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Opera suspicionată (OS)	Opera autentică (OA)
Suspicious work	Authentic work

OS	S.Ababei, Adaptive control algorithm in wind turbine speed regulation, In: Modelling and Optimization in the Machines Building Field (MOCM), vol.1, 2006, p.5-10.
OA	Hand, M.M., Johnson, K.E., Fingersh, L.J., Wright, A.D., Advanced Control Design and Field Testing for Wind Turbines at the National Renewable Energy Laboratory, Preprint. *To be presented at the World Renewable Energy Congress VII Denver, Colorado August 29 – September 3, 2004, May 2004.*

Incidența minimă a suspiciunii / Minimum incidence of suspicion	
p.7:43 – p.8:26	p.2:2 – p2:20
p.8:27– p.8:39	p.2:32 – p.2:39
p.10:8 – p.10:27	p.5:1 – p.5:19
p.10. Fig.3	p.5: Figure 2

ADAPTIVE CONTROL ALGORITHM IN WIND TURBINE SPEED REGULATION

ABABEI STEFAN

University of Bacau

Abstract. Wind turbines require active control systems to operate at variable rotational speeds. As turbines become larger and more flexible, advanced control algorithms become necessary to meet multiple objectives such as speed regulation, blade load mitigation, and mode stabilization. At the same time, they must maximize energy capture. The number and variability of influence factor in wind turbine regulation have made it necessary to develop an adaptive control algorithm. This algorithm is presented in this paper.

Keywords: Wind turbines, adaptive control algorithm,

1. POWER CONTROL OF WIND TURBINES

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output at wind speeds around 15 metres per second.

Wind turbines require active or passive regulation as power is derived from the free air stream which is, of course, not controllable. Active control includes varying the pitch of the whole blades or blade tips. Passive control results from blade profiles that produce aerodynamic stall at high wind speeds without a change of blade pitch.

Regulation, achieved by controlling the power extracted by the rotor, is necessary since there is little opportunity to store excess energy within the turbine (although there is very short term storage in large machines due to the inertia of the rotor and drive train, and small variations in rotor speed).

The philosophy of turbine control is based on three operational requirements:
1. The generation of maximum power up to the rated power.
2. Satisfactory electrical power quality.
3. The minimisation of variable and transient loads (especially fatigue inducing changing loads), thereby maximising turbine life

The degree to which these objectives are attainable (through a combination of good design and the use of control systems) is still subject to research and development.
Which ever system is employed (passive or active), control in some form is an essential machine requirement even if only as a means of preventing turbine runaway in high wind speed conditions.

1.1. STALL REGULATION

Passive control relies on the turbine's inherent machine characteristics, where the aerodynamic properties of the rotor limit the torque produced at high wind speeds. In stall regulation, control of the rotor power is achieved by exploiting the stall characteristics of the rotor blade. A blade is said to stall when the laminar flow over the

airfoil breaks down and the blade loses lift. This is analogous to an aircraft wing "stalling" when there is no longer sufficient lift to counteract gravity. This happens at low speed relative to the air.
The blade is designed in such a way that at the higher wind speeds, the stall conditions occur progressively from the root tip. The higher the wind speed, the greater the section of blade in stall.

The appeal of this form of regulation is the lack of moving parts or of an active control system.

Although stall regulation would appear very simple, it presents a highly complex aerodynamic design problem. Once blades have been designed and installed it is impossible to operate the turbine against a power setpoint without making other mechanical modifications. At above rated wind speed conditions the turbine is constrained to generate the desired power level. Although power is limited in a stall regime, there are still considerable rotor, nacelle and tower loads due to the rotor thrust.

There are also two other problem areas:
- Due to lack of sufficient torque at low wind speeds, the turbine may be unable to self start until the wind speed has increased (unless the generator is used as a motor to start the machine). Thus important power generation opportunities are lost, since the highest probability of wind speed is at the lower values.
- The blades or blade tips cannot be feathered in high wind speed when the machine has to be shut down.

Current research into stall regulated blades hopes to extend traditional airfoil theory into the stall region and hence to obtain more information about the stall regulation process.

1.2. VARIABLE PITCH CONTROL

Active control requires either
- the operation of the turbine to be modified in response to a measurement of its state or
- the load to be modified to match the output of the turbine to maintain optimum rotational speed. This is called positive feed forward control, from rotor speed to electrical load.

The principle of negative feedback pitch control is to alter the rotor aerodynamic characteristics and so influence the developed rotor power. There are two methods of implementing the blade pitch if there is too much power. These are:
- Reducing the angular incidence of the wind onto the blade (the angle of attack).
- Increasing the angle of attack (figure 1)

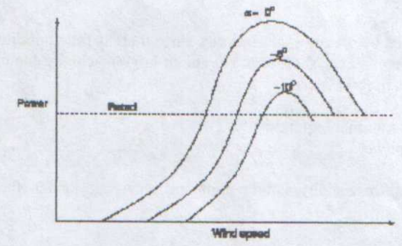

Fig. 1. Pitch Regulation – increasing incidence

Increasing incidence (assisted stall)

As wind speed increases the blade control section is moved such that its angle of incidence to the relative airflow increases The blade begins to stall and so rotor power falls (figure 1,).

When operating in stall, the rotor loses aerodynamic damping and there are increased drag loads. Although providing good aerodynamic braking this method is not as popular as the decreasing incidence option.

Decreasing incidence (pitch feathering)
This is the most popular method of pitch control. At higher speeds the control section of the blade is "feathered". This reduces rotor power, as seen in figure 2 (below).

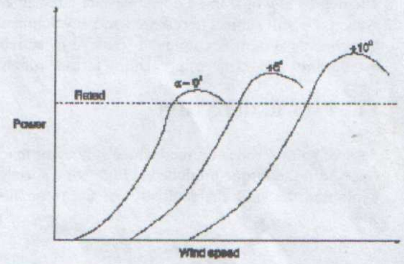

Fig. 2. Pitch Regulation – decreasing incidence

Both the above mentioned methods of pitch control are useful in starting the turbine. Blade pitch is adjusted to provide a high starting torque to move the rotor from rest.
The optimal amount of blade pitch control surface remains an unanswered question. Full span (i.e. all the blade) pitch control provides a larger control surface. However, as the most important proportion of the rotor torque is attributable to the outer section of the blade (the blade tips), a partial span control surface will be just as effective. By removing the controllable surface away from the critical root area, a fixed and hence stronger blade root can be constructed. A criticism of blade tip control is the location of the actuator mechanisms inside the blade, and at a distance from the hub. This requires a stiffer blade because of the increased forces at the tip.

1.3. PITCH CONTROL LOOP

A fundamental consideration is the bandwidth of the pitch control loop (related to the minimum change in wind speed that results in actuation of the pitch mechanism). It is important that the pitch servo mechanism is not subjected to excessive high frequency demand. Too responsive a control action will induce excessive torsional blade loads. The fatigue implications of such loads of high magnitude and frequency could be serious. The bandwidth of the control loop is intimately related to the drive train and the generator dynamics.

The pitch control servo mechanism can be either electrical or hydraulic. The bandwidth of the mechanism may well be a limiting factor to the closed loop system bandwidth. In this case the responsive control necessary for the load alleviation will be unobtainable.

The control system bandwidth also has important implications for the effect of measurement noise on the system performance. Measurement noise on the power, torque or speed signal, used for feedback, is by nature a wide band signal. The effective measurement noise spectrum, as seen by the actuator, is shaped by the controller and by the system dynamics. For example, derivative action will increase the system bandwidth but at the expense of increased pitch actuator response to measurement noise.

Control of rotor power by yaw

The principle of this method is to alter the effective rotor area in the free air stream by yawing the complete turbine rotor and nacelle. By altering the effective rotor area presented to the wind, the rotor power is controlled. Hohenemser and Swift [1983], compared the performance of passive and active yaw control on a 10kW machine. They concluded that passive mechanism was the preferable option on the basis of reliability. This is a common control method for small turbines and wind pumps, but in comparison to other techniques, it has received relatively little attention.

Aileron Control
This is another relatively uncommon control method in modern machines, but was a basic method of control in early Danish machines of the 1980's. The principle of operation is to selectively alter both lift and load forces by altering the aerodynamic characteristics of the blade airfoil. This in turn alters the aerodynamic efficiency of the rotor. Aileron control is common in aircraft for take-off and landing.

Miller and Puthoff, [1984], considered the use of ailerons in speed control following the loss of load, i.e. overspeed protection. They concluded that aileron control has advantages over pitch control in that it enables the use of a smaller actuator mechanism. The blade can therefore be made lighter and stronger.

As with rotor control by yaw, further study is needed to assess the practicality of aileron control.

2. ADAPTIVE SPEED CONTROL ALGORITHM

Wind turbine manufacturers have recently turned to variable-speed turbines to capture power over a wide range of wind speeds. These turbines require active control systems that meet different objectives depending upon the wind speed. A wind turbine can be described by the following simple relationship:

$$J_T\dot{\Omega} = Q_A - Q_E \qquad (1)$$

where
J_T rotor inertia, kg·m2
C_P rotor power coefficient
$\dot{\Omega}$ first derivative of with respect to time, *d/dt*
QA aerodynamic torque, N·m
QE generator torque, N·m

Basically, rotor rotation is a balance between the aerodynamic torque applied by the wind and the electrical torque applied by the generator. The power coefficient is a measure of the mechanical power delivered by the rotor to the turbine's low-speed shaft. It is frequently defined as the ratio of the mechanical power to the power available in the wind:

$$C_P = \frac{Q_A\Omega}{\frac{1}{2}\rho A W^3} = \frac{P}{P_{wind}} \qquad (2)$$

where:
Ω rotor angular speed, rad/s
ρ air density, kg/m3
W wind speed, m/s
P mechanical power delivered to rotor
Pwind power available in the wind

The mechanical power produced by a rotor is purely a function of the geometry and the incident velocity. The design parameters that affect aerodynamic performance include blade pitch (angle of attack), taper (solidity), and twist distribution. For a given blade, its geometric shape is usually fixed, i.e., the aerodynamic shape, taper, and twist distribution do not change. The *CP* for any fixed rotor geometry is a well-prescribed function of the blade tip speed ratio (ratio of blade tip speed to wind speed) with a single maximum value. The torque produced by the rotor can be controlled in two ways: by changing the geometry by varying the blade pitch angle, or by changing the rotor's rotational speed so the rotor operates at the optimal blade tip speed ratio.

When the wind turbine operates at variable rotational speeds, the standard control algorithm requires generator torque to be commanded along the following trajectory:

$$Q_E = k\Omega^2 \qquad unde \qquad k = \frac{1}{2}\rho A R^3 \frac{C_{PMAX}}{\lambda^3} \qquad (3)$$

where:
k torque control gain
R turbine radius, m
C_{PMAX} maximum rotor power coefficient
A rotor swept area
λ tip speed ratio at maximum power coefficient

The value of *k* is often derived from performance code simulations [2]. It can be determined experimentally via a lengthy process if the wind turbine can be operated at constant rotational speeds over a range of wind speeds. Ideally, commanding the rotor speed along this trajectory would yield maximum power coefficient values for all wind speeds.

The generator torque control trajectory was modified to actively accelerate and decelerate the rotor in response to wind speed fluctuations. Optimally Tracking Rotor control relies on the generator torque to assist in rotor acceleration and deceleration, which causes the turbine to operate more closely to the optimum tip speed ratio [4]. The standard generator torque control law is amended as follows:

$$Q_E = k\Omega^2 - G(Q_A - k\Omega^2) \qquad (4)$$

where *QA* can be determined by rearranging Eq. (1). Selection of the gain, *G*, must trade off acceleration and deceleration rate.

An approach that eliminates the need for prior knowledge of the turbine's performance and accommodates slowly changing aerodynamic properties caused by blade erosion is Model Reference Adaptive Control. A simple, highly intuitive gain adaptation algorithm improves capture in below-rated wind speeds compared to the standard controller [5].

This algorithm is similar to the standard controller.

$$Q_E = \rho M\Omega^2 \qquad (5)$$

The adaptive gain, *M*, incorporates all the terms in torque control gain, *k*, except for the air density, which is time varying and uncontrollable. The adaptive controller begins by changing *M* by some value *M*. At the end of the adaptation period, which could be tens of minutes to hours, the controller evaluates the turbine's performance. The average power coefficient for the adaptation period is compared to the average power coefficient for the previous adaptation period. If the magnitude is increasing, the next *M* will be of the same sign. Eventually *M* should converge to a value that results in maximum power capture. Figure 3 illustrates the improved energy capture for the adaptive controller compared to a standard controller. The adaptive controller produces more power, particularly at below-rated wind speeds, which translates into a 5.5% increase in annual energy production. Although this control algorithm does not require performance criteria such as *CPMAX* and λ, a wind speed measurement is necessary.

As wind turbines become larger and more flexible, advanced control becomes essential to achieve stable operation in turbulent, above-rated wind speeds. Blade pitch angle control is used to shed excess torque by regulating rotor speed to produce rated power. In addition to rotor speed regulation, load mitigation and vibration attenuation become important objectives. Current industry standard control algorithms use classical proportional-integral-derivative schemes in single-input-single-output loops to meet simple objectives. State-space based control designs have the potential to incorporate multiple inputs to achieve multiple objectives and to provide insight into the dynamic interactions influenced by feedback [6].

The highly nonlinear wind turbine dynamics must be linearized about an operating point to allow for state-space representations. Tools have been developed that provide linear wind turbine models with as many as 18 degrees of freedom [6].

The ability to use state-space based control design to regulate rotor speed in above-rated wind speeds and to enhance damping in low-damped flexible modes of the wind turbine was investigated by Wright [6]. Incrementally increasing the modeled states from 1 to 7 identified modes that tend to become unstable in closed-loop control, such as the drivetrain torsion mode. This mode was stabilized by creating an additional control loop that commanded slight variations in generator torque to accommodate drive-train torsion flexibility. In addition to stabilizing the mode, the demand on the blade pitch actuators was reduced

Finally, disturbance accommodating control (DAC) methods were used to reject wind disturbances that are modeled as steps (uniform over the rotor disk) or sinusoids (spatial variation resulting from vertical shear).

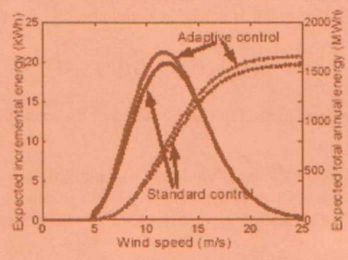

Fig. 3. Standard and adaptive control

4. CONCLUSIONS

Advanced control algorithms are necessary for the future deployment of multimegawatt, flexible wind turbines. Current research has advanced the understanding of variable speed operation via an adaptive algorithm. State-space based algorithms have been designed to stabilize lightly damped modes thereby reducing blade loads and tower deflection. DAC methods have been applied to reduce blade loads that result from passage of a coherent vortex through the rotor plane. Further development in each of these areas will enhance the reliability and performance of utility-scale wind turbines.

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