. The calculation of maximum possible power is based on the power curves of each wind turbine and measured wind speeds. Active Power Reserve can be used to support the power system in potentially critical situations, allowing the wind farm to quickly increase active power if needed. This is particularly relevant, for example, for quick responses to frequency drops in the electric grid.

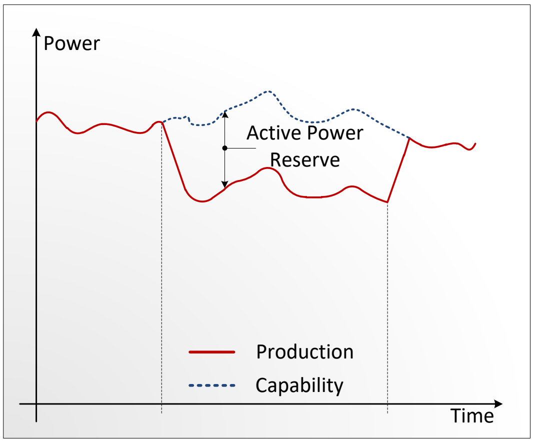

Fig. 4. Active power reserve control.

Primary frequency regulation of the electric grid: To maintain a stable nominal frequency in the electric grid, the generated power must be equal to the consumed power. If power generation exceeds consumption, the network frequency will increase; if consumption is greater than generation, the frequency will drop. According to technical requirements for WPPs, an immediate primary response to deviations in the grid frequency from nominal values is required (see Figure 5).

WPPs can respond to deviations in the grid frequency from nominal values at the level of both the wind turbine control system and the WPP controller. If the grid frequency exceeds a threshold, an automatic reduction in the output power of the WPP according to a set gradient is required (see Figure 5). With the activated function of reserving active power, the WPP control system can respond to a decrease in grid frequency by increasing the output active power using the active power reserve.

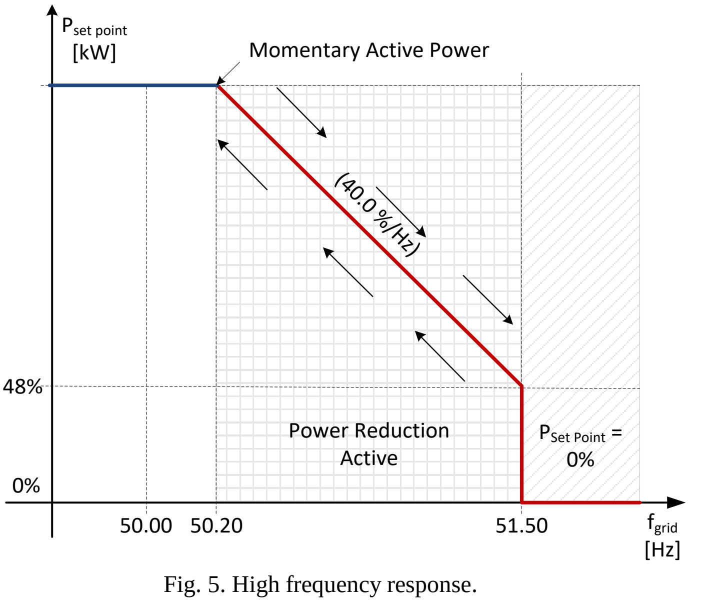

Fig. 5. High frequency response.

Reactive power regulation: Wind power plants must be able to regulate reactive power. This includes the ability to generate and consume reactive power in cos(φ), reactive power, or voltage regulation modes at the connection point to the electrical grid. This capability is important for the integration of wind power plants into the overall energy system, as it helps ensure stability and reliability of the network, especially in conditions where large volumes of wind energy require flexible energy flow control.

Compliance verification of wind power plants to technical requirements: Before connecting to the grid, WPPs must be certified for compliance with the aforementioned requirements, which includes verifying their ability to maintain network stability, withstand faults, and other key safety and functionality parameters. This process involves several stages, including the review of technical documentation, assessment of wind turbine capabilities, and validation of WPP models. Verification may be conducted through practical tests and simulation of validated models. These procedures are important to confirm the ability of wind power plants to effectively integrate into the network, maintaining stability and reliability.

Thus, the main task of the automatic control system for wind power plants is their integration into the energy system and compliance with the established technical requirements. This makes the process of controlling WPPs similar to controlling traditional power generation systems, ensuring stable and reliable production.

5. Goals and control strategies for wind power plants

The Levelized Cost of Energy (LCOE) is used as a metric to compare the cost-effectiveness of different energy generation sources, including WPPs. This measure represents the average cost per unit of electricity generated over the entire lifespan of an energy project. LCOE accounts for costs including capital investments, operational and maintenance expenses, fuel costs (if applicable), the expected lifetime of the project, and total energy production. According to a study conducted in 2020 [4], the cost of wind energy is expected to decrease by 17-35% by 2035 and up to 49% by 2050. The main factors contributing to this reduction include the design of larger and more efficient wind turbines, reductions in capital and operational costs, and increased productivity through the implementation of new efficient control systems. Thus, it can be summarized that the main goal of wind turbine and WPP control systems is to reduce LCOE while complying with the technical requirements of the electrical grid operators.

In the context of reducing LCOE, wind power plant control systems typically address the following subtasks:

- Maximizing electricity production at the wind turbine level;
- Maximizing electricity production at the WPP level;
- Extending the lifespan of wind turbines;
- Integrating into the power system;
- Predictive maintenance.

Maximizing energy production is a key goal in controlling wind power plants, especially in the context of optimizing the use of available wind resources. This goal is achieved by individually controlling each wind turbine, including adjusting the angle of the blades, orienting the turbine to the wind, and controlling the torque on the rotor shaft. Group control at the WPP level is also important, as it allows coordinating the operation of multiple wind turbines to optimally utilize the wind potential of the area [6]. The process of maximizing electricity production requires controlling and maintaining extreme loads and fatigue loads acting on the structure of wind turbines within acceptable limits. Proper balancing between the above indicators should at least ensure the calculated lifespan of wind turbines, reducing overall maintenance and repair costs.

Next, we will analyze the strategies and approaches to controlling wind power plants, which are the subject of active research in the scientific literature. The review will reveal not only the theoretical foundations of these approaches but also their practical effectiveness in real operating conditions.

5.1. Individual pitch control

Individual pitch control (IPC) is a technology used in wind turbines to optimize their performance and extend the lifespan of the equipment. IPC systems adjust the pitch angle of each blade independently, allowing for precise responses to instantaneous changes in wind loading [14]. Such control is crucial for minimizing asymmetric loads on the blades, caused by uneven wind profiles and gusts. Simulation results show that IPC can reduce fatigue loads by 34% (compared to the method of collective blade pitch control), primarily on the blades and the rotor of the wind turbine, leading to decreased frequency of maintenance and operational downtimes. Ultimately, this enhances the overall efficiency and reliability of the wind turbine. Verification of the simulation results on a real wind turbine showed outcomes comparable to those of the simulations [15].

Despite the high efficiency of IPC in reducing fatigue loads, mentions of its commercial implementation are rare in open sources. This may be due to drawbacks associated with IPC: it can cause accelerated wear of mechanical components due to the constant cyclic movements of wind turbine blades, and it can interfere with other wind turbine control systems. Incorrect calibration of such a system can, conversely, increase the fatigue loads on wind turbine components. Given the significant potential of this method in reducing fatigue loads, active scientific research into these systems, which began in the 2000s [15], continues to this day.

5.2. Control strategies for minimizing loads on wind turbines

Wake Control is aimed at redirecting turbulent flows created by upstream wind turbines to mitigate their impact on downstream turbines. This process is typically implemented by precisely adjusting the yaw angle of the front turbines relative to the wind direction. This control strategy is designed to reduce fatigue loads on components of wind turbines located in the wake flow. Additionally, this method helps optimize the distribution of wind flows, which can enhance the overall efficiency of capturing wind energy by the wind power plant [17],[18].

Experimental studies involving a pair of turbines have shown significant increases in electricity generation and reductions in fatigue loads [19]. Practical experience in implementing such a control strategy suggests that the real effect can be minimal compared to the complexity of its implementation and depends on the terrain's topology and the relative positioning of the wind turbines. This is indirectly confirmed by the existence of only two commercial products that implement this strategy: WakeAdapt by Siemens Gamesa [20] and Swarm™ by WindESCo [21], which claim to increase annual electricity generation by up to 1%.

The main challenge for the commercial implementation of this control strategy is the development of accurate models of wind power plants and wind flow, and their execution in real-time, which requires significant computational resources. From the above, we conclude that this strategy has performed well in simulations and holds considerable potential for further scientific research in the context of its application in commercial solutions.

5.3. Application of LiDAR technology in wind power plant control

LiDAR (Light Detection and Ranging) technology, which uses laser beams to measure wind speed and direction, offers significant advantages over traditional anemometers and wind vanes typically mounted on the nacelle behind the wind turbine. This advantage arises from the greater accuracy and speed of measurements conducted in the plane in front of the wind turbine, which avoids measurement distortions caused by turbulence from the turbine blades.

Enhancing the accuracy of wind speed measurements allows the control system to optimally select the rotor speed for maximum wind power extraction. Improving the accuracy of wind direction measurements enables more effective operation of systems ensuring that the wind turbine is oriented perpendicularly to the wind direction. Just by this improvement alone, the Annual Energy Production (AEP) can be increased by 2-4% [22]. When using the LiDAR system for wind power plant control, sensors can be installed at key points on certain wind turbines, which can provide sufficient data for effective control. Research has shown that the integration of LiDAR with Model Predictive Control and Wake Control has proven effective [23],[24].

A significant number of commercial implementations confirm the effectiveness of LiDAR systems [25]. They are actively being installed by manufacturers like Vestas, Siemens Gamesa, and others. From the aforementioned, we can conclude that LiDAR is an essential tool for implementing control strategies in wind turbines and wind power plants, where accurate and fast wind direction and speed data are crucial.

5.4. Model predictive control

Model predictive control (MPC) utilizes mathematical models of WPPs and forecasts of meteorological conditions to optimize control strategies over a given time horizon. The basis of the control strategy is solving optimization problems, where action plans are continuously adjusted based on new data and measurements.

Research indicates that the application of MPC can effectively reduce fatigue loads on wind turbine components, particularly by predicting wind speed fluctuations, which also helps minimize power fluctuations [26]. MPC can also foresee potential malfunctions and adapt the control system to prevent emergency situations [27].

However, implementing MPC in wind energy systems faces certain challenges. A key aspect is the accuracy of the predictive models: any inaccuracies can lead to suboptimal control decisions. The computational demands, especially for large-scale models that include multiple turbines or entire stations, require significant resources and can pose difficulties for real-time implementation. Current research is aimed at increasing the computational efficiency of MPC algorithms and the accuracy of prediction models.

With further development of computational technologies and forecasting methods, MPC is expected to play an increasingly important role in the renewable energy industry, providing more effective and reliable control of wind power plants.

5.5. Predictive maintenance

Predictive maintenance in WPPs involves the use of various data analysis technologies to predict potential equipment failures with the aim of enhancing its operational efficiency and reducing maintenance costs. These technologies enable the analysis of information from sensors monitoring various operational parameters of wind turbines, such as vibration levels, temperature, and other critical indicators.

Thanks to machine learning and neural networks, predictive maintenance systems can not only detect current issues but also forecast future failures, allowing for the scheduling of maintenance before emergency situations occur. This reduces unplanned downtime and contributes to more efficient power plant operations [28]. In particular, research [29] quantitatively estimates potential savings of up to 8% in direct operational and maintenance costs and up to 11% in production losses, assuming that 25% of major faults in generators and gearboxes can be diagnosed and repaired before they require major replacement.

Thus, predictive maintenance is a crucial tool in the control of modern WPPs, enabling not only reduced operational costs but also greater stability and safety in the production of wind energy.

6. Conclusion

This paper covers the main tasks, objectives, and architecture of wind power plant control systems, analyzing scientifically justified strategies for achieving these tasks. Various approaches to optimizing the operation of wind turbines and WPPs are considered, including individual pitch control, wake control, model predictive control and the application of LiDAR technology. It has been established that some strategies, such as LiDAR and Wake Control, have already been commercialized, while others still require further research for efficient commercial application. The significance of predictive maintenance and anomaly detection systems, which play an important role in achieving the objectives of WPP control systems, is also highlighted.

References

[1] World Population Review. Wind Power by Country 2024: https://worldpopulationreview.com/country-rankings/wind-power-by-country. (accessed on June 9, 2024)

[2] Laffitte, T., & Moshenets, I. (2023). Synchronized: The impact of the war on Ukraine's energy landscape. Foreign Policy Research Institute. https://www.fpri.org/wp-content/uploads/2023/12/ukraine-energy-landscape.pdf. (accessed on June 9, 2024)

[3] National Renewable Energy Laboratory. (2023). Ukraine fights to build a more resilient, renewable energy system in the midst of war. NREL. Retrieved from https://www.nrel.gov/news/features/2023/ukraine-fights-to-build-a-more-resilient-renewable-energy-system-in-the-midst-of-war.html. (accessed on June 9, 2024)

[4] Wiser, R., Rand, J., Seel, J., Beiter, P., Baker, E., Lantz, E., & Gilman, P. (2021). Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy*, 6(5), 555-565. https://doi.org/10.1038/s41560-021-00810-z.

[5] Wright AD, Fingersh LJ. Advanced Control Design for Wind Turbines: Part I: Control Design, Implementation, and Initial Tests. Prepared under Task No. WER8.2101. Technical Report. NREL/TP-500-42437; March 2008. Available from: https://www.nrel.gov/docs/fy08osti/42437.pdf. (accessed on June 9, 2024)

[6] Schlueter, A., Javid, M., Sørensen, P., Kristoffersen, J. R., & Christiansen, C. (2022). Wind farm flow control: prospects and challenges. Wind Energy Science, 7(2271), 1-15. https://doi.org/10.5194/wes-7-2271-2022.

[7] Altin, M., Teodorescu, R., Bak-Jensen, B., Rodriguez, P., & Kjær, P. C. (2010). Aspects of wind power plant collector network layout and control architecture. In *Proceedings of the Danish PhD Seminar on Detailed Modelling and Validation of Electrical Components and Systems 2010* (pp. 46-52). Fredericia, Denmark: Energinet.dk.

[8] Altın, M., Göksu, Ö., Teodorescu, R., Rodriguez, P., Jensen, B.-B., & Helle, L. (2010). Overview of recent grid codes for wind power integration. In Proceedings of the 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2010). IEEE. https://doi.org/10.1109/OPTIM.2010.5510521.

[9] Tsili, M., & Papathanassiou, S. (2009). Review of grid code technical requirements for wind farms. IET Renewable Power Generation, 3(3), 308-332. https://doi.org/10.1049/iet-rpg.2008.0070.

[10] International Electrotechnical Commission. IEC 61400-21: Measurement and assessment of power quality characteristics of grid connected wind turbines. Available from: https://webstore.iec.ch/publication/2604. (accessed on June 9, 2024)

[11] Institute of Electrical and Electronics Engineers. IEEE Std 1547-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. Available from: https://standards.ieee.org/standard/1547-2018.html. (accessed on June 9, 2024)

[12] Sourkounis C, Tourou P. Grid Code Requirements for Wind Power Integration in Europe. *Conference Papers in Science*. 2013;2013(1). https://doi.org/10.1155/2013/437674.

[13] Díaz-González, F., Hau, M., Sumper, A., & Gomis-Bellmunt, O. (2014). Participation of wind power plants in system frequency control: Review of grid code requirements and control methods. Renewable and Sustainable Energy Reviews, 34, 551-564. https://doi.org/10.1016/j.rser.2014.03.040.

[14] Etxegarai, A., Eguia, P., Torres, E., Buigues, G., & Iturregi, A. (2017). Current procedures and practices on grid code compliance verification of renewable power generation. Renewable and Sustainable Energy Reviews, 71, 191-202. https://doi.org/10.1016/j.rser.2016.12.051.

[15] Bossanyi, E. A. (2003). Individual blade pitch control for load reduction. Wind Energy, 6(2), 119-128. https://doi.org/10.1002/we.76.

[16] Ossmann D, Seiler P, Milliren C, Danker A. Field testing of multi-variable individual pitch control on a utility-scale wind turbine. Renewable Energy. 2021;170(2). https://doi.org/10.1016/j.renene.2021.02.039.

[17] Jiménez A, Crespo A, Migoya E. Application of a LES technique to characterize the wake deflection of a wind turbine in yaw. Wind Energy. 2010;13:559-572. https://doi.org/10.1002/we.380.

[18] Gebraad PMO, Teeuwisse FW, van Wingerden JW, et al. Wind plant power optimization through yaw control using a parametric model for wake effects – a CFD simulation study. Wind Energy. 2016;19:95-114. , https://doi.org/10.1002/we.1822.

[19] Campagnolo F, Petrović V, Schreiber J, et al. Wind tunnel testing of a closed-loop wake deflection controller for wind farm power maximization. J Phys: Conf Ser. 2016;753:032006. https://doi.org/10.1002/we.1822.

[20] Siemens Gamesa Renewable Energy. (n.d.). WakeAdapt: Optimizing Wind Farm Performance. Retrieved from https://www.siemensgamesa.com/products-and-services/services/wind-services/wake-adapt (accessed on June 9, 2024)

[21] WindESCo. (n.d.). Swarm™: Wind Farm Control. Retrieved from https://www.windesco.com/swarm (accessed on June 9, 2024)

[22] Scholbrock, A., Fleming, P., Schlipf, D., Wright, A., Johnson, K., & Wang, N. (2016). Lidar-enhanced wind turbine control: Past, present, and future. In 2016 American Control Conference (ACC) (pp. Date). IEEE. https://doi.org/10.1109/ACC.2016.7525113

[23] Schlipf D, Schlipf DJ, Kühn M. Nonlinear model predictive control of wind turbines using LIDAR. Wind Energy. 2012;16(7):1107-1129. https://doi.org/10.1002/we.1533

[24] Raach S, Schlipf D, Cheng PW. Lidar-based wake tracking for closed-loop wind farm control. Wind Energ Sci. 2017;2:257-267. doi:10.5194/wes-2-257-2017. Available from: https://www.wind-energ-sci.net/2/257/2017/ (accessed on June 9, 2024)

[25] Windar Photonics. Windeye. Available at: https://www.windarphotonics.com/windeye. (accessed on June 9, 2024)

[26] Sun, Y., Tang, X., Sun, X., Jia, D., Cao, Z., Pan, J., & Xu, B. (2018). Model predictive control and improved low-pass filtering strategies based on wind power fluctuation mitigation. Journal of Modern Power Systems and Clean Energy, 6(5), https://doi.org/10.1007/s40565-018-0474-5.

[27] Yang X, Maciejowski JM. Fault-tolerant model predictive control of a wind turbine benchmark. IFAC Proceedings Volumes. 2012;45(20):337-342. doi:10.3182/20120829-3-MX-2028.00134.

[28] Cañizo, M., Onieva, E., Conde, A., Charramendieta, S., & Trujillo, S. (2017). Real-time predictive maintenance for wind turbines using Big Data frameworks. *Proceedings of the 2017 IEEE International Conference on Prognostics and Health Management*, 70-77. https://doi.org/10.1109/ICPHM.2017.7998308.

[29] Turnbull, A., & Carroll, J. (2021). Cost benefit of implementing advanced monitoring and predictive maintenance strategies for offshore wind farms. Energies, 14(16), 4922. https://doi.org/10.3390/en14164922.

Сучасні стратегії керування вітроелектростанціями: технології, виклики та перспективи

Назарій Курилко, Роман Федоришин

Національний університет «Львівська політехніка», вул. С. Бандери, 12, Львів, 79013, Україна

Анотація

У цій статті досліджено еволюцію стратегій керування вітроелектростанціями (ВЕС), починаючи з простих стратегій, спрямованих на оптимізацію роботи окремих вітрових турбін, до розробки складніших систем, що керують ВЕС як єдиними цілісними об'єктами. Окрема увага приділяється ключовим вимогам до систем керування ВЕС та аналізу структури ВЕС у контексті їх інтеграції в загальну енергосистему. Вивчено основні цілі систем керування ВЕС, проведено детальний огляд та аналіз стратегій керування, над якими активно ведуться наукові дослідження. Виявлено стратегії керування ВЕС, які успішно знайшли комерційне застосування, і окреслено напрямки для подальших досліджень, необхідних для оптимізації та покращення цих стратегій.

Ключові слова: вітроелектростанція; вітрова турбіна; система керування; енергія вітру; стратегія керування.