Journal of Digital Food, Energy & Water Systems [JD-FEWS]

JDFEWS 5 (2): 1-16, 2024
ISSN 2709-4529

Micro-Grid Wind Energy Conversion System: Conventional and Modern Technologies - A Review

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Received: 30 July 2024

Review: 26 October 2024

Accepted: 13 December 2024

Published: 16 December 2024

Abstract - This paper thoroughly looks at how well the introduction of modern technology, especially an artificial neural network-based control mechanism, works compared to other conventional control methods in the applications of electric microgrid wind energy conversion systems. The study uses data analytic method to compare modern proposed technology (MPT) and conventional conversion systems (CCS) for controlling wind turbine systems by examining their advantages and disadvantages via data analysis methodology. Furthermore, the study explained the key factors influencing power quality output during the conversion process, such as pitch angle control, power coefficient, and tip speed ratio, across both methodologies. Poorer power quality results from the conventional conversion technologies' requirement to use mechanical sensors to alter the turbine rotor's rotational velocity. However, with the advent of artificial neural networks, mechanical sensors are no longer necessary, and power quality output is improved with little to no impact on wind turbine rotors. Therefore, compared to the conventional wind energy conversion system (WECS), introducing artificial neural networks with microcontrollers has demonstrated positive outcomes as one of the latest technologies. Hence, this study aims to identify key research areas and assist researchers and experts in gaining a current and thorough understanding of the efficacy of neural network applications in wind energy conversion systems.

***Keywords**:* Artificial *Neural Network, Wind Energy Conversion System, modern technologies, conventional methods.*

JDFEWS 5 (2): 1-16, 2024
ISSN 2709-4529

1.0 Introduction

Recent research has demonstrated that incorporating renewable energy sources (RES), including wind energy, into microgrid systems has attracted significant interest because of its multiple advantages, including less reliance on fossil fuels and lowered carbon emissions [1]. Given the rising demand for electricity and the exhaustion of traditional energy sources, it is imperative to augment electricity production by utilizing renewable energy sources such as wind and solar energy, among others [2]. Also, due to the need for an efficient and clean power system and the challenges associated with conversion, it is crucial for researchers to concentrate on the reliability and stability of system control within a power conversion framework. This study categorizes energy generation systems into two primary groups based on their potential exhaustibility: renewable power systems and conventional power systems, to ensure power quality from the green energy system. In reaction to the increasing demand for electricity in the 21st century, power generation systems scaled up, utilizing wind energy across capacities from several kilowatts to numerous megawatts [3]. This research examines green energies, mainly wind energy conversion systems (WECS), in the context of both conventional and modern harvesting methods. Research indicates that wind turbines are the primary component of the WECS, and they function primarily through rotors and blades. Characteristics such as pitch angle, power coefficient, and tip speed ratio influence the efficiency of these elements. The tip speed ratio (TSR) within regulatory limits can optimize turbine performance, particularly when the ratio is smaller than 1 [4].

Considering the difficulties posed by the wind turbine and its blades when controlled conventionally, conventional control is linked to mechanical control using sensors, which typically entail mechanical losses that lead to an output of low quality [5]. However, to remove the sensor influence on the mechanical output of wind turbines, it is necessary to implement contemporary technologies like grid-side converters (GSC), fuzzy logic controllers (FLC), and particle swarm optimisation (PSO). Also, to address these issues, researchers have presented an artificial neural network algorithm to regulate wind turbines. The effectiveness of this algorithm is thus evaluated by comparing previous research in this area using data analytical techniques.

2.0 Research Methodology

The number of publications on the application of conventional and modern technology in wind energy conversion system applications was investigated in this study through WEB sources via a data analysis methodology, which is synonymous with a systematic literature review (SLR). Pitch angle, tip speed ratio, and power coefficient—three key factors affecting the power output quality—are the main areas of focus for the artificial neural network controller's effectiveness on the wind turbine and its blade. The work of [6] shows that in global estimates, WECS is among the rapidly expanding technologies for energy sources, based on existing data regarding wind abundance in natural phenomena. Furthermore, the study of Ref [7] offers valuable insights into assessing the efficacy of WECS that employ both conventional and modern harvesting techniques. Consequently, in addressing the issue of mechanical strain on the turbine blade, a conventional approach is proposed for adjustments of both full-load and partial-load conditions. The operational series of a WECS dependent on wind speed is shown in Figure 1 and affects the performance of TSR tracking [8][9]. This calls for a more advanced technique for monitoring the maximum power point in WECS, as shown in the sketch, which involves determining the cut-out and cut-in speeds at a rated wind speed [10].

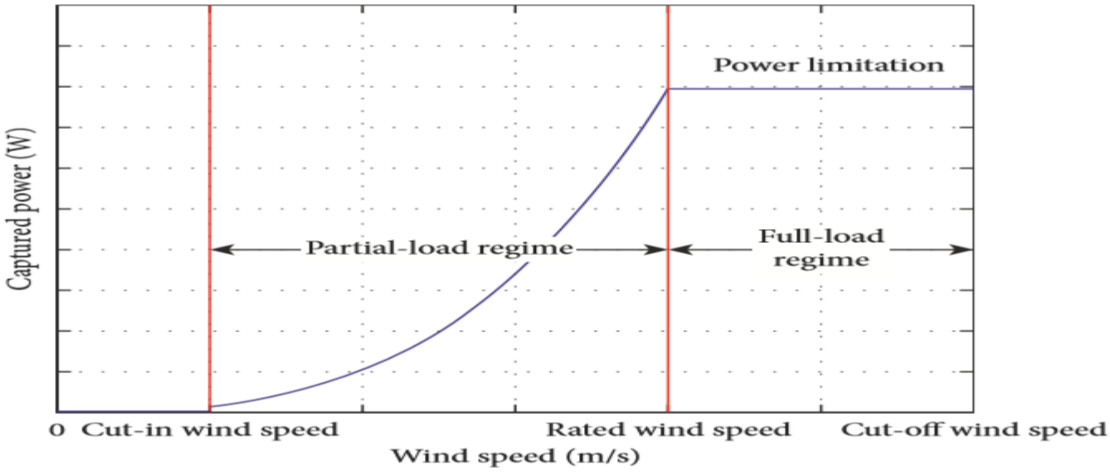


Figure 1 Wind Speed Operational Mode [14].

3.0 Wind energy conversion system under conventional systems

Figure 2 illustrates the mechanism through which the blade, located on the rotor hub, transforms the wind's kinetic energy into mechanical energy. The low-speed shaft, functioning as the principal shaft, firmly connects the hub. The generator transforms mechanical energy into electrical energy via the drive train. Electricity converter systems perform an intermediary between the grid and the generators, enabling the flow of electricity from the generator to the grid. These mechanisms are chiefly accountable for the conversion process, as corroborated by [2] in conventional technology. Ref [11], in their work's on conventional methodology, established that WEC system comprises two primary electrical components: the generator and the power converter. The author presents a realistic operation of the wind turbine power converter for WECS, utilizing independently stimulated DC motor control for converting kinetic energy into electrical energy with little mechanical losses.

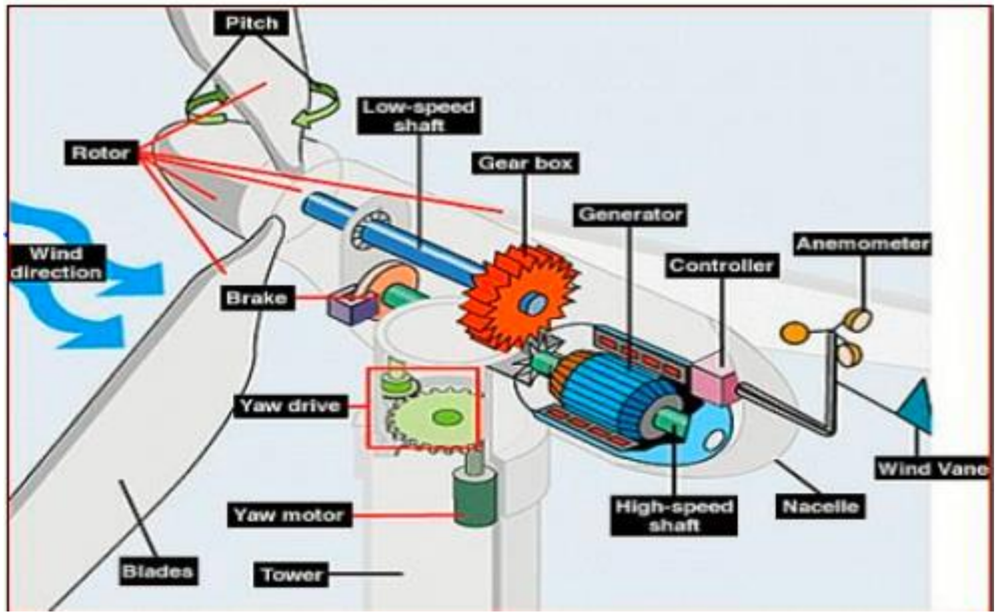
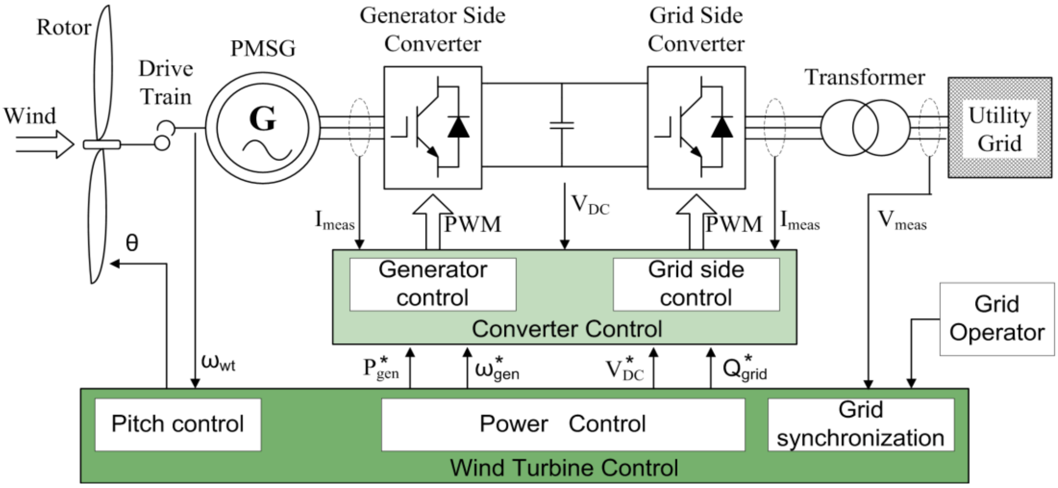


Figure 2: Side View of a Typical WEC System [2]

Also, in the work of [12], the author established that due to the unpredictability of wind, the voltages generated by the generator display persistent swings in both frequency and amplitude and lead to power loss in the energy generation. Ref [13] proves that the generated electric power is unsuitable for standard operational loads due to the parameters' variability, leading to so much energy wasted.

Also, a crucial aspect of the conversion process involves pitch control, power management, and synchronous grid operations, as illustrated in Figure 3, which depicts the entire wind turbine generator and its converter in operation [15]. When wind speeds exceed the specified threshold, the pitch angle control mechanism activates, thereby ensuring stable power generation [16] by modifying the turbine blade angle in relation to the wind speed rating value, which serves as the power control variable that may lead to unstable mechanical power output [17] under the conventional system. [18]. The TSR has a big impact on the power efficiency of WEC and an important part of wind turbine design because it quantifies the correlation between wind velocity and the velocity of the blade tips [19]. To study how blade solidity affects micro scale wind turbines with lower TSR, the blades need to be made stronger to overcome the torque frictions for their mechanical part and start working [20]; otherwise, the mechanical power output efficiency will be affected. Also, using conventional approaches, many control methods have been developed to obtain high-quality power from wind turbine generators. A good example is the adjustment of wind turbines using permanent magnet generators (PMG), adjusting the turbine rotor speed, and synchronizing the generators, among others. All these innovations aim to evaluate the efficiency of energy generation by improving control over the primary parameters influencing wind turbine operation in the WECS under conventional evaluations but come with imitations [14].



4.0 Power Coefficient, Pitch Angle, and Tip Speed Ratio Operations

Pitch angle, tip speed ratio, and power coefficient are the three main control factors that can be managed using various algorithms or contemporary controllers like maximum power point tracking (MPPT), maximum power control (MPC), magnetic synchronous controls (MSC), generator synchronous controls (GSC), pitch angle control (PAC), power coefficient (PC), and artificial neural networks (ANN), among others, in light of the many difficulties with the current methods and controls of wind energy harvesting in the WECS.

The International Electrotechnical Commission (IEC) designated the power coefficient (Cp) as a critical metric for assessing wind turbine performance [21]. The Cp quantifies the correlation between actual power output and the wind power available to the turbine blades. The results indicate that the electrical power generated by wind turbines is mostly affected by the performance coefficient, but the mechanical power is exactly proportional to the cube of the wind speed [22]. The Cp of a horizontal axis turbine is often affected by various factors, including

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ISSN 2709-4529

the number of blades, the TSR (λ), and the blade pitch angle (β). The Cp of a turbine is defined as the coefficient power tip speed ratio and pitch angle, respectively Cp (λ, β), which indicates the turbine's efficiency, together with the blade TSR and the pitch angle, respectively [23] and [24]. Blade pitch actuators control the speed of the rotor, which lowers the wind turbine's mechanical torque output and performance coefficient. The three-blade and the horizontal-axis models have been proven to be the most common types of wind turbines [25]. In [26], the authors show how to use a proportional-integral (PI) controller to control the pitch angle with the goal of keeping the output voltage constant. Pitch angle control is the most efficient technique for modifying a wind turbine's aerodynamic thrust when wind speed surpasses the rated speed conventionally. Incorporating sliding mode control, feedforward, and feedback systems into the robust wind turbine systems' robust controller improves pitch angle control's reliability [27]. The blade element momentum (BEM) method, Buhl's wake state model, and the Viterna-Corrigan post-stall model, all can enhance the Cp of a tiny wind turbine rotor. This subsequently enhances the efficiency of energy production, as indicated by [28].

Another crucial parameter is the TSR, whose operation significantly impacts the quality of power production in the WECS. Figure 4 presents a standard TSR control block diagram with an implementation of the TSR controller. The results demonstrated that an increase in the TSR correlates with a drop in the ideal maximum power, indicating a direct influence of the TSR on power production. It has been shown that a simulated Savonius turbine reached its highest power coefficient of 0.31 at a TSR of 0.97, proving that a hybrid turbine works well [29]. Ref [30] looks at how TSR affects the performance of Savonius wind turbines with flexible blades using a quasi-2D model and a two-way fluid-structure interaction method, with the goal being to improve aerodynamic efficiency. It has also been demonstrated that the TSR influences the aerodynamic noise of a small wind turbine while maintaining an optimal power output [31]. To enhance energy output while maintaining a low rotor speed, it is unwise to use a uniform turbine-specific rating across all turbines in a wind farm [32].

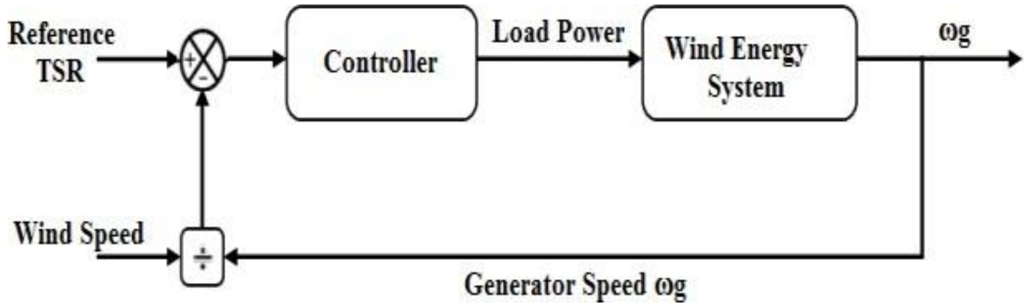

Figure 4. Block diagram of TSR-based MPPT control [29].

5.0 Artificial Neural Network Based Control

Having examined and evaluated different controllers on WECS, an artificial neural network is evaluated and proposed in this review work. An ANN is a computational model that simulates the human brain's operations to provide novel solutions. The term "Modern operating systems" refers to specialized operating systems made for systems, like FreeRTOS, VxWorks, Embedded Linux, and ANN. Numerous fields, such as industrial automation, robotics, power control systems, and energy systems, use modern technology.

According to Ref [33], to enhance power quality (PQ) in wind energy conversion systems (WECS), the author used a neural network (NN) controller for pitch angle management by backpropagation training, as illustrated in Figure 5. Using a multi-layer perceptron backpropagation ANN (MLP-BP ANN) and a dynamic voltage restorer (DVR) as a series compensator, the author created a model matrix in his study that produces an enhanced mechanical power output. By tracking wind speed faster than an anemometer WECS operation, ANN can efficiently monitor turbine maximum power in static and dynamic circumstances [34].

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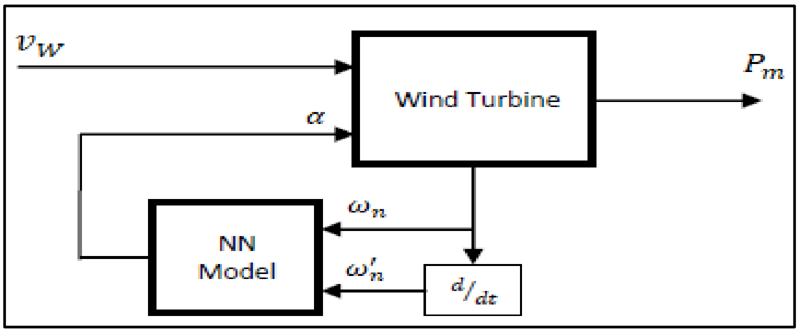

Figure 5 Block Diagram of NN Control Based of pitch angle in WEC system [33]

6.0 Wind Energy Integrations to the Grid with modern technology

Rapid industrial knowledge advancement has led to improved control algorithms in connecting WECS to the grid [35, 36]. Research indicates that in early wind turbine systems, it was common to directly link a wind turbine to the electrical grid, a method occasionally termed the "Danish concept." The AC grid can interconnect a wind farm at multiple voltage levels, ranging from low to very high. A high-voltage alternating current (HVAC) transmission system and an insulated bipolar voltage-source converter (VSC), both suitable for grid connections, can achieve this [37]. Ref [38] proposed that a grid connection with a soft start efficiently decreases peak currents, alleviating stress on the gearbox and limiting the impact on the power system, along with related expenses. During an inquiry, [39] advocates for energy transition using power-electronic systems to incorporate energy from renewable sources into the electric grid. The findings reveal that the integration of renewable energy sources with power electronics, which represents one of the traditional methods of integration in WECS, significantly impacts system stability in multiple ways [40]. The low inertia of wind turbines inside synchronous renewable grids hinders reliable power modulation in the traditional system, but rapid power reserve management, an alternative approach, facilitates this without requiring exact grid frequency measurements [41]. While [42] submitted that a power grid often uses phase-locked loop (PLL) procedures to connect to the main electrical network when it is operating under a certain control scheme, [43] suggested that a genetic algorithm could be used on a double-fed induction generator (DFIG) to add power to the power grid using modern methods. Figure 6 depicted the representation and regulation of a wind energy system connecting to the grid through doubly fed induction generators. A rotor-side filter, a grid-side filter, an MPPT controller, a DC-link capacitor, and three-phase voltage source converters (VSCS) and their controller are some of the parts that make up the system of DFIG-based wind turbines.

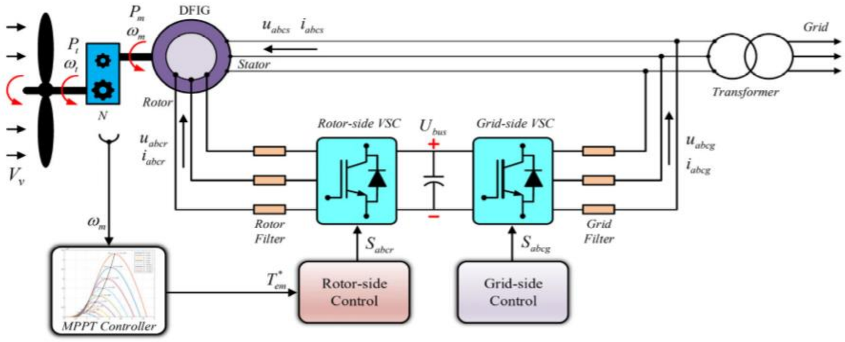

Figure 6. Designing Speed Wind Turbine with (DFIG). [43].

This advanced technology's output response demonstrates enhanced power delivery efficiency [44]. However, [45] posits that using a multipole permanent magnet synchronous generator (PMSG) with MPPT controller is better than a DFIG. This is because the PMSG doesn't need a gearbox, has lower losses, requires less maintenance, and is lighter, more efficient, more reliable, and does not need an external excitation current when connecting to the grid [46]. In conclusion, Ref [47] said that a sliding-mode controller (SMC) design makes it easier to control nonlinear systems and gives stable systems strong and flexible responses. Similarly, [48] confirms this assertion.

The study in [49] develops a Sliding Mode Control (SMC) for wind turbine systems employing a dual-output asynchronous generator directly connected to the power grid, enhancing stability in both frequency and voltage. Ref [50] found that system faults, device failures, load disconnections, and changes in generated power all influence the power balance of electric networks. However, modern controller technology can help fix these problems. However, a later study shows that adding wind energy to the power grid greatly affects how well the system works. Because of this, Ref [51] suggested that using the Distribution Static Compensator (DSTATCOM) and Battery Energy Storage System (BESS) together can improve the power quality of the grid-connected WECS. Ref [52] proposes integrating a fuzzy logic controller with a phase-locked loop (PLL) approach to improve the quality and efficiency of electricity transmission to the grid. Although solid-state transformers (SSTs) can integrate voltage conversion, reactive power correction, and active power transmission, no study has comprehensively examined the full utilization of all SST compensatory functions, as found in [53]. Thus, the authors introduce a novel type of wind farm design utilizing an SST interface, which basically replaces the traditional reactive power compensator and grid connections [54].

The various types of WECS that were empirically examined to determine which generated the most power and which performed better with contemporary technology than the earlier approaches are listed in Table 1. Similarly, there are contemporary methods like artificial neural networks (ANN), magnetic synchronous controls (MSC), generator synchronous controls (GSC), pitch angle control (PAC), power coefficient (PC), maximum power point tracking (MPPT), maximum power control (MPC), and more.

Table 1: The empirical summary table

Author's Names and Year of Publication	Wind Energy System	Algorithm/Controller	Methodology/Software Used	Inference Drawn/GAP	Performance Metrics
Guediri et al. (2023).	WT+DFIG	Hybrid Genetic Algorithm (GA) controller	Multilevel Inverter (MLI) technique; MPPT technique Active and reactive energy control MATLAB/SIMULINK	GA offers greater efficiency, significant results and enhanced stability to WT, compared to classic PI regulator	WT stability improvement Power quality enhancement
Chen et al. (2023)	WT-driven PMSG	Gray Wolf Optimization (GWO) algorithm Blade Pitch controller	Model predictive control technique Blade pitch control MATLAB	Direct control of WT output power was realized across various wind speeds. GWO exhibited slightly fast minimization times compared to MATLAB's unconstrained optimization function. The approach offers WT independent control and mechanical stability.	WT stability augmentation. Regulation/maximization of load output power. Enhancement of power generation efficiency.
Sharma (2023)	PV-Wind hybrid RES	Modified Fuzzy Logic controller (FLC)	Shunt active power filtering MPPT technique Electromagnetic control method MATLAB/SIMULINK	Electromagnetic control's effectiveness depends on DC link capacitor voltage control.	Power quality enhancement System voltage profile enhancement Overall system power factor Reduction of system peak losses.

Rawa et al. (2023)	Hybrid RES	DVR-PI controller Gorilla Troops Algorithm (GTA)	DVR control MATLAB/SIMULINK	DVR-PI controller exhibited fast response and minimal objective function. The control technique excelled in voltage quality and harmonic rejection.	Power quality enhancement. System voltage profile enhancement.
Junejo, Gilal, and Doh (2023)	H-type VAWT	Physics-informed optimization Multi-objective Grey Wolf Optimization (GWO)	Advanced Direct Vector control WT rotational speed control Matrix Inequality (MI) technique SIMULINK, CFD tools	WT power efficiency significantly increased. Low-inertia turbines ideal for maximum power conversion.	Enhancement of WT power efficiency Improvement of power output and system stability Improvement of active power gain Optimization of WT power conversion
Aghaei et al. (2023)	VAWT	Radial Basis Function Neural Networks (RBFNN) controller Markov chain Monte Carlo (MCMC) algorithm	Reinforcement Learning (RL) technique MATLAB	Proposed method specifically addressed limitations typically associated with conventional solutions. Algorithm-controller combination outperforms MPPT. Total energy output was maximized, rather than instantaneous output power.	Maximization of WT output power Optimization of WT power output Improvement of power capturing
Pourrajabian et al. (2022)	HAWT	GA optimization algorithm	Blade Geometry control Tip Speed Ratio (TSR) control MATLAB	GA optimization minimized emitted noise along with the maximized power coefficient.	Maximization of WT output power.

Hosseini et al. (2022)	WT	Jensen Wake Model + Particle Swarm Optimization (PSO)	Tip Speed Ratio (TSR) control Computational Fluid Dynamics (CFD) tools/Large-Eddy Simulation (LES)	TSR reduction mitigates noise, bird/bat collisions, and leading-edge erosion; it addresses environmental concerns.	Reduction of wake losses Turbine downwind power maximization
Chhipą et al. (2022)	Grid-connected DFIG-based WECS	MPPT controller Vector controller	Vector control; Active and reactive power control MPPT technique MATLAB/SIMULINK	Proposed system performs well with variable wind speed control. THD was maintained within IEEE 519 standard’s permissible limits.	Improvement of WT power conversion
Pehlivan et al. (2022)	PMGS-based WECS, (VSVPWT)	FLC with GA	Pitch angle control MATLAB/SIMULINK	GA optimized specified pitch angle controller for multiple coefficients. FLC with GA achieved optimal power output quickly and sustainably.	Maximization of WT output power Optimisation of WT power output
Palanimuthu et al. (2022)	Grid-connected Permanent Magnet Vernier Generator (PMVG)-based WT	Integral Sliding-Mode DC-Link Voltage Controller	Active and reactive power control Variable Exponential Reaching Law-based Sliding Mode control	Control schemes stabilized DC-link voltage and converter peak current.	Fault ride-through (FRT) capability Reduction of system peak losses.
Iqbal et al. (2020)	VSWT	Fuzzy based Model-Predictive controller	Pitch angle control MATLAB/SIMULINK	Fuzzy logic controller offers higher performance than conventional PI controller	Reduction of WT loading effect Improvement of power capturing/conversion

				This technique sustains rotor speed within its limit	Optimisation of WT power output
Mousa et al. (2020)	5-ϕ PMSG-based VSWT (VSVPWT)	Integral Sliding Mode Controller (ISMC)	MPPT technique Pitch angle control MATLAB/SIMULINK	ISMC offers higher performance than conventional PI controller.	Overall system power factor Overall system efficiency Maximization of WT generated power Optimisation of WT power output Reduction of mechanical stress/instability
Hussain et al. (2019)	Grid-connected Wind Power Plant	Distribution Static Compensator (DSTATCOM) controller	Voltage Source Converter (VSC) control PI controller based PLL technique MATLAB/SIMULINK software	DSTATCOM controller improved power factor. The controller provided real and reactive power compensation. Controller was effective for voltage regulation.	Power quality enhancement. Overall system power factor. System voltage profile enhancement.
Zhou & Liu (2018)	WECS	Pitch controller	Pitch angle control Nonlinear PI/PD control method MATLAB/SIMULINK	WECS output power was highly sensitive to pitch angle changes. Nonlinear control reduces power fluctuations better than fixed control. PI control achieved precise speed tracking and accurate pitch adjustment	Optimisation of WT power output Improvement of power capturing/conversion WT stability improvement Reduction of mechanical stress
Yao et al. (2017)	FSIG-based PMSG-based Wind Farms	StatComs	Capacity Configuration method	The controller provided reactive power compensation.	Fault ride-through (FRT) capability Power quality enhancement

				Controller was effective for voltage regulation.	WT output voltage regulation
Memije et al. (2016)	WT Generator	Newton Raphson algorithm Perturb & Observe (P&O) algorithm	MPPT technique Wind speed control MATLAB/SIMULINK	The Newton-Raphson method provided rapid and accurate wind speed estimates. Wind speed estimation improved MPPT performance.	Power output improvement. WT stability improvement. Reduction of mechanical stress.
Wei et al. (2015)	PMSG-based VS WECS	ANN-based Reinforcement Learning (RL) MPPT algorithm	MPPT control RL technique	Learned MPPs generate optimal speed-power curve for fast MPPT. RL allows WECS to operate without turbine or wind data.	Optimisation of WECS power generation
Barzola et al. (2015)	PMSG-linked WT	Damping control algorithm Proportional-Integral (PI) Controller	Bidirectional DC-DC converter control PSCAD software	Bidirectional DC-DC converters effectively managed energy flow between the system and the grid. Controlling of bidirectional DC-DC converter effectively maintained voltage stability and optimized power output.	Improvement of power oscillation damping. Improvement of active power gain. Voltage stability improvement. Reduction of mechanical stress. Cost saving
Rekha & Immanuvel (2014)	1-ϕ Grid-connected Wind Energy Generation system	FLC	MPPT & SVPWM technique Modified Phase Locked Loop (PLL method)	Modified PLL method reduced Total Harmonic Distortions (THD) in single-phase wind generation.	Power quality enhancement Optimisation of WT power output

Khajuria & Kaur (2012)	VSWT	Speed controller	Pitch angle control MATLAB/SIMULINK	Speed controller adjusted blade pitch for accurate power output.	WT output voltage regulation
Beltran et al. (2012)	DFIG-based WT	Higher-order sliding mode controller	MPPT technique WT simulator FAST	Controller rapidly stabilized WT to desired operating point.	Improvement of WT power conversion. WT stability improvement. Reduction of mechanical stress. Cost saving.
Li et al. (2011)	PMSG-based WT	Vector control mechanism. Machine- and Grid-Side Converter controller (MSC and GSC).	Two side-by-side voltage source PWM converter control. Direct-Current Vector control (DCVC). Integrated control of PMSG maximum power extraction, reactive power, and grid voltage support controls. MATLAB/SIMULINK.	The DCVC approach offers improvement to power quality and stability of the electricity supplied to the grid.	Improvement of power capturing/conversion Power quality enhancement Optimization of WT power output Reduction of mechanical stress
González et al. (2010)	PMSG-based WT	Modified Perturb&Observe (P&O) algorithm	MPPT technique Sensorless wind speed control PSIM software	Large reduction of turbine mechanical stress. Modification of P&O algorithm yielded improved MTBF.	Improvement of system MTBF System voltage profile enhancement Reduction of mechanical stress Cost saving
Arifujjaman et al. (2006)	Small WT Emulator	Maximum Power controller	WT speed and rotor speed control	The controller enables WT operation at optimum tip-speed ratio.	Improvement of power capturing/conversion

5.0 Conclusions

Researchers have looked closely at the control of conventional and modern wind energy conversion systems, focusing on artificial neural network techniques. To fill in the gaps in the literature and offer a framework for further research, this paper evaluates a few of the control strategies used in wind turbine operations. The paper closely examines the primary contemporary wind energy techniques, including grid-side converters (GSC), fuzzy logic controllers (FLC), and particle swarm optimisation (PSO), among other algorithms. The methods were the focus of this study, revealing several application areas for better use and decision-making. The studies and evaluations conducted demonstrate the significant potential of modern technology in the field of wind energy. According to the study, using artificial neural networks in conjunction with microcontrollers has proven to be a successful modern technology compared to the conventional wind energy conversion system (WECS) in solving the problem related to mechanical sensors connected to wind turbines and leading to poor power output. This thorough analysis aims to assist academics and experts in gaining a current and comprehensive understanding of the efficacy of applications of artificial neural network algorithms in wind energy conversion systems. Thus, more research on applying alternative algorithms for parameter control, development complexity, memory restrictions, and computational complexity, especially for tip speed control—may be necessary.

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