IJETIR

ISSN (Online) 2583-0554

Impact Factor: 5.731

International Journal of Emerging Technologies and Innovative Research (IJETIR)

Volume 4, Issue 10, October 2024

Identification of Most Suitable Control Strategy for Wind Turbine Operation

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Abstract: *Non-conventional energy is being embraced globally as a viable alternative to conventional fossil fuels generators. This is in direct response to the challenge of depleting fossil fuel reserves and its impact on environmental pollution. Wind energy has continued to play a significant role and can be regarded as the most deployed renewable energy source, however the effciency level and cost effectiveness of a wind turbine (WT) system with regards to wind application is very much dependent on its control. This research paper reviews the various control methods associated with wind energy control. More recently there has been an attempt to review these control techniques but the authors have focused more on the maximum power point tracking (MPPT) techniques and pitch angle control of WTs how- ever discussions around stall control of the WT is not presented in these research papers. This review paper presents a detailed review of the various operational control strategies of WTs, the stall control of WTs and the role of power electronics in wind system which have not been documented in previous reviews of WT control. This research aims to serve as a detailed reference for future studies on the control of wind turbine systems.*

Keywords: Wind turbine, Wind turbine control, Pitch control, Artificial Intelligence, MPPT strategies

I. INTRODUCTION

The rapid development of wind energy systems is a direct response to the growing need for alternative energy sources. For wind turbine control systems utilizing AI and ML are presented and show how AI can be utilized in wind farm control schemes to maximize the power extracted from wind currents, as well as monitor the condition of the wind turbine system [1]. Data obtained from the global wind energy council (GWEC) [2] reflect an increase in installed global wind capacity to about 651 GW at the end of 2019. This represents a 10% increase in global wind capacity compared to 2018. It is expected that installed wind capacity would increase exponentially over the next couple of years as a result of the continuous demand for alternative energy source. WTs have evolved over the years from simple designs to complex generation units. Due to this complexity and the high dependence of wind energy systems on climatic and environmental factors, there is the need to incorporate control systems to ensure the efficient operation of WTs and effectively utilizing the wind energy such that maximum power can be generated [3]. Control systems are incorporated into WTs to enhance the ability of the WTs to cope with the variability of wind in producing energy in a cost effective and reliable manner.

The primary objectives of WT control schemes is to provide stability for grid integration, mitigation of static and dynamic mechanical loads, maximization of power production and continuous power supply to the grid [4]. In order to achieve the aforementioned control objectives, it is important to optimally control the WT generator torque and blade pitch angle. The torque control of the generator allows varying the speed of the turbine rotor by applying MPPT strategies to achieve as much as possible maximal extraction of wind power. With changes in wind speed, the rotor torque increases or decreases, so the generator torque must be the shock absorber for the turbine to turn at optimum speed while the pitch angle control achieves smooth power production by controlling the input torque of wind.

The advances in power electronic systems have also contributed to various improvements in the control of WT systems especially when considering the quality of the WT system. For a stable grid integration and variable speed operation of any wind energy system, the role of power electronics components of the WT cannot be emphasized [5]. This research paper therefore also considers the role of power converters in the control of a WT system.

Various research papers have extensively discussed the individual control methods associated with wind systems however only a few research papers have attempted to present in one research paper a detailed review of the various control strategies. More recently there has been an attempt to review these control techniques but the authors have focused more on the MPPT techniques and pitch angle control of WTs. The authors in [6] focused on the pitch angle controller for WTs without discussing the pitch control of wind turbines itself. Though the authors in [6] mentioned the classification of the WT operating regions this was not discussed. In [7], the authors focused on the pitch control methods without discussing the pitch angle controller. This review paper fills this gap. It is also important to point out that this review paper also discusses power electronics interfacing for grid integration of WTs. This review paper therefore presents a detailed re- view of the various operational control strategies of WTs, the stall and pitch control of WTs, the various MPPT strategies and the role of power electronics in the control of WT systems. The control targets of the WT operational regions are as follows:

- Maximal power production bearing in mind the load and constraints of the WT components.
- Ensuring the safe operation of the WT.
- Providing the required power quality at point of grid connection.
- Prevention of extreme loads and minimizing damages which may arise due to fatigue.

II. THE PROBLEM: CHALLENGES IN WIND FARMS MONITORING AND CONTROL SYSTEMS

The first issue, as stated in the introduction, is wind speed forecasting. Wind currents and densities are time varying and nonlinear, so an efficient wind turbine control system needs to be able to adapt to these types of conditions. The amount of power a wind farm can produce is directly related to the wind currents that pass through the wind farm. Historical wind current data is available for many locations globally, however, the actual wind speed and density measured by each tower's anemometer and barometer, respectively, can vary from forecasted wind speeds and densities by as much as fifteen percent [7]. The National Center for Atmospheric Research (NCAR) has recently updated its weather prediction model to include AI to lower the error rate of weather forecasts .

Another important factor to consider with respect to wind currents through a wind farm is wake turbulence [8]. The wake turbulence is caused by oscillations in wind currents due to impact with the wind turbine blades (WTB) and can have a negative effect on the wind currents through a given wind farm. To limit wake turbulence, a detailed analysis of wake currents through a potential wind farm location is necessary before placing the towers, as reported in [9]. If towers are placed too close together, the tower clustering effect, caused by wind currents hitting the wind turbine towers, can have a negative impact on the wind currents through a wind farm, and thus requires a detailed analysis to determine proper tower placement. Due to the nonlinear nature of wind power generation, traditional linear controllers such as PID with static reference set points are not ideal for wind turbine control systems. Theflow control prospects and challenges with respect to wake turbulence and wind farms are presented.

Wind power is another factor that needs to be considered when designing controllers for wind farm systems. Wind power is directly related to the wind speed, wind density, blade pitch, blade size, and blade tip speed ratio. As the blade size is constant and blade tip speed ratio is dependent on the rotor shaft speed and the blade size, the variable parameters for wind power generation control are wind speed, wind density and blade pitch [10]. As the issues with wind speed and density have already been considered, the main challenge with wind power forecasting is the blade pitch of each wind turbine in a wind farm. The blade pitch is controlled by actuators that are given commands by proportional-integral (PI) controllers, which have been relatively successful in implementation. The main issue with using proportional-integral-derivative (PID) controllers is that the rate at which the wind speed and density change can be much faster than PID controllers can compute and adapt to and, therefore, the optimal blade pitch may not be achieved, thus compromising efficiency [11]. It is for this reason that AI algorithms and nonlinear controllers are preferable; more research should be devoted to this area.

III. POWER CONTROL METHODS IN WIND TURBINES

WTs are typically designed to withstand extreme weather conditions but they are not designed for extreme speeds or rotational torques. At very large aerodynamic torques or rotational speeds, the force on the blades of the WT is enormous and can tear the turbine apart. To avoid this, WTs are always designed with a cut-out speed above which brakes will slow the turbine [12] to a halt. However, there is s range of wind speeds before the cut-out speed where the WT employs various control strategies to deal with high wind speeds that would otherwise pose a threat to the turbines. All WTs are therefore designed with a kind of power control technique. This can either be stall control or pitch control. Stall control of WTs is further classified as passive and active stall control [13]. In figure 1 gives a description of these control strategies while Table 1 shows a summary of the advantages and drawbacks of the stall and pitch control methods.

A. Passive stall power control

Passive stalled controlled WTs have their blades bolted to the hub at a fixed angle. The geometry of the rotor blade profile is aerodynamically designed to ensure that in high wind speed conditions, it creates turbulence on the side of the rotor blade which not facing the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor. The rotor blade of a passively stalled controlled WT is slightly twisted along its longitudinal axis to ensure a gradual stalling of the rotor blades rather than abruptly when the wind speed reaches its critical value [14]. This is a very simple and low cost technique which does not require the installation of additional actuators, however because this method is largely dependent on natural stalling of the turbine blades the control process is very limited and the WT is exposed to torque spikes and power swings.

B. Active stall power control

In response to this apparent setback of the passive stall control, the active stall power control of WTs was introduced. Active stall controlled WTs are tied with active power control mechanisms and pitchable blades similar to pitch controlled WTs. The active stall control of WTs is popular with larger WTs rated at 1 MW and above though this can also be applied to constant speed WTs designed to operate in high speed wind conditions [15]. During low wind speed conditions the WT blades are pitched in steps to get large torque. In order to prevent the overloading of the WT generator at its rated power, the active stall controlled WT increases the angle of attack of the rotor blades in order to make the blades go into a deeper stall rather than decreasing the angle of attack to reduce the lift and rotational speed of the blades [16]. In comparison to the passive stall, active stall control enables power output control more accurately to avoid overshooting the rated power of the WT at the beginning of a wind gust. Another advantage of active stall control over passive stall control is the possibility of running the WT almost exactly at rated power at all high wind speeds. A passive stall controlled WT will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall. The above method of controlling is better when the economic operation is needed and higher power production and easily controllable.

C. Pitch control

Pitch controlled WTs use an electronic controller to sense the output power of the WT several times per second. An electronic signal is generated which pitches the turbine blades out of the wind when the power level goes above the prescribed safe level. The turbine blades are pitched or turned back into the wind at an optimal angle of attack to catch the wind when the power level gets lower. Minimal power loss can be achieved by pitching the WT blades [16] and these results in the captured power being equal to the electrical power produced by the wind generator. Pitch controlled WTs have an active control system which varies the pitch angle of the turbine blades [17] to decrease torque and rotational speed in WTs. This type of control is usually employed in high wind speeds only where high rotational speeds and aerodynamic torques can damage the equipment.

D. AI and ML in Wind Farm Controllers and Control Schemes

AI in wind turbine systems can be separated into three sub-categories: (1) artificial neural networks (ANN); (2) support vector machines (SVM); and (3) swarm optimization algorithms (SOA). ANNs are adaptive, self-organizing, fault tolerant, easy to implement, and have very high accuracy when used for prediction, so they have been implemented in many cases for predicting wind speed, density, and power. SVMs [18] have primarily been used for fault detection and classification and have a very high accuracy in doing so. SVMs have been proposed for prediction purposes as well, although they tend to not perform as efficiently as ANNs. SOAs are population based bionic algorithms that mimic swarm characteristics in nature. A commonly used SOA algorithm is the particle swarm optimization algorithm (PSO), which, It is "an algorithm modeled on swarm intelligence that finds a solution to an optimization [19] problem in a search space or model that predicts the social behavior in the presence of objectives]".

Machine learning is a subsection of AI but deals more with learning models and making predictions based on those models than making inferences about potential decisions based on the environment and the pervious action taken by the AI. ML algorithms, such as SVM, are great for classifying faults in electrical systems, as well as mechanical faults in gear boxes and bearings. Basically, any signal that has a table of normal operating conditions for a specific component can be controlled using a ML algorithm.

Based on the literature, conventional PID controllers [20] are not the best choice for mapping nonlinear parameters, though several researchers have proposed hybrid controllers that utilize AI and ML algorithms in tandem with PID controllers. One of the biggest issues associated with wind farms is that they are typically located in remote locations or offshore. Due to this challenge, accurate monitoring and detailed maintenance schedules are necessary to prevent the wind farm from shutting down due to damaged wind turbine components. AI can be an extremely useful tool for predicting how and when a generator may fail, or how likely the WTBs will be damaged from severe weather events or bird strikes. It is also necessary to monitor the bearings for the rotor shaft, the actuators for the pitch and yaw control, and the gearbox.

Table 1: Comparative study of control methods

Control Technique	Merits	Demerits
Passive stall	Simple and low complexity. Low cost and cheaper than other control systems. It is robust compared to the active stall and pitch control. It has a faster response to wind gusts compared with other control systems.	Not suitable for large WTs. It is less efficient in low wind speeds. It causes variations in the maximum steady state power as a result of variations in grid frequencies and air density.
Active stall	Higher power production compared to the passive control method as a result of the blade angle of the WT being optimized according to the wind speed. Better and more accurate con2rol of power output. The ability to counteract power peaks very efficiently without a change in rotational speed. Lower load and power peaks compared to pitch control.	Forced reduction of the generator rotor speed to stall the rotor blades during an increase in wind speed.
Pitch control	Efficient power control. Assisted start up. Emergency stop.	High power variations in high wind speed conditions. Extra complexities and increased costs as a result of the pitch mechanism

AI, ML enabled control	Resolve complexity of WT system, predict varying wind speed, and optimize wind form generation. Monitor mechanical components and detects faults	They are not scalable i.e. once an ANN is trained to do certain task, it is difficult to extend for other tasks without retraining the neural network

The difference between pitch control and stall control of WTs is mostly noticeable in high wind speeds. While the stall controlled systems rely on aerodynamic designs of the blades to control the aerodynamic torque or the rotational speed of the turbine in high wind speeds, the pitch controlled systems use an active pitch control for the blades. This allows the pitch controlled system to have a constant power output above the rated wind speed while the stall controlled systems are not able to keep a constant power output in high winds. The pitch control and active stall control of WTs are both based on the rotating actions on the WT blade [21]. The difference in mode of operation is the turning of the WT blades. While pitch control turns the blade away from the wind in order to reduce the lift force on the turbine blades, the active stall control is the control of the WT turns the turbine blades into the wind.
As seen in Fig. 1 with passive stall control the output power of the WT slightly peaks higher than the rated limit before decreasing until it reaches the cut-out speed. This behavior ensures the wind generator does not experience overloading as the wind speed goes above the nominal values. The passive stall control of WTs presents a very simple control system which is devoid of all complexities associated with WT control and the moving parts [22] of the WT rotor. Passive stall control is implemented in constant speed WT systems so that the rated power of the WT is not exceeded in high wind speed conditions. This invariably means poor power regulation as a result of constrained operations

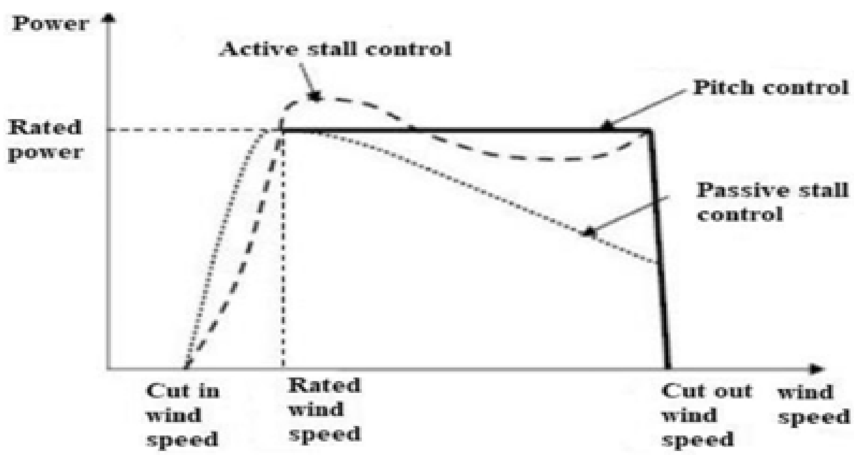

Figure 1 WT Control Method Curves

IV. CONCLUSION

This paper has reviewed the various concepts of WT control available in literature, providing AI and ML also play a big role in maintaining the stability of a wind farm during mechanical and electrical fault conditions. Utilizing AI and ML, researchers and engineers can build predictive models to aid in maintenance schedules for remote wind farm locations to help prevent wind farms from being disconnected from the grid due to faults caused by old and aging equipment. Most review literatures only discuss the pitch control of WTs, however this literature review has presented discussions around the stall control of WTs reviewing both passive and active stall control of WTs. A detailed review of the pitch control of WTs is presented and the MPPT methods available have also been summarized. The electric pitch controller and hydraulic controller for pitch control have also been discussed. The hydraulic converter has a tendency to loose oil viscosity in regions with lower temperatures; therefore it is believed that it may be better suited in warmer climates like the African continent. An overview of power electronic interfaces for grid integration of WTs has also been presented. It is believed that this paper will serve as a suitable comprehensive reference for future researches on WT systems.

ACKNOWLEDGEMENT

This research received Laboratory infrastructure, research and design facility from electrical engineering department, Bhagwant University Ajmer and Mahila Engineering College Ajmer.

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