

A Neural Network Control Strategy for Improved Energy Capture on a Variable-Speed Wind Turbine

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Abstract: Pitch control has so far been the dominating method for power control in modern variable speed wind turbines. This paper proposes an improved control technique for pitching the blades of a variable speed wind turbine, using Artificial Neural Networks (ANN). The control objective is decided according the two states of operation: below rated operation and above rated operation. In the below rated power state, the aim of control is to extract maximum energy from the wind. In the above rated power, the control design problem is to limit and smooth the output electrical power. A model has been constructed and evaluated with experimental data obtained from Vestas V-47 660 kW wind turbine.

Key-Words: Artificial Neural Networks, Pitch Control, Variable-Speed Wind Turbines, Control Trajectories

1 Introduction

The use of wind power is one of the cheapest methods of reducing CO₂ emissions in electricity production. In the long run, ecologically energy supply can only be guaranteed by integration of renewable resources. The worldwide potential of wind power means that its contribution to electricity production can be of significant proportions. Wind turbines produce electricity by using the natural power of the wind. The wind is a clean and sustainable energy source. It does not create pollution and it will never run out.

Wind energy is seriously growing in response to environmental problems of traditional energy sources and turbines technological improvements [1]. The part of this kind of energy is each day more important in windy regions. Thus, the wind turbine power quality impact on the power grid increases. However, wind energy costs is still too high to compete with traditional sources on less windy sites. More careful design techniques must be introduced into wind turbines control to ameliorate these problems. This control must be done taking into account the whole wind turbine behaviour. Perturbations from wind have also to be considered.

The main objective of this article is to present an ANN-based controller. The control design was differentiated for two parts: below rated operation and above rated operation. Below rated operation,

the aim of controller is to extract maximum energy from the wind. The pitch angle of the rotor blades is fixed at its optimal value and turbine speed is adjusted to follow the changes in wind speed. Above rated power, the control design problem is to limit and smooth the output electrical power.

An accurate model was constructed and evaluated with experimental data obtained from Vestas V-47 660 kW [2] wind turbine. This turbine is chosen were as it represents one of the most popular wind turbines installed in recent years. There is therefore a comparative large amount of data available in the public domain, compared with other available turbines. In order to simulate this wind turbine, a model was developed and implemented in a MatLab/Simulink environment. The advanced numerical capabilities built into Simulink provided an excellent simulation engine for development of nonlinear wind turbine models.

This model can be, and will be used to study in the future alternative control strategies.

2 Wind turbine model

The challenge of wind energy research lies in the development of wind turbines that are optimized with respect to both cost and performance. A prerequisite for the cost-effective design of such turbines is the availability of a systematic

methodology that generates accurate and reliable dynamic models of the complete system within the design phase with relatively low modeling effort [3].

The purpose of the model is to simulate the dynamical behaviour and the electrical properties of a wind turbine. According [4], the modeling of the wind turbine should create a model as simple as possible from a mechanical point of view, but capable of providing a good description of the electrical characteristics of a wind turbine.

The wind turbine model consists of different component models: wind model, aerodynamic model, transmission model, and of the electrical components such as induction generator, soft starter, capacitor bank, and transformer model [5]. A simplified scheme can be seen in Fig. 1.

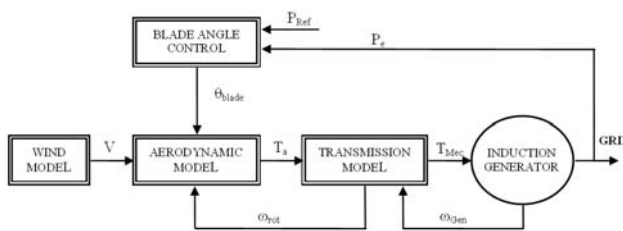


Fig. 1. Simplified scheme of wind turbine model.

2.1 Turbine aerodynamics

In the developed model, a simplified model is used for the aerodynamics with (real and random generated) wind speed as input. The aerodynamic transfer at the rotor is modeled as a steady-state nonlinear process characterized by the non-dimensional curves of coefficient of performance $C_p(\lambda, \beta)$ as a function of tip speed ratio λ and the rotor pitch angle β [6]. The power coefficient curves from Vestas V47-660 wind turbine, used in this article, are shown in Fig. 2.

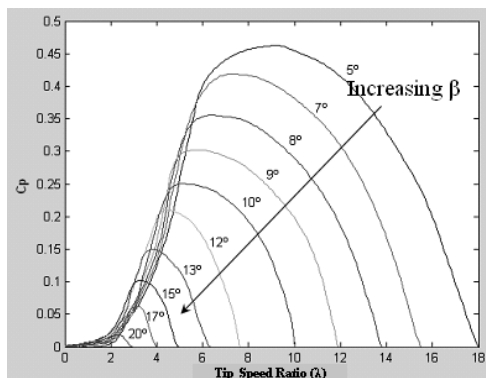


Fig. 2. Power coefficient vs. tip speed ratio with varying β .

The amount of power produced by a wind turbine can be expressed as:

$$P_t = \frac{1}{2} C_p(\lambda, \beta) \rho A V^3 \quad (1)$$

where P is the power, A the rotor disk area, ρ the air density, and V the wind velocity.

The tip speed ratio λ is given by:

$$\lambda = \frac{\omega R}{V} \quad (2)$$

where ω (rad/s) is the rotor rotational speed and R the radius of the blades.

From expression (1) we can conclude that, manipulation of the power coefficient C_p using λ and β will result in manipulation of the power produced by the wind turbine.

3 The control problem

Using a wind turbine for production of electrical energy requires reliable operation. Especially at high wind speed fluctuations from the wind result in large mechanical loads of the turbine. Therefore an active control system is often used to realize a long lifetime of turbine and produce high quality power or increase energy capture. In control engineering terms, the wind turbine is a dynamic system excited by a disturbance input, the wind, and measurement noise [7].

Basically, the control design objectives are: maximization of energy capture in partial load, limiting and smoothing of electrical power in full load, and minimization of the turbine transient loads and thereby maximization of the turbine lifetime in both partial and full load.

3.1 Variable speed control trajectories

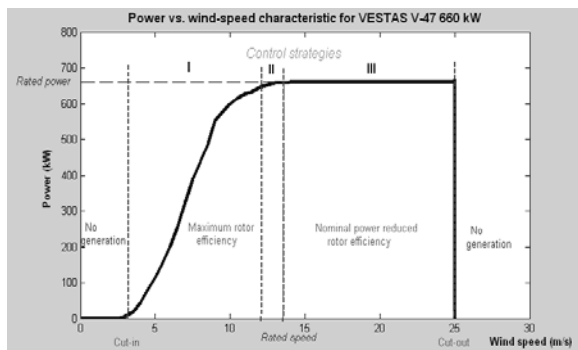
In practice, there exist limits on wind turbine operation for wind speed variations due to the system's mechanical or electrical limitations. The turbine is normally operated between a lower and upper limited wind speed. A typical power curve is shown in Fig. 3-a). It can be started at a cut-in wind speed (v_{ci}), and shut down at a cut-off wind speed (v_{co}). When the wind speed drops too low, the produced energy by the turbine is not enough to compensate for the consumed energy by the turbine, the turbine is then stopped. When the wind is too high it is again stopped since it would be

uneconomic to construct the turbine to be robust enough to operate in all wind speeds.

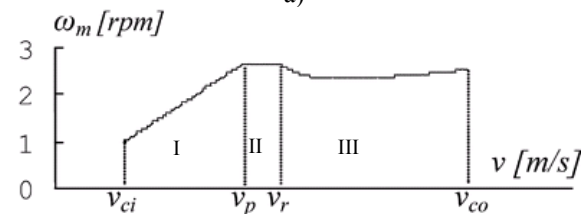
All wind turbines have an upper rotor rotational speed limitation. V_p is the corresponding wind speed at which the rotor speed reaches its maximum.

The high wind speeds are not encountered frequently enough to make it economic to extract the energy available. At a predetermined rated wind speed (V_r) the power input to the wind turbine will have reached the limit for continuous operation. When the wind speed exceeds this level the excess power in the wind must be discarded by the rotor to prevent turbine overloading.

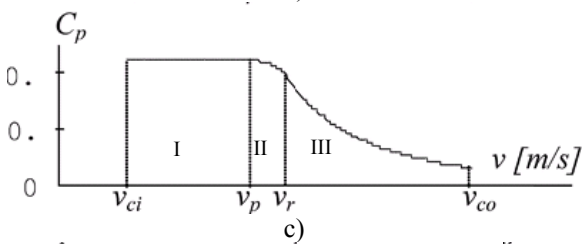
To effectively extract wind power while maintaining safe operation, the wind turbine should be controlled according to the three following modes of operation [8]: Area I: Variable speed – Optimum λ ; Area II: Constant speed – Variable λ ; Area III: Constant speed – Constant power.



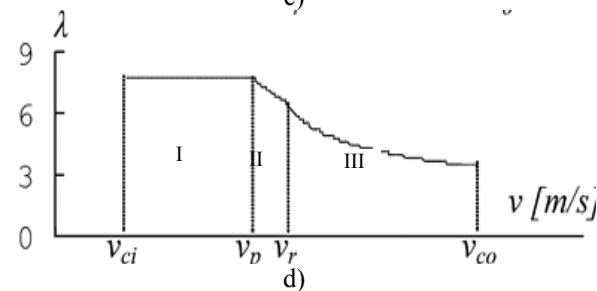
a)



b)



c)



d)

Fig. 3. Operation modes of a wind turbine considering limitations.

3.2 Area I: Variable speed – Optimum λ

As we can see from Fig. 3, at low wind speeds ($v_{ci} < v < v_p$) the operational point of the turbine should be held at the maximum point on the C_p surface. The turbine rotational speed ω , should be adjusted to obtain a constant tip-speed ratio, resulting in maximum turbine efficiency. The rotor power increases with the cube of the wind speed whereas the turbine rotational speed changes linearly proportional to the wind speed.

3.3 Area II: Constant speed – Variable λ

In area II, the rotational turbine speed reaches the speed limit. The wind turbine is controlled to prevent the turbine rotational speed from varying. The operation at optimal tip-speed ratio is not possible at all wind speeds. At higher wind speeds the speed limitation ensures that the tip-speed ratio reduces. The C_p value is no longer maximized and thus decreases slowly. The rotor power increases at a lower rate than in area I.

4 Pitch control

A well known information that is fundamental to control dynamics is that the rotor speed change is relatively slow because of the large inertia involved. Pitch control is relatively fast and can be used to limit the rotor speed by regulating input aerodynamic power flow, especially when near the high-speed limit. The pitch actuator consists of a mechanical and hydraulic system which is used to turn the blades of the wind turbine along their longitudinal axis. By varying the pitch angle, the aerodynamic torque input to the rotor is altered and hence the output power. Because the inertia of the blades is large and the actuator should not consume a great deal of power, the actuator has limited capabilities. Its dynamics are non-linear with saturation on both pitch angle and pitch rate. The actuator dynamics are depicted in Fig. 4.

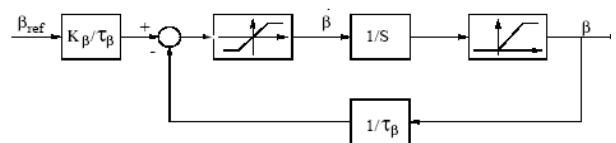


Fig. 4. Pitch actuator.

The actuator model describes the dynamic behaviour between the pitch demand from the pitch controller to the actuation of this demand. According to data from Vestas V47-660 wind turbine, the saturation level of the pitch angle is 5° to 20° , and the saturation level of pitch rate is $\pm 5\%/s$.

5 Neural network pitch controller

The purpose of this controller is to capture the maximum of wind energy below rated wind speed and to maintain the rated power above the rated wind speed by adjusting the pitch angle of the rotor blades. As we can see in **Error! Reference source not found.**, the power coefficient and the turbine's tip-speed ratio are strongly influenced by blade pitch angle and their relationship are strongly nonlinear.

ANNs have been proved a successful method in identification and control of dynamic systems. In fact, control of nonlinear systems is a major application area for ANNs. Their approximation capabilities of Multilayer Perceptron (MLP) made them a popular choice for modeling nonlinear systems and for implementing general purpose nonlinear controllers [9].

The design of an efficient blade pitch controller for a variable-speed wind turbine is crucial if the power smoothing and increased energy capture capabilities are to be fully realized. For this purpose a MatLab/Simulink environment is used for the development of the wind turbine model and a ANN is developed to control the pitch angle of the blades. The advanced numerical capabilities built into Simulink, provided an excellent simulation engine for development and control of such a system.

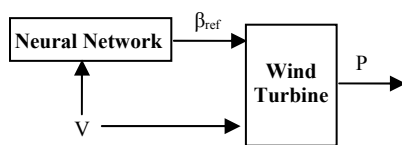


Fig. 5. Model for a ANN pitch controller.

Fig. 5, illustrates a model of such a pitch controller. The highly nonlinear characteristics of this problem match very well to neural network applications. The neural network has one input, 50 neurons in a hidden layer, and one output. As we can see, the neural network, using wind speed V as input, generate the desired pitch angle β .

To obtain data to train the network, 1000 samples of wind speed varying from v_p to v_{co} (12 to 25 m/s), was used. For each wind speed, the value of β

(between 5 and 20 degrees) that minimize the difference between the power generated and the rated power (660 kW) was collected. Thus, 1000 pairs of wind speed and β was collected to train the network.

The network is trained offline in batch mode, using the Levenberg-Marquardt method.

6 Simulation and results

Basically the main idea is that, blade pitch can be changed to provide power smoothing in high wind speeds. This section verifies the performance of the proposed neural controller by looking into the responses of the wind turbine model to wind speed variation.

Randomly varying wind speed, were the wind speeds are above the rated speed (12 m/s) up to 25 m/s, the cut out speed, is illustrated in Fig. 6. This wind speeds will be used to evaluate the performance of the wind turbine system using the ANN pitch controller.

Characteristic data about the wind turbine system used in this article can be seen in [2].

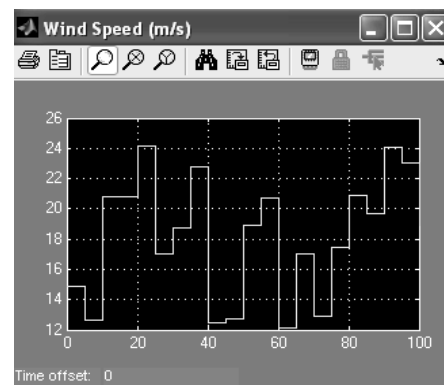


Fig. 6. Wind speed variation.

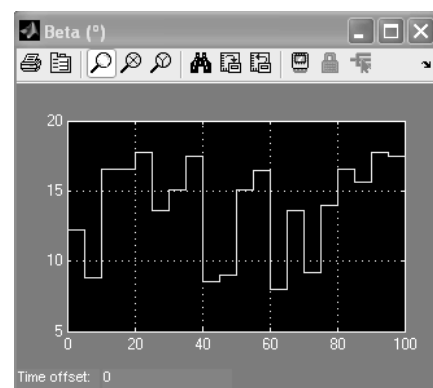


Fig. 7. β produced by the ANN.

What Fig. 8 shows is the rated power of the turbine (660 kW), the power produced by the turbine without pitch angle (upper line) and the power produced by the turbine by changing the pitch angle according the ANN controller results (Fig. 7).

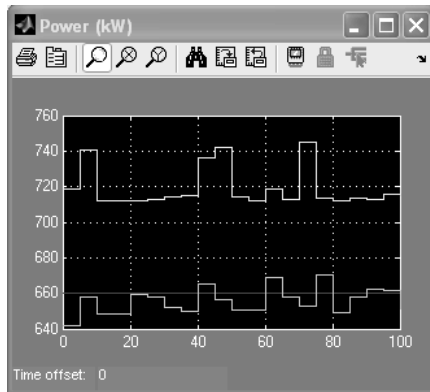


Fig. 8. Power produced.

7 Conclusion

In this paper, an ANN is adopted to control the pitch angle of rotor blades since the characteristics of the power coefficient vs. tip-speed ratio with respect to pitch angle variations are highly nonlinear. The behaviour of the presented model is quite satisfactory. In fact the ANN controller exhibits a good performance obtaining a smooth power produced by the turbine during high wind speeds, and the output power is kept nearly constant.

Matlab NN Toolbox [13] has proved a very powerful tool for building the purposed architecture and perhaps extended to build a more complex model. Nevertheless, more experimental work will be needed to validate that the controller would be a practical alternative to actual existing controllers in wind turbines. A comparison must be made between real results and the results of the simulation model.

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