INNOVATIONS IN OPERATIONAL CONTROL METHODS AND STRATEGIES FOR WIND TURBINE SYSTEMS

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Abstract: Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Wind energy plays significant role and can be considered as the most deployed renewable energy source; however, the efficiency level and cost-effectiveness of a wind turbine system with regard to wind application are mainly dependent on its control. There is a most important recent technique named **Maximum Power Point Tracking (MPPT) that is used in wind turbines.** MPPT allows tracking the optimal operation points of the wind turbine system under fluctuating wind conditions and the tracking process speeds up over time. Irrespective of the knowledge of intangible turbine mechanical characteristics such as its power coefficient curve, power characteristic, or torque characteristic, MPPT can be achieved. So in this paper, wind turbine systems, control methods and strategies for wind turbine systems, and MPPT control methods and strategies for wind turbine systems had been studied.

Keywords: *Wind turbine system, Control methods, Control strategies, Maximum Power Point Tracking techniques and Maximum Power Point Tracking strategies.*

1. INTRODUCTION

Nowadays, renewable energies are gaining more attraction in the global energy market and in society. In recent years, these energy sources have become a concrete alternative to reduce the dependence on fossil fuels, giving both environmental and economic benefits (Savino et al., 2017). Renewable resources include biomass energy, hydropower, geothermal power, wind energy, and solar energy ("Renewable Resources," 2022.). Out of these renewable energy sources, wind turbines are an increasingly important source of intermittent renewable energy and are used in many countries to lower energy costs and reduce reliance on fossil fuels (A. Kumar et al., 2018). Wind turbine is an electro-mechanical device that converts the power of moving air into electric power. When wind blows, the wind turbine blades spin clockwise by capturing the energy of the wind. This triggers the main shaft of the wind turbine, connected to a gearbox within the nacelle, to spin. The gearbox sends that energy to the generator, converting it to electricity (Wind energy solutions., 2021). Statistics show that the cost of wind production has dropped enormously in recent years, from two million dollars per M.W. to one million in the last decade(Sahu, 2018). Some low-speed wind turbines have ascertained that there is a great potential for energy harvesting at low wind velocities with significant possible improvement in energy conversion efficiency (Venkatramakrishnan et al., 2020).This energy efficiency and cost-effectiveness are based upon their control. Active control by complementing the primary technologies in wind turbines can help significantly in attaining the industry's objectives of safe and cost-efficient energy production. One of the important tasks of a control strategy for wind turbines is to limit the power output to the turbine to the

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level that the mechanical and electrical components of the turbine are able to handle (Sawant et al., 2021). In figure 1, ω, T_g, β, ω_{ref}, T_{gref} and β_{ref} denotes the rotational speed of the turbine rotor; generator reaction torque; pitch angle of the turbine blades; the rotational speed of the turbine rotor; generator reaction torque and the pitch angle of the turbine blades.

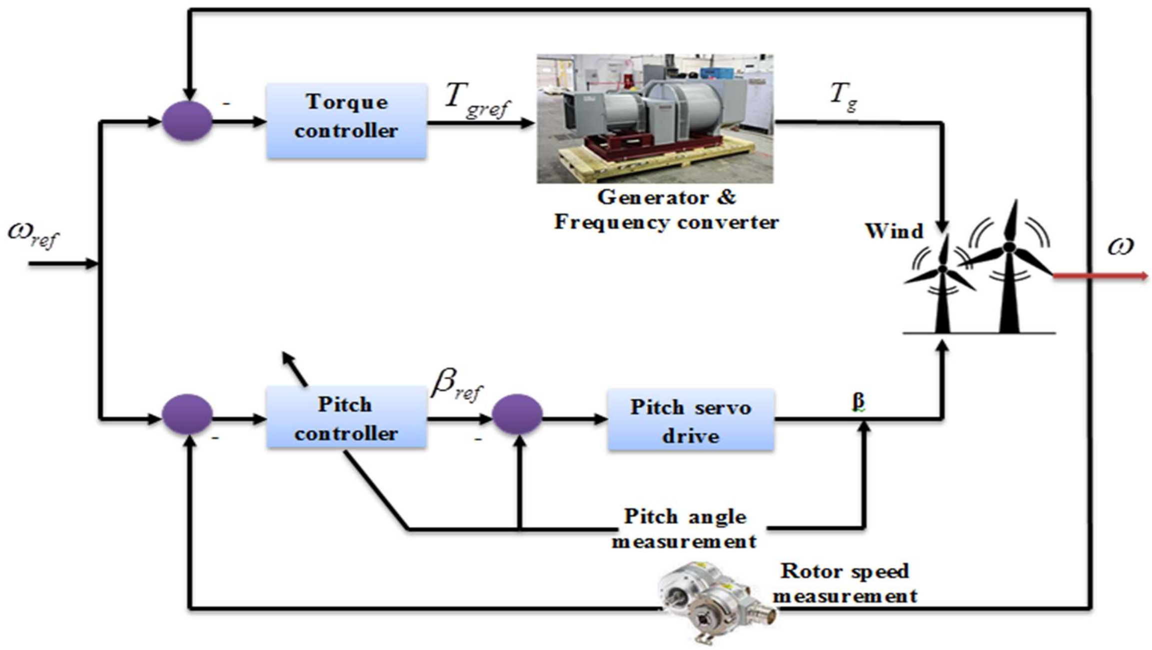

Figure 1: Classical wind turbine control system

Advanced wind turbine control can reduce the loads on wind turbine components while capturing more wind energy and converting it into electricity (Abbas et al., 2022). There are some of the following control methods and strategies used to optimize or limit the power extracted from the wind (Porté-Agel et al., 2020) (Patil A. K.2020).

- ✓ Pitch adjustment
- ✓ Yaw
- ✓ Rotational speed control
- ✓ Controlling the generator wind speed
- ✓ Blade angle adjustment
- ✓ Rotation of the entire wind turbine

There is another important technique named MPPT. They are a necessity in wind turbine systems for maximum extraction of available wind energy based on wind speed. There are some problems in using the control methods and strategies like slow response and incorrect detection of direction for maximum power, inability to locate accurate maximum power point under swift wind variations, etc (Veers et al., 2022).

The survey paper is explained as follows: section 2 explains the survey on the operational control systems and strategies for wind turbine systems; section 3 indicates the analysis, and the paper is concluded in section 4.

2. LITERATURE REVIEW

In the recent three decades, remarkable advances in wind turbine design have been achieved along with modern technological developments. The control systems have also grown much more complex as wind turbines themselves have evolved. As a trend towards larger rotors and higher megawatt ratings continues, and pressure to drive down the cost of energy gives no sign of easing, further advances in control systems will be critical. In this paper, section 2.1 defines the survey on wind turbine systems; section 2.2 illustrates the operational control methods and strategies for wind turbine systems; section 2.3 describes the survey on MPPT technique for control of wind turbine system and section 2.4 explains the survey on the MPPT strategies for wind turbine system.

2.1. SURVEY ON WIND TURBINE SYSTEM

A wind turbine system is a process of converting the kinetic energy in wind into clean electricity. When the wind spins the wind turbine blades, a rotor captures the kinetic energy of the wind and converts it into rotary motion to drive the generator (Z. Zhang et al., 2017). Wind turbines are classified into two general types: horizontal axis and vertical axis. A horizontal axis machine has its blades rotating on an axis parallel to the ground. A vertical-axis machine has its blades rotating on an axis perpendicular to the ground (Patil A. K.2022).

(Palanimuthu et al., 2022)investigated the fault ride-through for Permanent Magnet Vernier Generator (PMVG) based wind turbine system using a coordinated active and reactive power control strategy. The reactive power control was implemented on the grid-side converter to meet the reactive current requirement of the grid code. The comparative results showed that the applied coordinated control schemes and variable exponential reaching law (VERL) based voltage control methods contributed reasonably to grid fault conditions in PMVG-based wind turbine systems. PMSG did not maximize electricity extraction in the wind turbine system.

(Nair & Narayanan, 2020) explained the emulation of a Wind turbine system using vector controlled induction motor drive. One Degree of freedom (1-DOF) and two degrees of freedom (2-DOF) control structures were applied for wind turbine emulation. From the simulation results with 2-DOF control, it was found that the wind turbine emulator achieved very good tracking of speed dynamics of the Wind Turbine - Generator System along with good disturbance rejection and robustness to parameter inaccuracies. The wind turbine emulation scheme based on proposed 2-DOF design II, has very low parameter sensitivity.

(Li et al., 2020) described the opportunistic maintenance strategy for offshore wind turbine systems considering optimal maintenance intervals of subsystems. An opportunistic maintenance model was applied to optimize the maintenance strategy by combining maintenance activities of individual subsystems to a grouping maintenance activity. From the comparative analysis, the performance of the opportunistic model can be attained well when the numbers of wind turbines were higher. Maintenance activities cannot be carried out without any block in the model.

(Gou et al., 2022) explained the weighted assignment fusion algorithm of evidence conflict based on euclidean distance and weighting strategy and application in the wind turbine system. Multi-source information fusion analysis framework was applied from 3 areas such as information, algorithm, and decision-making. Overall from the results, the improved algorithm under the distance strategy has better results in diagnosing and predicting system faults and it was more effective in improving energy utilization efficiency. The screening process was important but it was not described.

(Zhao et al., 2020) described the fast frequency support from wind turbine systems by arresting frequency nadir close to settling frequency. In the applied scheme, rotor speeds of wind turbine systems were applied not to be recovered to the optimal operating points during the primary frequency control. The simulation results showed that the frequency was already reduced to an unbearable value at 400 s when no remedy was done. It should be noted that the cut-in wind speed was 6 m/s.

2.2. OPERATIONAL CONTROL METHODS AND STRATEGIES FOR WIND TURBINE SYSTEM

Optimal Control of Wind Energy Systems with its full assessment of a variety of optimal control methods makes a welcome contribution to the wind power control literature. Power control ability refers to the aerodynamic performances of wind turbines, especially in the power-limiting operation range. All wind turbines have some sort of power control (Gao & Sheng, 2018)(Guerrero et al., 2017). Further, increased flexibility of turbine structures brings to the fore-front the task of mitigating damaging loads at blade roots and tower base (Nguyen & Kim, 2021)(Astolfi, 2021). Table 1 explains the operational control methods for wind turbine systems with their findings and disadvantages.

Table 1: Operational control methods for wind turbine system with its findings and disadvantages

AUTHOR NAME	CONTROL METHODS	FINDINGS	DISADVANTAGES
(Qi et al., 2021)	Blade angle adjustment	Analysis showed that the distance between the micro-plate and the blade leading edge from the blade thickness direction and the chord length direction has significant effects on the aerodynamic performance of the blade	Only relying on the velocity streamlines diagrams cannot compare and analyze the effect of the plate widths on the wind turbine blade
(Zhu et al., 2020)	Dynamic stall control	Results showed that the vortex generators were highly promising in controlling the dynamic stall of the wind turbine airfoil	There were some unsteady responses of the airfoil with and without vortex generators
(Sierra-Garcia & Santos, 2022)	Pitch control	Simulation results indicated that for low and medium wind speeds, an improvement of 21% was obtained with respect to the PID controller, and 7% with respect to the standard fuzzy controller	It fails to track the nonlinearity of the system
(Mohammadi et al., 2018)	Stall and yaw control	Results showed that flicker emission level, voltage fluctuation, and mechanical loads for the stall-controlled wind turbine were less than those in the yaw-controlled turbine	The yaw error and mechanical control strategies can affect the flicker emission and mechanical loads in wind turbines
(Ullah et al., 2020)	Dynamic stall control	It was found that a reduction in optimum stall deflection δ from 16° at a rated wind speed of 10 ms^{-1} to 12° for low wind speed operation at 5ms^{-1}. A significant increase in the maximum coefficient of lift control max by 32%	The scope of application has been limited mostly to simple airfoils

(Mohammadi et al., 2017)	Yaw and Stall Control	Results showed that a wind turbine can operate well with other control. The stall control can better control the output power, output voltage, and direct current link voltage at high wind speeds	Wind turbines operating at above-rated wind speeds had not presented
(Hosseini et al., 2022)	Pitch angle adjustment	When comparing with the proportional-integral controller, the power quality for the fuzzy controller was increased from 2.941 % to 4.762 % for wind with an average speed of 12 meters per second	Sometimes in different situations, pitch control was a weak link in wind turbines.
(L. Zhang et al., 2021)	Blade angle adjustment	When comparing with no various pitch, adjustment law showed an enhanced average value of synthetic force and a decreased fluctuation	A prototype wind turbine cannot improve output power because of its even negative under most azimuth angles

(Pelin et al., 2018) explained the hydraulic systems used for the pitch control of wind turbines. This kind of control was significant for protecting the turbine in the case of high values of wind speed reducing the extreme loads. Experimental results clarified that the pitch control controlled by self-organizing fuzzy sliding mode control can perform better than that controlled by fuzzy sliding mode control. PID control law and stating the error and the gain were not analyzed completely.

(Zhao et al., 2021) described the frequency control method for micro-grid with a hybrid approach of fast frequency response optimized power point tracking method (FFR-OPPT) and a pitch angle of the wind turbine. Simulation results illustrated that the control strategy can control the frequency of the micro-grid close to its schedule value effectively, accompanied by a decrease in the frequency and range of pitch angle adjustment. The frequency adjustment method cannot adapt to the rapid adjustment demand of grid frequency.

(Jianglin et al., 2018) explained the fault-tolerant pitch control using adaptive sliding mode estimation. The applied fault tolerant control (FTC) scheme integrates a traditional proportional integral controller as a baseline system to attain nominal pitch performance. From the experimental analysis, it had been proved that pitch control successfully attained significant load reduction. The response time of the conventional controller was very high when compared to other techniques.

(Gonçalves et al., 2022) described the passive control of dynamic stall in an H-Darrieus vertical axis wind turbine using blade leading-edge protuberances. The custom experimental setup was also developed for the purpose to define the leading-edge geometry to be subsequently tested in the wind tunnel. Results showed the efficiency of the power gets enhanced between 46% and 20% for wind velocities ranging from 5.5 m/s to 9 m/s. The half and complete turbine torque results, shown did not portray any meaningful discrepancies.

(Manerikar et al., 2021) investigated the horizontal axis wind turbines' passive flow control methods. CFD analysis of the NACA 23024 aerofoil was carried out in which the coefficient of lift and drag were calculated and compared with and without the Vortex Generator (aerofoil). From the analysis of results, it was found that the turbine blade simulations showed that lifting enhanced at higher angles on the inside of the blade could increase the overall energy generation by 0.5 to 1%.

(Asgharnia et al., 2018) described the performance and robustness of optimal fractional fuzzy PID controllers for pitch control of a wind turbine using chaotic optimization algorithms. Fuzzy PID (FPID) and fractional-order fuzzy PID (FOFPID) were applied to improve pitch control performance. Simulation results demonstrated that the FOFPID controller could reach better performance and robustness while guaranteeing fewer fatigue damages in different wind speeds when compared with FPID and other controllers. Sometimes, FOFPID might not preserve due to modeling and wind speed uncertainties.

(Mousavi et al., 2022) explained the fault-tolerant optimal pitch control of wind turbines using a dynamic weighted parallel firey algorithm (DWPFA). The applied scheme integrates a fractional-calculus-based extended memory (EM) of pitch angles along with a fractional-order proportional-integral-derivative (FOPID) controller to enhance the performance of the wind turbine. The results indicated that DW-PFA attains the best rank, followed by FOFA and FPSOMA. When wind energy level and direction change continuously, the pitch actuation system cannot provide immediate precise responses.

2.3. MPPT TECHNIQUES FOR CONTROL OF WIND TURBINE SYSTEM

MPPT techniques are major control methods usually employed to maximize the turbine energy conversion efficiency by regulating the rotational speed of variable-speed wind turbines (Azzouz et al., 2019). The wind turbine system must be designed to operate at its maximum power for different conditions. So, over the last few decades, considerable progress has been made in the MPPT techniques and consequently, many MPPT methods have been developed (Sabzevari et al., 2017). Table 2 explains the MPPT techniques for the control of the wind turbine system.

Table 2: MPPT techniques for the control of wind turbine system with its findings and disadvantages

AUTHOR NAME	MPPT TECHNIQUES	FINDINGS	DISADVANTAGES
(Mousa et al., 2019)	Variable step size perturb and observe (VS P&O)	Simulation results illustrated the VS-PO superiority (efficiency:87.1% to 91.2%) over both the conventional P&O (CPO) and modified P&O (MPO) techniques	Poor tracking possibly in under sudden changes in irradiance such as the slow convergence of rising time towards maximum power point
(H. Wang et al., 2018)	Model Predictive Control	From the findings, the maximum output power was about 9.34 kW and the frequency deviation was reduced to -0.52 Hz	Compensations with Droop control were not relatively strong, and they rely too much upon the droop factors.
(Mishra et al., 2020)	Drift Free P & O	It had been found from results that in applied MPPT technique, dc-link power attains its same maximum value at 7 m/s in 0.4 s which shows a good transient performance	At a steady state, the operating point oscillates around the MPP giving rise to the waste of some amount of available energy
(Youssef et al., 2019)	VS P&O	Findings proved that the applied method was effective on the basis of the improved efficiency (87% to 90%) and the fast system response	Sometimes there will be low responses it will be a little complicated to solve
(Youssef et al., 2018)	Model Predictive Control	Results indicated from the applied technique, it can be observed that the system operates at the optimal power coefficient value (0.48). Moreover, the tip speed ratio reaches the maximum value (8.1)	It needs a large number of model coefficients to describe a response

(Ihedrane et al., 2019) explained the control of the power of a Doubly Fed InductionGenerator (DFIG) with the MPPT Technique for wind turbines' variable speed. Applied control was deployed to a DFIG whose stator was directly connected to the grid in contrast to the rotor. Results showed that the indirect field-oriented control showed the reliability and robustness of the applied control and provide better control for injecting power into the grid. It was not possible to control independently the input variables like voltage or current.

(Priyadarshi et al., 2018) described the fuzzy space vector pulse width modulation-based inverter control realization of grid integrated photovoltaic wind system with fuzzy particle swarm optimization maximum power point tracking algorithm for a grid-connected wind power generation system. The experimental results have been validated using MATLAB/Simulink interfaced real-time dSPACE DS 1104 controller. The applied hybrid system achieved high performance of maximum power.

(Chetouani et al., 2021) explained the design of optimal backstepping control for a wind power plant system using the adaptive weighted particle swarm optimization. The performance and robustness of the applied method were compared to the conventional backstepping and the proportional-Integral control strategies of a 5 MW wind power plant system under parameter variations. The methodology makes sure that the tracking system's robust stability and reduces the response time to 1.8 (m s).

(Mokhtari & Rekioua, 2018) described the high performance of MPPT using an ant colony algorithm (ACO) in the wind turbine. The algorithm was used to determine the optimal PI controller parameters for speed control. Analysis obtained with ACO presents a better optimization and the power coefficient, in this case, was more than the power coefficient obtained by using the classical regulators for the speed control. Limitations were the stagnation phase, exploration and exploitation rate, and convergence speed of the algorithm.

(Yang et al., 2018) explained the passivity-based sliding-mode control (PB-SMC) design for optimal power extraction of a Permanent Magnetic Synchronous Generator (PMSG) based variable speed wind turbine. Additional input was utilized to lead the closed-loop system to the output strictly passive. Results indicated that PB-SMC can rapidly achieve MPPT with the least overshoot under step change of wind speed and stochastic wind speed variation for effectively restoring the PMSG system under pitch angle variation.

2.4. MPPT STRATEGIES FOR WIND TURBINE SYSTEM

MPPT strategy purpose was applied in the wind turbine to extract maximum power from a variable speed wind turbine based on squirrel cage induction machine drive (Amrane& Chaiba, 2018)(Becheri& Naimi, 2018). The strategy is based upon the monitoring and the judgment of the power rotational speed characteristic with the aim to find the optimum rotational speed that corresponds to the optimal produced power (Seghir et al., 2018)(Yaakoubi et al., 2018). Table 3 explains the MPPT strategies for wind turbine systems with their findings and disadvantages.

Table 3: MPPT strategies for wind turbine system with its findings and disadvantages

AUTHOR NAME	MPPT STRATEGIES	FINDINGS	DISADVANTAGES
(Sonet, 2018)	Optimal torque control (OTC), Tip speed ratio (TSR), and Hill climb search (HCS) control	Results indicated that the settling time for the HCS was longer than the TSR and the OTC methods	Quantity, proper placement, expected precision of the sensors, and the possible increment of the energy was not analyzed properly
(Uddin& Amin, 2018)	HCS Control and TSR	The applied controller reduces the steady-state power fluctuation of the DFIG when compared with a constant TSR-based MPPT controller at variable wind speeds.	The machine sometimes experiences severe jolt if the parameters of the TSR controller were not calculated precisely
(Leelakrishnan et al., 2020)	TSR	Analysis indicated that a TSR of 1.8 showed better performance with minor domain losses for low wind regional wind speed	It was impossible to have precise wind speed
(Chawda et al., 2020)	Incremental Conductance	Results showed that the applied strategy increases the output power of the wind turbine of solar up to 7% with the maximum power tracking of 0.1 s	Trade-off of a few watts with power loss of maximum power
(Zand et al., 2021)	Incremental Conductance	From simulation results, it was found that self-predictive incremental conductance was efficient when compared with another MPPT strategy	The method seemed to be complex
(Deng et al., 2020)	OTC	Simulation results indicated that comparing the existing method, the applied method enhances the accuracy of the effective wind speed estimation by 2-7% and the energy production efficiency by 0.35%.	Slow response for wind variations, resulting in the less energy capture

(Kadri et al., 2020)	OTC	Results showed the effectiveness of the applied control strategy and the energy management algorithm	It has a slow power transfer rate
(Ngo et al., 2020)	HCS	At times t = 0.4s and 0.7s, the wind speed changes, and the system with the Fuzzy controller set up faster than the system with the HCS controller	Strategy never makes a move towards a lower value guaranteed to be incomplete

(Saidi et al., 2020) explained the advanced non-linear integral back-stepping control (IBSC) design for variable speed wind turbine power maximization based on the TSR approach during a partial load operation. The applied method has a fast and robust tracking capability. Analysis showed that the best aerodynamic efficiency achievable results were 99.28% by the applied method. Sometimes tip speed ratio unnecessarily increases its speed.

(Bashetty et al., 2020) described the design of a robust adaptive controller for the pitch and torque control (ASPR) of wind turbines. Using MATLAB for three cases namely pitch control, torque control, and the combined case, simulation were done. Results indicate that this adaptive controller can be used for any size of wind turbine as long as the plant satisfies the ASPR condition. ASPR did not satisfy the relative degree condition.

(Novaes Menezes et al., 2018)explained the review on wind turbine control and its associated methods. Control of wind turbines plays a key role in wind energy applications. MPPT strategy named HCS and power signal feedback were used for the wind turbine control. From the analysis, it was found that simulations have been showing promising results for smart rotor applications. There was only lesser control methods had been tested for a wind turbine.

(M. B. H. Kumar et al., 2018)described the control techniques and methodologies for maximum power extraction from wind turbine systems. Power signal feedback (PSF) and TSR were the strategies used. From the analysis, it had been identified that MPPT of 98.04%, TSR of 92.32%, OTC of 90.66%, and PSF of 91.5% algorithms have better efficiency and give a fast response. Some methods used wind speed measuring instruments and few of them do not use the measurement of wind speed.

(Putri et al., 2018)explained the maximum power extraction improvement using a sensorless controller based on adaptive perturb and observe algorithm for PMSG wind turbine application. HCS and PSF strategies were used. Results indicated that the applied method can extract a higher maximum power and has a higher efficiency of 93.87% than the conventional P&O method. It was difficult to determine the effect of MPPT.

(Wu et al., 2020)investigated the wake characteristics and power generation efficiency of a small wind turbine under different TSRs. Significant findings indicated that the turbine at the TSR of 5.2 produces a smaller torque but a larger power output when compared with that at the TSR of 3.0. This comparison further displays that the turbine at the TSR of 5.2, even with larger power output, still produces a turbine wake that has smaller velocity deficits and smaller turbulence intensity.

(Posa, 2020)explained the influence of TSR on the wake features of a vertical-axis wind turbine. The present computational approach was validated by means of comparisons with Particle Image Velocimetry (PIV) experiments. Analysisshowed that at the highest simulated values of TSR > 2:0 coherence on the windward edge of the wake was mainly associated with the shear layer shed from the blades when they were facing the incoming freestream.

3. RESULTS AND DISCUSSION

This section explains the maximum power production enhancement using the yaw control method for wind turbines and the effect of the MPPT controller for the output power of the wind turbine along with a load resistance of 50 Ω. There are different types of yaw control work for a wind turbine for identifying maximum power increase. It had been compared, and can be concluded that the inline turbines with yaw angles of 20, 16, and 0 (Wind tunnel experiments)(Nouri et al., 2020); 3 by 3 wind farms 1st and 2nd rows only yawed (FLORIS)(van Zalk & Behrens, 2018); 12 turbines 6 yawed and 6 non yawed (FLORIS)(Howland et al., 2019) and 3 Inline turbines front row yawed by 20 degrees (LES) (J. Wang et al., 2017). Figure 2 explains the power production increase using the yaw control works for a wind turbine.

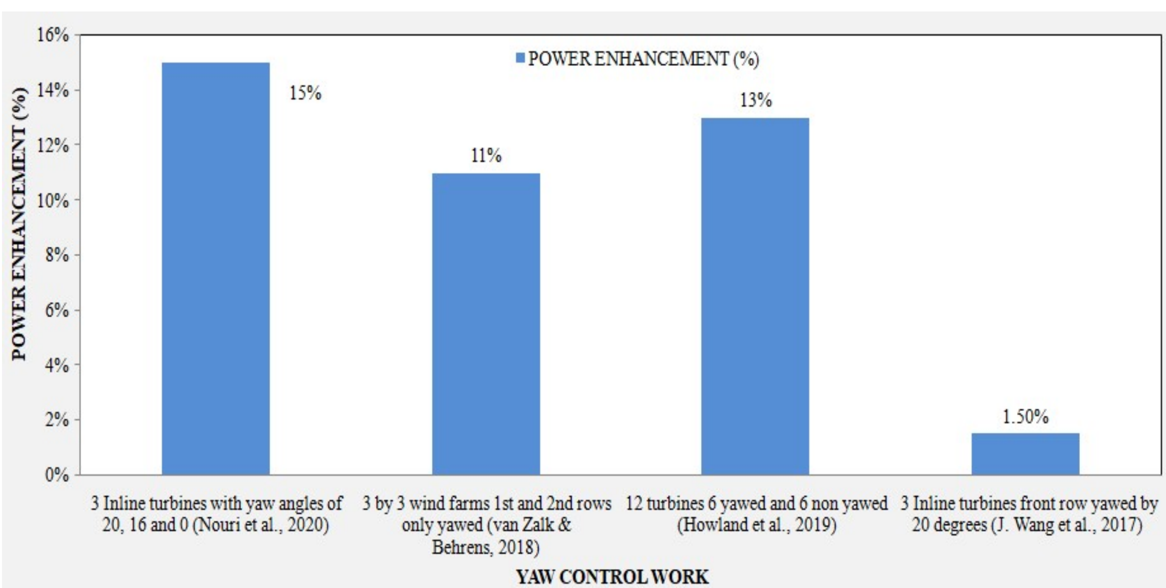

Figure 2: Power production increase using the yaw control works for wind turbine

It is clear from figure 2 that the work of yaw controls 3 Inline turbines with yaw angles of 20, 16, and 0 (Wind tunnel experiments)(Nouri et al., 2020)showed a higher power increase (15%) for wind turbines when compared with the other yaw control works. 3 Inline turbines front row yawed by 20 degrees (LES) (J. Wang et al., 2017) showed a lower production of 1.50% only. Further, the output power of the wind turbine along with load resistance of 50 Ω with the effect of the MPPT controller had been analyzed(Vaz et al., 2018). Figure 2 analyzes the effect of the MPPT controller for identifying the output power of the wind turbine along with a load resistance of 50 Ω.

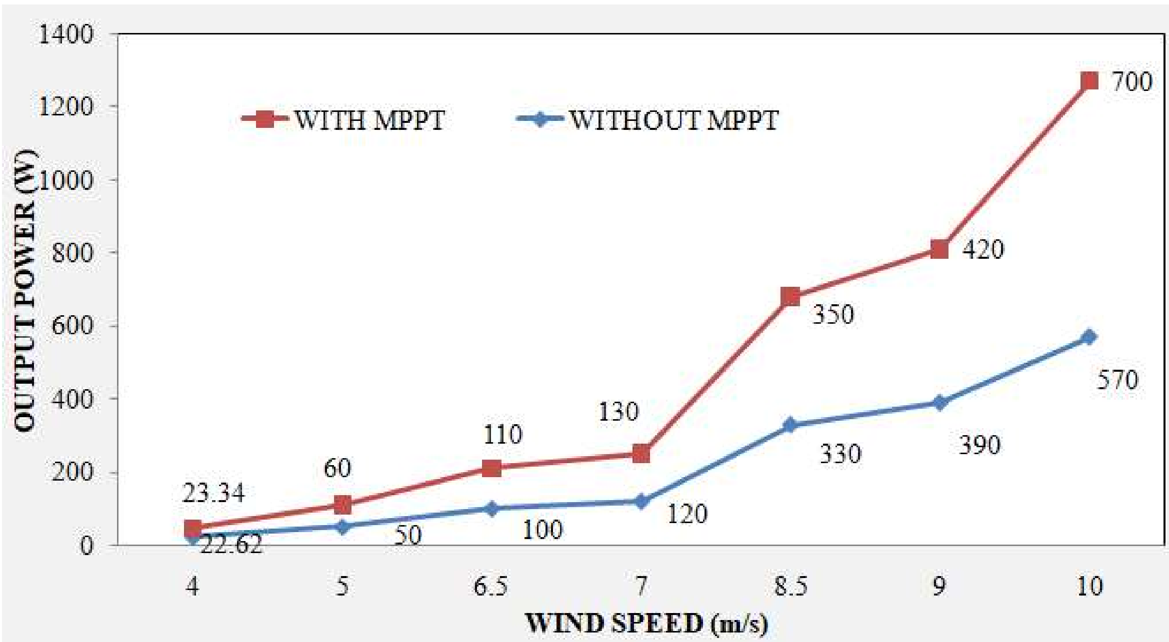

Figure 3: Output power identification of the wind turbine from MPPT controller with load resistance of 50 Ω

It was found from figure 3, the turbine system produced the output power of 23.34 W with MPPT at the wind speed of 4m/s. Similarly, for other wind speeds 5, 6.5, 7, 8.5, 9, and 10, analysis had been done and produced the output power of 60, 110, 130, 350, 420, and 700. Without MPPT at the wind speed of 4m/s, the turbine system received an output power of 22.62 W, which is lower than that of MPPT.(Syahputra & Soesanti, 2019)..

4. CONCLUSION

Wind turbine system has been receiving the widest attention among the various renewable energy systems. Extraction of maximum possible power from the available wind power has been an important research area among which wind speed sensor less MPPT control has been a very active area of research. The MPPT technology ensures the maximum output power of the wind turbine under the rated wind speed. It plays an important role in improving the efficiency of wind energy utilization. The optimal power curve is also a base for several MPPT methods. However, it will change with the change in running time and the external parameters. So in this paper, the effective method of MPPT method validating the output power of the wind turbine had been analyzed in the results section. The limitation is that these control methods and strategies have a few disadvantages like slow responses, Poor tracking, incorrect detection and complex method, etc. So for future research, the researchers should consider these disadvantages and find a solution for them.

REFERENCES

Abbas, N. J., Zalkind, D. S., Pao, L., & Wright, A. (2022). A reference open-source controller for fixed and floating offshore wind turbines. *Wind Energy Science*, *7*(1), 53–73. https://doi.org/10.5194/wes-7-53-2022

Amrane, F., & Chaiba, A. (2018). A novel direct power control for grid-connected doubly fed induction generator based on hybrid artificial intelligent control with space vector modulation. *Revue Roumaine Des Sciences Techniques Serie Electrotechnique et Energetique*, *61*(3), 263–268.

Asgharnia, A., Shahnazi, R., & Jamali, A. (2018). Performance and robustness of optimal fractional fuzzy PID controllers for pitch control of a wind turbine using chaotic optimization algorithms. *ISA Transactions*, *79*, 27–44. https://doi.org/10.1016/j.isatra.2018.04.016

Astolfi, D. (2021). Wind turbine operation curves modelling techniques. *Electronics (Switzerland)*, *10*(3), 1–18. https://doi.org/10.3390/electronics10030269

Azzouz, S., Messalti, S., & Harrag, A. (2019). Innovative PID-GA MPPT controller for extraction of maximum power from variable wind turbine. *Przeglad Elektrotechniczny*, *95*(8), 115–120. https://doi.org/10.15199/48.2019.08.26

Bashetty, S., Guillamon, J. I., Mutnuri, S. S., & Ozcelik, S. (2020). Design of a robust adaptive controller for the pitch and torque control of wind turbines. *Energies*, *13*(5), 1–22. https://doi.org/10.3390/en13051195

Becheri, H., & Naimi, A. (2018). Sensorless Speed for Powers Control of Wind Turbine Conversion Chaine Based on DFIG Using MPPT Strategy. *2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC)*, *13*(3), 1–11.

Chawda, G. S., Mahela, O. P., Gupta, N., Khosravy, M., & Senjyu, T. (2020). Incremental conductance based particle swarm optimization algorithm for global maximum power tracking of solar-PV under nonuniform operating conditions. *Applied Sciences (Switzerland)*, *10*(13), 1–16. https://doi.org/10.3390/app10134575

Chetouani, E., Errami, Y., Obbadi, A., & Sahnoun, S. (2021). Design of Optimal Backstepping Control for a Wind Power Plant System Using the Adaptive Weighted Particle Swarm

Optimization. *International Journal of Intelligent Engineering and Systems*, *14*(6), 125–136. https://doi.org/10.22266/ijies2021.1231.12

Deng, X., Yang, J., Sun, Y., Song, D., Yang, Y., & Joo, Y. H. (2020). An Effective Wind Speed Estimation Based Extended Optimal Torque Control for Maximum Wind Energy Capture. *IEEE Access*, *8*, 65959–65969. https://doi.org/10.1109/ACCESS.2020.2984654

Gao, Z., & Sheng, S. (2018). Real-time monitoring, prognosis, and resilient control for wind turbine systems. *Renewable Energy*, *116*, 1–4. https://doi.org/10.1016/j.renene.2017.10.059

Gonçalves, A. N. C., Pereira, J. M. C., & Sousa, J. M. M. (2022). Passive control of dynamic stall in a H-Darrieus Vertical Axis Wind Turbine using blade leading-edge protuberances. *Applied Energy*, *324*, 1–15. https://doi.org/10.1016/j.apenergy.2022.119700

Gou, L., Zhang, J., Li, N., Wang, Z., Chen, J., & Qi, L. (2022). Weighted assignment fusion algorithm of evidence conflict based on Euclidean distance and weighting strategy, and application in the wind turbine system. *PLoS ONE*, *17*(1 1), 1–20. https://doi.org/10.1371/journal.pone.0262883

Guerrero, J. M., Lumbreras, C., Reigosa, D. D., Garcia, P., & Briz, F. (2017). Control and Emulation of Small Wind Turbines Using Torque Estimators. *IEEE Transactions on Industry Applications*, *53*(5), 4863–4876. https://doi.org/10.1109/TIA.2017.2708027

Hosseini, E., Behzadfar, N., Hashemi, M., Moazzami, M., & Dehghani, M. (2022). Control of Pitch Angle in Wind Turbine Based on Doubly Fed Induction Generator Using Fuzzy Logic Method. *Journal of Renewable Energy and Environment*, *9*(2), 1–7. https://doi.org/10.30501/jree.2021.293546.1226

Howland, M. F., Lele, S. K., & Dabiri, J. O. (2019). Wind farm power optimization through wake steering. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(29), 14495–14500. https://doi.org/10.1073/pnas.1903680116

Ihedrane, Y., Bekkali, C. El, Bossoufi, B., & Bouderbala, M. (2019). Control of power of a DFIG generator with MPPT technique for wind turbines variable speed. *Green Energy and Technology*, 105–129. https://doi.org/10.1007/978-981-13-1945-7_5

Jianglin, L., Ron, P., & Xiaoyuan, Z. (2018). Fault-tolerant wind turbine pitch control using adaptive silding mode estimation. *Renewable Energy*, *116*, 219–231.

Kadri, A., Marzougui, H., Aouiti, A., & Bacha, F. (2020). Energy management and control strategy for a DFIG wind turbine/fuel cell hybrid system with super capacitor storage system. In *Energy* (Vol. 192). Elsevier Ltd. https://doi.org/10.1016/j.energy.2019.116518

Kumar, A., Khan, M. Z. U., & Pandey, B. (2018). Wind Energy: A Review Paper. *Gyancity Journal of Engineering and Technology*, *4*(2), 29–37. https://doi.org/10.21058/gjet.2018.42004

Kumar, M. B. H., Saravanan, B., Sanjeevikumar, P., & Blaabjerg, F. (2018). Review on control techniques and methodologies for maximum power extraction from wind energy systems. *IET Renewable Power Generation*, *12*(14), 1609–1622. https://doi.org/10.1049/iet-rpg.2018.5206

Leelakrishnan, E., Sunil Kumar, M., Selvaraj, D., Sundara Vignesh, N., & Abhesheka Raja, T. S. (2020). Numerical evaluation of optimum tip speed ratio for darrieus type vertical axis wind turbine. *Materials Today: Proceedings*, *33*, 4719–4722. https://doi.org/10.1016/j.matpr.2020.08.352

Li, M., Wang, M., Kang, J., Sun, L., & Jin, P. (2020). An opportunistic maintenance strategy for offshore wind turbine system considering optimal maintenance intervals of subsystems. *Ocean Engineering*, *216*, 1–12. https://doi.org/10.1016/j.oceaneng.2020.108067

Manerikar, S. S., Damkale, S. R., Havaldar, S. N., Kulkarni, S. V, & Keskar, Y. A. (2021). Horizontal axis wind turbines passive flow control methods: a review. *IOP Conference Series: Materials Science and Engineering*, *1136*(1), 1–18. https://doi.org/10.1088/1757-899x/1136/1/012022

Mishra, J., Pattnaik, M., & Samanta, S. (2020). Drift-Free Perturb and Observe MPPT Algorithm with Improved Performance for SEIG-Based Stand-Alone Wind Energy Generation System. *IEEE Transactions on Power Electronics*, *35*(6), 5842–5849. https://doi.org/10.1109/TPEL.2019.2952324

Mohammadi, E., Fadaeinedjad, R., & Naji, H. R. (2018). Flicker emission, voltage fluctuations, and mechanical loads for small-scale stall- and yaw-controlled wind turbines. *Energy Conversion and Management*, *165*, 567–577. https://doi.org/10.1016/j.enconman.2018.03.094

Mohammadi, E., Fadaeinedjad, R., Shariatpanah, H., & Moschopoulos, G. (2017). Performance evaluation of yaw and stall control for small-scale variable speed wind turbines. *Canadian Conference on Electrical and Computer Engineering*, 1–4. https://doi.org/10.1109/CCECE.2017.7946599

Mokhtari, Y., & Rekioua, D. (2018). High performance of Maximum Power Point Tracking Using Ant Colony algorithm in wind turbine. *Renewable Energy*, *126*, 1055–1063. https://doi.org/10.1016/j.renene.2018.03.049

Mousa, H. H. H., Youssef, A. R., & Mohamed, E. E. M. (2019). Variable step size P&O MPPT algorithm for optimal power extraction of multi-phase PMSG based wind generation system. *International Journal of Electrical Power and Energy Systems*, *108*, 218–231. https://doi.org/10.1016/j.ijepes.2018.12.044

Mousavi, Y., Bevan, G., & Kucukdemiral, I. B. (2022). Fault-tolerant optimal pitch control of wind turbines using dynamic weighted parallel firefly algorithm. In *ISA Transactions* (Vol. 128). https://doi.org/10.1016/j.isatra.2021.10.019

Nair, R., & Narayanan, G. (2020). Emulation of Wind Turbine System Using Vector Controlled Induction Motor Drive. *IEEE Transactions on Industry Applications*, *56*(4), 4124–4133. https://doi.org/10.1109/TIA.2020.2987993

Ngo, Q. V., Yi, C., & Nguyen, T. T. (2020). The maximum power point tracking based-control system for small-scale wind turbine using fuzzy logic. *International Journal of Electrical and Computer Engineering*, *10*(4), 3927–3935. https://doi.org/10.11591/ijece.v10i4.pp3927-3935

Nguyen, T. T., & Kim, H. M. (2021). Cluster-based predictive PCC voltage control of large-scale offshore wind farm. *IEEE Access*, *9*, 4630–4641. https://doi.org/10.1109/ACCESS.2020.3048175

Nouri, R., Vasel-Be-Hagh, A., & Archer, C. L. (2020). The Coriolis force and the direction of rotation of the blades significantly affect the wake of wind turbines. *Applied Energy*, *277*, 1–23. https://doi.org/10.1016/j.apenergy.2020.115511

Novaes Menezes, E. J., Araújo, A. M., & Bouchonneau da Silva, N. S. (2018). A review on wind turbine control and its associated methods. *Journal of Cleaner Production*, *174*, 945–953. https://doi.org/10.1016/j.jclepro.2017.10.297

Palanimuthu, K., Mayilsamy, G., Lee, S. R., Jung, S. Y., & Joo, Y. H. (2022). Fault Ride-through for PMVG-based Wind Turbine System Using Coordinated Active and Reactive Power Control Strategy. *IEEE Transactions on Industrial Electronics*, 1–11. https://doi.org/10.1109/TIE.2022.3194638

Patil, A. K., & Thosar, A. (2022). Wind Turbine Faults, Faults Diagnosis and Fault Management Systems: A Review. *Mathematical Statistician and Engineering Applications*, *71*(4), 5134-5152.

Patil, A., & Thosar, A. (2020, February). Fault Simulation and Severity Analysis in Wind Energy System. In *2020 International Conference on Industry 4.0 Technology (I4Tech)* (pp. 7-12). IEEE.

Pelin, R. I., Barsănescu, P. D., & Tiţa, I. (2018). Hydraulic systems used for pitch control of wind turbines: A literature overview. *IOP Conference Series: Materials Science and Engineering*, *444*(4), 1–9. https://doi.org/10.1088/1757-899X/444/4/042013

Porté-Agel, F., Bastankhah, M., & Shamsoddin, S. (2020). Wind-Turbine and Wind-Farm Flows: A Review. In *Boundary-Layer Meteorology* (Vol. 174, Issue 1). Springer Netherlands. https://doi.org/10.1007/s10546-019-00473-0

Posa, A. (2020). Influence of Tip Speed Ratio on wake features of a Vertical Axis Wind Turbine. *Journal of Wind Engineering and Industrial Aerodynamics*, *197*, 1–13. https://doi.org/10.1016/j.jweia.2019.104076

Priyadarshi, N., Padmanaban, S., Bhaskar, M. S., Blaabjerg, F., & Sharma, A. (2018). Fuzzy SVPWM-based inverter control realisation of grid integrated photovoltaicwind system with fuzzy particle swarm optimisation maximum power point tracking algorithm for a grid-connected PV/wind power generation system: Hardware implementation. *IET Electric Power Applications*, *12*(7), 962–971. https://doi.org/10.1049/iet-epa.2017.0804

Putri, R. I., Pujiantara, M., Priyadi, A., Ise, T., & Purnomo, M. H. (2018). Maximum power extraction improvement using sensorless controller based on adaptive perturb and observe algorithm for PMSG wind turbine application. *IET Electric Power Applications*, *12*(4), 455–462. https://doi.org/10.1049/iet-epa.2017.0603

Qi, Y., Xu, S., & Huang, D. (2021). Investigation on aerodynamic performance of horizontal axis wind turbine by setting micro-plate in front of the blade leading edge. *Renewable Energy*, *179*, 2309–2321. https://doi.org/10.1016/j.renene.2021.08.035

Renewable Resources. (2022). *National Geographic*. https://education.nationalgeographic.org/resource/renewable-resources

Sabzevari, S., Karimpour, A., Monfared, M., & Naghibi Sistani, M. B. (2017). MPPT control of wind turbines by direct adaptive fuzzy-PI controller and using ANN-PSO wind speed estimator. *Journal of Renewable and Sustainable Energy*, *9*(1), 1–15. https://doi.org/10.1063/1.4973447

Sahu, B. K. (2018). Wind energy developments and policies in China: A short review. *Renewable and Sustainable Energy Reviews*, *81*, 1393–1405. https://doi.org/10.1016/j.rser.2017.05.183

Saidi, Y., Mezouar, A., Miloud, Y., Kerrouche, K. D. E., Brahmi, B., & Benmahdjoub, M. A. (2020). Advanced non-linear backstepping control design for variable speed wind turbine power maximization based on tip-speed-ratio approach during partial load operation. *International Journal of Dynamics and Control*, *8*(2), 615–628. https://doi.org/10.1007/s40435-019-00564-3

Savino, M. M., Manzini, R., Della Selva, V., & Accorsi, R. (2017). A new model for environmental and economic evaluation of renewable energy systems: The case of wind turbines. *Applied Energy*, *189*, 739–752. https://doi.org/10.1016/j.apenergy.2016.11.124

Sawant, M., Thakare, S., Rao, A. P., Feijóo-Lorenzo, A. E., & Bokde, N. D. (2021). A review on state-of-the-art reviews in wind-turbine-and wind-farm-related topics. *Energies*, *14*(8), 1–30. https://doi.org/10.3390/en14082041

Seghir, B., Chandra, A., & Miloud, R. (2018). A New Control Strategy for Power Quality Improvement Using MPPT from Hybrid PV-Wind Connected to the Grid. *Canadian Conference on Electrical and Computer Engineering*, 1–6. https://doi.org/10.1109/CCECE.2018.8447644

Sierra-Garcia, J. E., & Santos, M. (2022). Deep learning and fuzzy logic to implement a hybrid wind turbine pitch control. *Neural Computing and Applications*, *34*(13), 10503–10517. https://doi.org/10.1007/s00521-021-06323-w

Sonet, M. (2018). *Sonet Mollick Design and Implementation of Maximum Power Point Tracking Algorithms for Wind Energy Conversion*.

Syahputra, R., & Soesanti, I. (2019). Performance improvement for small-scale wind turbine system based on maximum power point tracking control. *Energies*, *12*(20), 1–18. https://doi.org/10.3390/en12203938

Uddin, M. N., & Amin, I. K. (2018). Adaptive Step Size Based Hill-Climb Search Algorithm for MPPT Control of DFIG-WECS With Reduced Power Fluctuation and Improved Tracking Performance. *Electric Power Components and Systems*, *46*(19–20), 2203–2214. https://doi.org/10.1080/15325008.2018.1533603

Ullah, T., Javed, A., Abdullah, A., Ali, M., & Uddin, E. (2020). Computational evaluation of an optimum leading-edge slat deflection angle for dynamic stall control in a novel urban-scale vertical axis wind turbine for low wind speed operation. *Sustainable Energy Technologies and Assessments*, *40*, 1–20. https://doi.org/10.1016/j.seta.2020.100748

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

Vaz, J. R. P., Wood, D. H., Bhattacharjee, D., & Lins, E. F. (2018). Drivetrain resistance and starting performance of a small wind turbine. *Renewable Energy*, *117*, 509–519. https://doi.org/10.1016/j.renene.2017.10.071

Veers, P., Bottasso, C. L., Manuel, L., Naughton, J., Pao, L., Paquette, J., Robertson, A., Robinson, M., Ananthan, S., Barlas, A., Bianchini, A., Bredmose, H., Horcas, S. G., Keller, J., Madsen, H. A., Moriarty, P., Nolet, S., & Rinker, J. (2022). Grand Challenges in the Design , Manufacture , and Operation of Future Wind Turbine Systems. In *Wind Energy Science*.

Venkatramakrishnan, S. R., Pandey, J. K., Mondal, A. K., & Karn, A. (2020). Low speed wind turbines for power generation: A review. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *67*(1), 146–169.

Wang, H., Yang, J., Chen, Z., Ge, W., Ma, Y., Xing, Z., & Yang, L. (2018). Model Predictive Control of PMSG-Based Wind Turbines for Frequency Regulation in an Isolated Grid. *IEEE Transactions on Industry Applications*, *54*(4), 3077–3089. https://doi.org/10.1109/TIA.2018.2817619

Wang, J., Foley, S., Nanos, E. M., Yu, T., Campagnolo, F., Bottasso, C. L., Zanotti, A., & Croce, A. (2017). Numerical and Experimental Study of Wake Redirection Techniques in a Boundary Layer Wind Tunnel. *Journal of Physics: Conference Series*, *854*(1), 1–13. https://doi.org/10.1088/1742-6596/854/1/012048

Wind energy solutions. (2022). *GE renewable energy* https://education.nationalgeographic.org/resource/renewable-resources

Wu, Y. T., Lin, C. Y., & Hsu, C. M. (2020). An experimental investigation of wake characteristics and power generation efficiency of a small wind turbine under different tip speed ratios. *Energies*, *13*(8), 1–19. https://doi.org/10.3390/en13082113

Yaakoubi, A. E., El Harrak Hajri, M., Attari, K., Amhaimar, L., & Asselman, A. (2018). Advanced control strategies of SCIG based wind turbines for MPPT. *ACM International Conference Proceeding Series*, 1–5. https://doi.org/10.1145/3286606.3286813

Yang, B., Yu, T., Shu, H., Zhang, Y., Chen, J., Sang, Y., & Jiang, L. (2018). Passivity-based sliding-mode control design for optimal power extraction of a PMSG based variable speed wind turbine. *Renewable Energy*, *119*, 577–589. https://doi.org/10.1016/j.renene.2017.12.047

Youssef, A. R., Ali, A. I. M., Saeed, M. S. R., & Mohamed, E. E. M. (2019). Advanced multi-sector P&O maximum power point tracking technique for wind energy conversion system. *International Journal of Electrical Power and Energy Systems*, *107*, 89–97. https://doi.org/10.1016/j.ijepes.2018.10.034

Youssef, A. R., Mohamed, E. E. M., & Ali, A. I. M. (2018). Model predictive control for grid-tie wind-energy conversion system based PMSG. *Proceedings of 2018 International Conference on Innovative Trends in Computer Engineering, ITCE 2018*, 467–472. https://doi.org/10.1109/ITCE.2018.8316668

Zand, S. J., Hsia, K., Eskandarian, N., & Mobayen, S. (2021). Improvement of self-predictive Incremental Conductance. *Energies*, *14*, 1–14.

Zhang, L., Gu, J., Zhu, H., Hu, K., Li, X., Jiao, L., Miao, J., Liu, J., & Wang, Z. (2021). Rationality research of the adjustment law for the blade pitch angle of H-type vertical-axis wind turbines. *Renewable Energy*, *167*, 484–496. https://doi.org/10.1016/j.renene.2020.11.104

Zhang, Z., Fang, H., Gao, F., Rodriguez, J., & Kennel, R. (2017). Multiple-vector model predictive power control for grid-tied wind turbine system with enhanced steady-state control performance. *IEEE Transactions on Industrial Electronics*, *64*(8), 6287–6298. https://doi.org/10.1109/TIE.2017.2682000

Zhao, X., Lin, Z., Fu, B., & Gong, S. (2021). Research on frequency control method for micro-grid with a hybrid approach of FFR-OPPT and pitch angle of wind turbine. *International Journal of Electrical Power and Energy Systems*, *127*, 1–10. https://doi.org/10.1016/j.ijepes.2020.106670

Zhao, X., Xue, Y., & Zhang, X. P. (2020). Fast frequency support from wind turbine systems by arresting frequency nadir close to settling frequency. *IEEE Open Access Journal of Power and Energy*, *7*(1), 191–202. https://doi.org/10.1109/OAJPE.2020.2996949

Zhu, C., Wang, T., Chen, J., & Zhong, W. (2020). Effect of single-row and double-row passive vortex generators on the deep dynamic stall of a wind turbine airfoil. *Energies*, *13*(10), 1–11. https://doi.org/10.3390/en13102535