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AN OVERVIEW OF ADVANCED CONTROL STRATEGIES FOR WIND ENERGY SYSTEMS

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ABSTRACT

Wind energy systems have gained traction as a viable alternative to conventional energy sources that are becoming scarce. Control methods suited to wind energy systems are discussed in depth in this article. The emphasis is on hard computing or control techniques such as proportional integral-derivative (PID), optimal, nonlinear, adaptive, and robust, as well as soft computing or control techniques such as neural networks, fuzzy logic, genetic algorithms, and the fusion or hybrid of hard and soft control techniques. Finally, some potential future paths are proposed at the end of this review. This overview is not meant to be a comprehensive examination of the subject, and any omissions of other works are entirely accidental. Offshore wind is the utilization of wind turbines to generate mechanical power, which is then used to spin electric generators to generate electricity. When opposed to burning fossil fuels, wind power is a popular sustainable, renewable energy source that has a considerably lower environmental effect. Many single windmills are linked to the electric power transmission network to form wind farms. Onshore wind is a low-cost energy source that is competitive with, and in many cases, cheaper than, coal and gas facilities.

KEYWORDS: *Electricity, Renewable Energy Wind Energy, Soft Control, Transmission.*

1. INTRODUCTION

Among other renewable energy sources, wind energy is a rapidly expanding sector. This is due to the fact that wind energy is clean, geographically accessible, low-cost, and especially beneficial in rural regions(1)(2)(3)(4). It is, however, intermittent and needs a large initial investment, rising transmission costs, and a large geographical area. A wind energy conversion system (WECS) is a physical system with three main components in theory. The first is a rotor with blades attached to it. The rotor rotates as the wind passes between the blades, creating mechanical power. The second is a transmission, which sends electricity from the rotor to the generator. The last kind is an electric generator, which transforms mechanical energy into electrical energy. Axes are the basic classifications for wind energy converters. As a result, there are two different kinds of wind energy converters(5). The horizontal converter is the most common. This consists of two or more blades that are designed for maximum aerodynamic efficiency(6)(7)(8).

A yaw mechanism is also included in this design, which rotates the rotor blades to face the direction of the wind. The vertical axis converter is the second kind of converter, with blades arranged vertically. As a result, this converter can collect wind regardless of wind direction. However, owing to lower efficiency, complex maintenance, and huge land usage, this converter's utilization has declined in recent decades. provides details on the categories and dynamics modeling of wind energy conversion systems (WECSs)(9)(10)(11). A number of recent literature reviews have focused on different elements of WECSs. discusses problems relating to dynamics modeling in the context of control design. provides classifications and comparisons of various kinds of WECSs based on angular velocities and generator types. Summarizes investigations into issues that have arisen as the integration of WECSs into power grids has increased, such as system stability and dependability, power quality, wind energy transmission and storage, and so on. In terms of control, describes WECSs in various operating areas and the associated conventional and sophisticated control methods, with the proportional-integral-derivative (PID) and multi-input, multi output (MIMO) approaches being the most prominent(12)(13)(14). In addition, surveys on electrical control systems, including fuzzy and neural network control, are available. However, the hard and soft computing methods, as well as the impacts of hybrid techniques, are not properly highlighted in the aforementioned overviews. The goal of this article is to give a comprehensive review of sophisticated control techniques used in WECSs. We chose a specific number of articles for each method and evaluated them in chronological order(15)(16)(17).

1.1 Types of Hard Control:

- ***PID Control:*** PID control methods based on the regulation of power electronic circuits to optimize the efficiency of wind energy conversion. In particular, between the wind generator and a resistive load in, a thyristor rectifier controlled by the firing angle alpha is inserted. The controller is an integrator that simply calculates the integration of the error between the reference maximum power, which is obtained from the angular speed variations of the wind rotor, and the actual output power, which is measured from the load voltage and current. However, the integrator gain is not calculated with precision in this work. The authors of worked on the same WECS pattern, with an AC-DC-AC connection between the WECS and the utility grid. The rectifier in the AC-DC portion and the inverter in the DC-AC part are controlled by firing angles R and I, respectively. In , R and I are controlled by two distinct proportional-integral (PI) controllers, the PI gains of which are computed ideally based on the nonlinear dynamic model of the system for two different sampling rates. The authors aim to evaluate the impact of multi-rate sampling vs single-rate sampling on system performance by creating this control method. As a consequence, the multi-rate controller performs better than the other. Meanwhile, proposed using a PI controller to turn fluctuations of conjunction with an optimum method based on the power speed characteristic curve to calculate control actions on the inverter in order to consistently achieve maximum power(18)(19)(20)(21).
- ***Optimal Management:*** Various optimum control methods have been suggested, mostly to collect the greatest amount of wind power. used a permanent-magnet synchronous generator to solve the maximum power point tracking (MPPT) issue over a fixed-pitch WECS (PMSG)(18). To drive the system to run at maximum power points, an algorithm coupled the derivative of PMSG stator frequency with the anticipated maximum output DC power against DC voltage characteristic curve of the WECS. Within this control frame, there is no need to utilize the anemometer sensor to detect wind speed. By wind prediction calculation, the suggested approach outperformed certain existing methods that used the sensor or did not use the sensor. Proposed the extreme seeking control utilizing wind turbulence as sinusoidal probing signals after studying several existing MPPT algorithms in the literature that need the availability of the power coefficient and tip speed ratio connection. The suggested optimization method generates optimum rotational speed references based on the phase shift, which is performed using the Fast Fourier Transform, between the power coefficient derived from the measured electrical power and the observed rotational speed(22)(23). These ideal values are then input into a PI controller, which controls the generator speed. Simulation results showed that this control system is capable of maintaining the WECS at maximum efficiency points. However, since wind turbulenceis sluggish, a consistent outcome cannot be assured. Provides an overview of the maximizing of wind energy collection by variable speed WECSs from the standpoint of energy optimization. The article discusses several solutions to

the control issue of WECSs in the below-rated speed (partial load) operating area, including both linear and nonlinear models, as well as MPPT, sliding mode, and fuzzy methods. Another limitation, mechanical load fluctuations, was taken into consideration in the optimization phases in addition to energy optimization(24).

- ***Stable Control:*** Uncertainties such as disturbances and miss-match modeling are prevalent in the control design phase of WECSs to some extent. Researchers suggested robust control methods to WECSs to ensure controller performance under unanticipated uncertainty. Under the limitations of maximum energy extraction and load variations, the proposed multi-variable controllers were able to maintain close-loop stability. On the same WECS, Compares the performances of the H2 controller with the H controller. The simulation indicates that the H approach is more resilient but has slower reactions, making it suitable for fixed-speed WECSs(25). H2 regulators, on the other hand, are ideal for variable-speed WECSs. transformed the nonlinear model of a WECS into an energy-based system and then synthesized the controller using Hamiltonian energy theory, taking disturbances from modeling into account but utilizing a different control technique. The authors demonstrated that the resultant control rule can keep the system L2 stable even when modeling mistakes are present. WECSs are extremely sensitive to wind speed, and their model parameters vary as a result. Gain scheduling control utilizing Linear Time Varying (LPV) models of WECSs has been extensively pursued based on this characteristic. The LPV design was used by scholar to regulate the electrical torque and power factor of the Doubly-Fed Induction Generator (DFIG) in WECSs. The synthetic controller is not only responsive to wind fluctuations, but also to changes in induction parameters and generator stator voltage dips. Recognizing the lack of gain scheduled control to WECSs in, where anemometers are needed to detect wind speed, suggested Kalman Filtering to estimate wind speed from wind turbine torque, which is then input into gain scheduled controller. Gain scheduling is used in conjunction with a PI controller in to guide the WECS to optimum operating positions.
- ***Adaptive Control:*** When it becomes impossible to build an accurate model of nonlinear systems with uncertain dynamics, adaptive control becomes appealing. Adaptive control methods have been proposed in a variety of WECS control systems due to their extremely nonlinear features. A direct adaptive control was suggested in to guide WECSs on the optimum trajectory. The Lyapunov function analysis-based control composition consists of two controllers: a supervisory regulator that is created using the system's limits and an adaptive regulator that utilizes Gaussian nodes to build the network. A "smooth" function switches two regulators between two areas, one near to equilibrium points and the other elsewhere. In a simulation, quick error tracing was shown. Similar to the previous control structure, substituted the adaptive neural network-based controller with a PID controller, the adaptation law of which was similarly developed using Lyapunov stability analysis. Another self-tuning PID control approach proposed in is to train a neural network including wavelet nodes connected to an infinite impulse response filter to simulate system dynamics before updating PID controller settings. Instead of utilizing the Lyapunov method for self-regulated control, Hui and Bakhshai investigated an adaptive algorithm that can update optimum operating conditions in response to changes in WECSs. The suggested framework employs a modified Hill Climb Search (HCS) to determine the optimum wind speed for maximum power points, as well as a memory to hold updated optimal values.

1.2 Types of Soft Control:

- ***Uncertainty in Control:*** WECSs have also made extensive use of knowledge-based control techniques. Due of space constraints, this article intentionally concentrates on the most current work in fuzzy control given in WECSs. Proposed a fuzzy logic-based output state feedback control method for regulating output power indirectly through the DC link current of WECSs. The concept is to use a Takagi-Sugeno (TS) fuzzy model as a collection of discrete linear systems to explain the nonlinear dynamics of WECSs in general. The Linear Inequality Matrix (LMI) method is then used to calculate each observer and control gain for each linear system. The final controller has an excellent tracking behavior and is resistant to parameter changes. However, in this suggested approach, state space models of WECSs are still needed. Developed fuzzy controllers for WECSs in both below and above rated wind speed modes to avoid building mathematical models of WECSs. The first controller, which maximizes wind energy extraction, has two inputs: the difference between optimum and actual tip speed ratios, as well as the derivative of this difference, and one output: generator voltage.

- ***Controlled by Neural Networks:*** In mechanical wind velocity sensors are replaced with neural network estimators, which use a three-layer artificial neural network (ANN) with two inputs: wind turbine power and generator speed, to estimate wind velocities based on the power curve characteristic. The optimum rotor speed references are calculated using the anticipated wind speed. The input of PI controllers on converter sides is the source of the difference between these references and real rotor speed. Furthermore, utilized an ANN approximator to adjust for potential power coefficient drifts. Similarly, used phase voltages and currents as inputs to the ANN, with the predicted wind speed as the output. To compute the reference rotor speed, proposed using a Jordan recurrent ANN with four input signals: wind velocity, rotor speed, power output, and desired maximum power. The learning method is back propagation, and the output of the ANN is sent back via a delay unit. The control system was successfully implemented to a WECS based on PMSG.

1.3 Types of Hybrid Control:

- ***PID and fuzzy:*** developed a PD controller based on the TS fuzzy model of the pitch system. The TS fuzzy model is made up of three sub-linear systems, with PD gains synthesized using either the pole placement technique or LQR. In compared to the traditional PI controller, the overall fuzzy-PD controller resulted in reduced pitch angle and rotor speed variations. In, the error between the reference and observed generator speeds, as well as the derivative of this error, were both supplied to a Mamdani-type fuzzy controller that drives the generator torque for maximum wind capture. In, a closed-loop optimum fuzzy reasoning technique was used to update PID parameters in order to improve the controller's resilience by combining both fuzzy-PD and fuzzyPI controllers into one fuzzy-PID controller. In a traditional PID controller was initially constructed, and then PID parameters were updated using fuzzy inference.
- ***Neural and Fuzzy Networks:*** used generalized predictive control (GPC) to adjust pitch angle for all operating areas based on output power command to smooth out the power output of a wind farm with different wind turbine generators. However, when wind velocity varies rapidly, the error between output power and command grows, causing the GPC controller to become unstable. To solve this issue, a fuzzy neural network (FNN) technique was employed. In addition, the FNN was used in to adaptively change controller parameters that regulate released frequency and power in wind power generating systems.
- ***D. Genetic and Fuzzy Algorithms:*** In, a fuzzy controller was created to collect the most power from wind kinetic energy. The Takagi-Sugeno-Kang fuzzy controller is identified

from input-output data using the fuzzy clustering method, which takes the observed rotor speed and produced power as inputs and the predicted maximum power as output. The identification method is integrated into a genetic algorithm-based optimization process that reduces the difference between the estimated maximum power produced by the fuzzy controller and the maximum power generated by the generator. As a result, the controller is capable of monitoring the optimum extracted power.

2. DISCUSSION

In many parts of the globe, wind energy has the potential to play a significant role in future energy supply. Wind turbine technology has advanced to a highly dependable and sophisticated level in the past 12 years. Large wind turbines and novel system uses, such as offshore wind farms, will be made possible by the expanding global market. These advancements will result in additional cost reductions, and wind energy will be able to compete with traditional fossil fuel power generating technologies in the medium future. However, further study will be needed in several areas, such as the network integration of a large penetration of wind energy. The following are some of the areas suggested for further research in the field of WECSs:

- More realistic, physics-based dynamic (both lumped and distributed-parameter) models for current and future WECSs.
- Industry-standard embedded platforms for the integrated WECSs with advanced algorithms for optimum, model predictive, robust, reconfigurable, adaptive, networked, and resilient control systems.
- Neural networks, fuzzy logic, genetic logic, genetic programming, swarm intelligence, probabilistic reasoning, and other advanced algorithms based on soft computing methods.
- More advanced WECS software packages for modeling, analysis, design, development, testing, and validation, with modularity and power grid and Internet connection capabilities.
- Finally, all of the above-mentioned research and development activity must be focused on the key problems of decreased cost, practicality, industry-standardization compliance, and physical and cyber security.

3. CONCLUSION

An overview of WECS control methods was given in this article. This review focused on hard control methods like PID, optimum, robust, adaptive, predictive, and sliding mode, as well as soft control approaches like fuzzy logic and neural networks, and the merging of hard and soft control techniques. The sliding mode control approach dominated the field's applications owing to its beneficial characteristics of rapid convergence and resilience to system uncertainties, according to the review of contributions of hard and soft control methods to WECSs. Soft control methods' use in WECSs has exploded in recent years, owing to their appealing characteristics of nonlinear identification and control (neural networks), human knowledge and reasoning in the form of membership functions and rules (fuzzy logic), and global no derivative-based optimization (genetic algorithms). Finally, based on the aforementioned control methods, it is reasonable to conclude that hybrid WECS strategies are very promising since they may take use of the best characteristics of both hard and soft control techniques.

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