Power Transition Enhancement for Variable-Speed, Variable-PitchWind Turbines using Model Predictive Control Techniques

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Abstract: - Humans have used the power of the wind for many centuries. The first documented windmill was used by the Persians in approximately 900 AD. The windmill appeared in Europe during the middle ages. It was used for many mechanical tasks such as sawing wood, pumping water, grinding grain, and powering tools. Modern horizontal axis wind turbines have become an economically competitive form of clan and renewable power generation. As a result, the wind industry has recently experienced tremendous growth. Optimizing wind turbines for specific sites by varying rotor diameter, hub height, and generator capacity can make wind turbines even more economically competitive.

Keywords—Model predictive control, variable pitch wind turbines, pitch control, power optimization.

I. INTRODUCTION

When electrical generators were invented, it was natural for people to turn the generators with windmill rotors. These small wind turbines were popular in rural areas of America. In the 1930s, the Rural Electrification Administration set about to expand the central electrical grid. This was the end of the wind turbine for a few decades. Interest in wind energy reappeared after the oil crisis of the 1970s and 1980s. With lower cost of energy in the 1990s, interest in wind energy subsided in the U.S. However, Europe continued to support wind energy and development continued there.

Various wind turbine designs have been proposed and built over the years. The horizontal axis wind turbine (HAWT) has proven to be the most effective. The closest runner-up to the HAWT is the Darrieus design. Although the Darrieus design has some advantages, such as being able to locate much of the heavy equipment at ground level, it does not capture energy from the wind as efficiently as the HAWT. This can be seen in Figure1.1 The modern three-blade and high speed two-blade curves are horizontal axis designs. The figure shows that these two designs have the highest efficiencies. For these reasons, all commercially available large wind turbines of today are a variation of the HAWT.

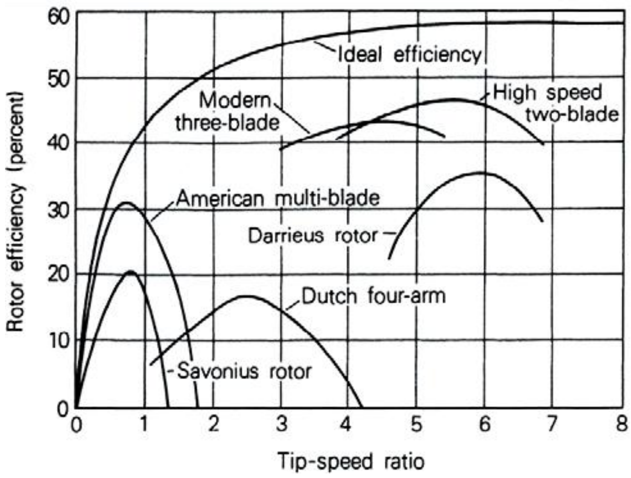

Figure 1.1: Rotor Efficiency versus Tip-Speed Ratio for Various Rotor Types

Modern Wind Turbine

The modern wind turbine is a highly tuned and complicated piece of machinery. The typical modern wind turbine is a three-bladed, variable speed, upwind, horizontal axis wind turbine with active pitch and yaw control.

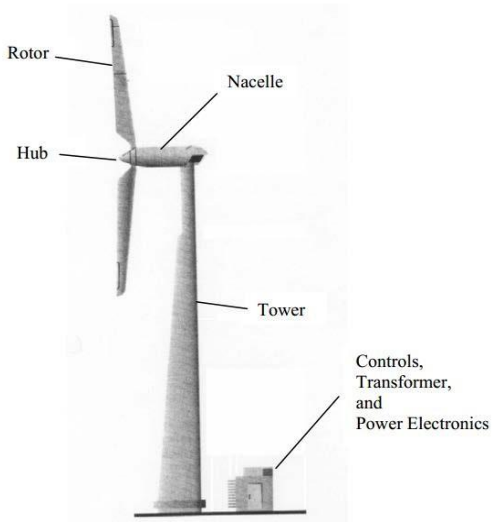

Figure 1.2: Wind Turbine Layout

Variable speed operation allows the rotor RPM to vary, which permits the rotor to operate at its maximum efficiency at every wind speed.

Figure 1.2 shows the general layout of a turbine. The rotor is attached to the nacelle by the hub. The nacelle sits on top of the tower and houses the majority of the wind turbines functional components. A cut-out view of the nacelle is shown in Figure 1.3. This figure shows the arrangement of the drive train.

The drive train system consists of three blades, a low-speed shaft, a gearbox, a high-speed shaft and a generator. The low-speed shaft connects the low-speed shaft to a two or three-stage gearbox, followed by a high-speed shaft connected to the generator the wind strikes the wind turbine blades, causes them to spin and further makes the low-speed shaft rotate, 2) the rotating low-speed shaft transfers the kinetic energy to the gearbox, which has the function of stepping up the rotational speed and rotating the high-speed shaft, 3) the high-speed shaft causes the generator to spin at high speed which is close to the rated speed of the generator, 4) the rotating generator converts the mechanical power to electrical power.

Usually, the output voltages of the generator are low, and hence there will be the need for a transformer to step up the generator output voltage for the purpose of directly connecting to the grid.

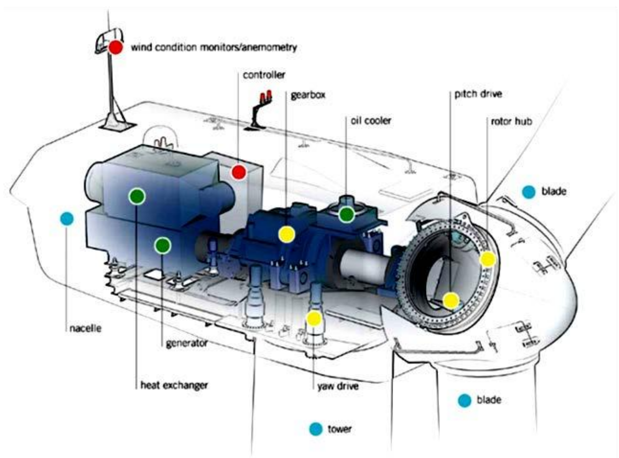

Figure 1.3: Nacelle Layout

Wind Turbine Size

The size of wind turbines has increased substantially since the 1980's. The size of onshore turbines has reached a point where the levelized cost of energy for even larger machines will be adversely affected by transportation and assembly costs [14]. Offshore wind turbine designs, however, continue to increase in size. A wind turbine manufacturer, REPower Systems, currently offers a 5 MW turbine with a 126 meter rotor diameter, and Clipper Wind power has recently formed a center of excellence for the development of a 7.5 MW offshore wind turbine.

Pitch angle control

The pitch angle control is a mechanical method of controlling the blade angle of the wind turbine when the captured wind power exceeds its rated value or wind speed exceeds its rated value. In this way, pitch angle control is enabled to limit the maximum output power to be equal to the rated power, and thus protect the generator when the wind speed experiences gusts. The pitch angle controller is only activated at high wind speeds.

II. LITERATURE SURVEY

M. Rashwan, M. A. Sayed, Y. A. Mobarak, G. Shabib and zG. Buja, [1] the wind turbine operating area can be divided into several regions, depending on wind speed. Transition from fixed speed to variable speed wind turbines has been a significant element in the Wind energy technology improvements. This has allowed adapting the turbine rotational speed to the wind speed variations with the aim of optimizing the aerodynamic efficiency. In this paper, a multivariable control strategy based on model predictive control (MPC) techniques for the control of variable-speed variable-pitch wind turbines is introduced. The main advantages of the proposed controller are that it is easily adaptable for different conditions in addition to its very fast response. The proposed control strategy is described for the two operating regions of the wind turbine, i.e. both partial and full load regimes. Pitch angle and generator torque are controlled simultaneously to maximize the captured energy and smooth the power generated while reducing the pitch actuator activity. Simulation results show an excellent performance in improving the transition from power optimization to power limitation of the wind turbine.

D. Bianchi, H. Battista, and R. J. Mantz, [2] A Wind Energy Conversion System (WECS) differs from a conventional power system. The power output of a conventional power plant can be controlled whereas the power output of a WECS depends on the wind. This nature of WECS makes it difficult for analysis, design and management. Various approaches have been developed to study the behaviour of WECS. In this paper, the steady state characteristics of a WECS using doubly fed induction generator (DFIG) is analysed using MATLAB. The dynamic steady-state simulation model of the DFIG is developed using MATLAB. Simulation analysis is performed to investigate a variety of DFIG characteristics, including torque-speed, real and reactive-power over speed characteristics. Based on the analysis, the DFIG operating characteristics are studied.

Table 1: Summary of Literature Survey

SR. NO.	TITLE	AUTHORS	YEAR	METHODOLOGY
1	Power transition enhancement for variable-speed, variable-pitch wind turbines using model predictive control techniques	A. M. Rashwan, M. A. Sayed, Y. A. Mobarak, G. Shabib and G. Buja	2023	A multivariable control strategy based on model predictive control (MPC) techniques for the control of variable-speed variable-pitch wind turbines is introduced.
2	Wind Turbine Control Systems: Principles, Modelling and Gain Scheduling Design	D. Bianchi, H. Battista, and R. J. Mantz	2022	The steady state characteristics of a WECS using doubly fed induction generator (DFIG) is analysed using MATLAB.
3	Modelling, Simulation and Analysis of Doubly Fed Induction Generator for Wind Turbines	B. Babypriya and R. Anita	2021	Since modern wind turbines are large, flexible structures operating in uncertain environments, advanced control technology can improve their performance.
4	Gain-scheduled Linear Quadratic Control of Wind Turbines Operating at High Wind Speed	K. Z. Ostergaard, P. Brath and J. Stoustrup	2020	State estimation and linear quadratic (LQ) control of variable speed variable pitch wind turbines.
5	Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation	R. G. de Almeida and J. A. Pecas Lopes	2020	A control scheme that allows doubly fed induction wind generators (DFIWG) to participate effectively in system frequency regulation.

B. Babypriya and R. Anita [3] Wind energy is a fast-growing interdisciplinary field that encompasses multiple branches of engineering and science. Despite the growth in the installed capacity of wind turbines in recent years, larger wind turbines have energy capture and economic advantages, the typical size of utility scale wind turbines has grown by two orders of magnitude. Since modern wind turbines are large, flexible structures operating in uncertain environments, advanced control technology can improve their performance. The goal of this article is to describe the technical challenges in the wind industry relating to control engineering.

K. Z. Ostergaard, P. Brath and J. Stoustrup, [4] This paper addresses state estimation and linear quadratic (LQ) control of variable speed variable pitch wind turbines. On the basis of a nonlinear model of a wind turbine, a set of operating conditions is identified and a LQ controller is designed for each operating point. The controller gains are then interpolated linearly to get a control law for the entire operating envelope. The states and the gain-scheduling variable are not online available and an observer is designed. This is done in a modular approach in which a linear estimator is used to estimate the non-measured state variables and the unknown input, aerodynamic torque. From the estimated aerodynamic torque and rotor speed and measured pitch angle the scheduling variable effective wind speed is calculated by inverting the aerodynamic model. Simulation results are given that display good performance of the observers and comparisons with a controller designed by classical methods display the potential of the method.

R. G. de Almeida and J. A. Pecas Lopes, [5] this paper proposes a control scheme that allows doubly fed induction wind generators (DFIWG) to participate effectively in system frequency regulation. In this control approach, wind generators operate according to a deloaded optimum power extraction curve such that the active power provided by each wind turbine increases or decreases during system frequency changes. The control strategy defined at the wind generator to supply primary frequency regulation capability exploits a combination of control of the static converters and pitch control, adjusting the rotor speed and the active power according to the deloaded optimum power extraction curve. Results obtained in a small isolated system are presented to demonstrate the effectiveness of the approach.

III.PROBLEM IDENTIFICATION

This paper deals with variable-speed, variable-pitch wind turbine control design, in order to achieve the objectives of maximizing the extracted energy from the wind, and improving the transition between the two modes of the wind turbines i.e. the partial load and the full load. MPC controller has been devolved for the wind turbine control.

A dynamic model of a variable-speed, variable-pitch wind turbine, with all variable constraints using torque and pitch control, is introduced. Simulation results show the robustness of MPC. Soft and nonlinear action of this controller can improve the transition between power optimization and power limitation of the wind turbine torque control at partial load regime (low wind speed) and blade pitch control at full load regime (high wind speed). The designed controller ensures the best performance in terms of efficiency with an acceptable drive train transient loads and better implementation simplicity compared to some existing controller strategies.

IV. CONCLUSION

Blade pitch control has primarily been used to limit aerodynamic power in above rated wind speeds in order to keep the turbine within its design limits and to optimize energy capture at below rated conditions. Collective pitch control techniques have been successfully utilised for this purpose But as rotor size increases there is an increased interest in utilising pitch control to alleviate loads experienced by wind turbines by pitching the blades individually. The basic technique of individual pitch control is borrowed from the helicopter industry.

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