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Design of PID and LQR Controllers for Large Wind Turbines

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A B S T R A C T

Many people are interested in renewable energy sources due to environmental concerns, and wind power is one of the most promising. It is one of the fastest growing sources of power and is thought to have the capacity to fulfil global electricity demands. To achieve this purpose, wind turbines should be designed to extract the most energy while reducing component and system loads. Because wind power is still a growing technology, the many wind turbine layouts create a problem in determining the most effective approach to regulate and manage the wind turbines. This work compares the performance of PID and LQR controllers for wind turbine speed analysis and control. Simulation results for PID and Optimal Linear Quadratic Regulator controllers are given. Finally, it was discovered that the Optimal Linear-Quadratic Regulator (LQR) provides a greater dynamic response than the PID controller for wind turbine speed control.

Keywords: Wind Turbine, Wind Energy Conversion Systems (WECS), Horizontal Axis Wind Turbines (HAWT), Vertical Axis Wind Turbines (VAWT), PID Controller, LQR Controller

1. Introduction

Because of environmental concerns, there is a great deal of interest in renewable methods of electrical power generation, with wind power being one of the most promising. However, it is not yet a mature technology, and several challenges remain unresolved. One such topic is the best way to control wind turbines. Modifications have been made to large wind turbines to make them variable-speed, variable-pitch (VSVP) turbines, which are believed to improve efficiency. Many various control systems for VSVP wind turbines have been developed, but the control tactics, including those in this work, are usually equivalent. Depending on the rated wind speed, control strategies for VSVP wind turbines are frequently classified into two types. When wind speeds fall below the rated value, the generator torque is modified such that the wind turbine follows the maximum power point for that wind speed. In places where winds are faster than the rated wind speed, the wind turbine's blade pitch angle is managed to maintain rated power despite fluctuations in wind speed. The single-input, single-output (SISO) controller serves as the foundation for these fundamental controls, and the power control contains two control loops that comprise controls for the generator torque and blade pitch. Additional control loops are required for load reduction measures such as tower damper and individual pitch control (IPC). As the tower damper, a second pitch loop with a Nacelle acceleration input can be employed to reduce the tower load.

Optimizing power output and reducing loads while utilising the fewest possible control inputs and turbine measurements is one of the main goals of wind turbine control. Controls are usually designed to accomplish multiple objectives concurrently, such as power management and load minimization. Power controllers were developed in the 1970s and 1980s using conventional control design approaches like proportional integral (PI). In these many circumstances, it is difficult to apply classical controls to achieve multiple control objectives. The need for many control loops typically increases the complexity of the control system. Because the controller bases its control solely on a single measured turbine output and lacks direct knowledge of the turbine's system dynamics, it is challenging to manage control structure interaction issues using classical control methodologies. Modern controllers can determine system states by using a linear model of the turbine.

Most modern control design strategies use a full-state feedback rule, which sends back a linear combination of turbine states to the turbine. The stability of the closed-loop system is predicted to increase with improvements in the full-state feedback rule. This suggests that wind turbine controllers may be designed to accomplish many control goals simultaneously, such as maximising power or controlling speed and damping in various flexible turbine modes. In order to position the plant poles in the complex plane in a way that would support closed-loop stability, pole placement control design algorithms estimate the gains in the full-state feedback law. The full-state feedback law gains are established in other control design methodologies, such as Linear Quadratic Regulator (LQR) design, by minimising a function.

2. Controllers Design

Classical control design approaches based on the proportional-integral-derivative (PID) approach were employed for numerous major wind turbines erected in the 1970s and 1980s. Most fixed-speed machines of the time featured stiff drive trains and big rotors with considerable inertia. Wind turbulence was discovered to easily ignite the machine's initial drive-train torsion mode. The damping in this mode was extremely low for turbines with synchronous generators. The control system's goals were to manage power while also providing dampening to this mode utilizing blade pitch.

It was frequently discovered that a high controller bandwidth was required to adequately operate the machine in the midst of turbulent wind intake. Rothman contrasted rotor gust load responses at "moderately rapid pitch rates" with a loop bandwidth of 2 radians/second (r/s) to a slower system with a bandwidth of 0.2 r/s. He determined that, while loads related to low frequency wind changes were sufficiently reduced, a considerably more responsive control system was required to lessen structural stress due to high-frequency wind inputs. Fast pitch control has been suggested as a means of reducing machine loads. None of the research investigated the effect of rapid pitch rates on blade loads.

In these many circumstances, it was challenging to use classical controls to achieve multiple control objectives. The widespread use of many control loops made the control architecture and system behaviour more complex. The controller used only a single measured turbine output as the basis of its control and had no direct knowledge of the turbine's system dynamics, therefore it was impossible to tackle control-structure interaction issues efficiently using classical control methods. Modern control systems using state-space techniques more effectively address these issues since the controller uses a model to determine system states. Full-state feedback enables the development of controllers that can dampen crucial flexible modes in addition to optimising power or controlling speed.

2.1 Control Objective

To reduce the cost of provided energy while meeting safety and power quality standards, a WECS should be created. The idea that minimising energy costs necessitates increasing energy capture and safeguarding the WECS from excessive dynamic mechanical loads prompts us to identify the best management strategy for wind turbines. The many different ways wind turbines can be configured to function are referred to as modes of operation. These types of operation are frequently combined in order to achieve control objectives over the whole operational wind speed range because wind turbines operate in a variety of conditions. The four types of wind turbines are (I) fixed-speed fixed-pitch, (II) fixed-speed variable-pitch, (III) variable-speed fixed-pitch, and (IV) variable-speed variable-pitch as a result of the control aim.

Fixed-speed Fixed-pitch (FS-FP)

In this system, the asynchronous electric machine is directly connected to the power network. Its torque characteristic cannot be altered as a result. The generator speed is consequently fixed to the power line's frequency. The WECS is said to operate at a predetermined tempo as a result. The speed varies by a few percent along the generator's torque characteristic as a result of the slip. Because no additional gear is provided on purpose to carry out the control mechanism, FS-FP WECS are rather straightforward and inexpensive. Their performance is therefore really poor.

Fixed-speed Variable-pitch (FS-VP)

Maximum power conversion is only feasible at a single wind speed due to fixed-speed operation. As a result, conversion efficiency cannot be optimised below the rated wind speed. This kind of turbine is frequently set up to operate at a fixed pitch that is lower than the desired wind speed. However, variable-pitch operating in light winds might enhance capturing of energy. By continuously changing the pitch angle, power is constrained in winds that are faster than the rating. Pitch-to-stall and pitch-to-feather are two ways that pitch control can be utilised to control power. The second approach is also referred to as "active stall" or "combi stall," whereas the first approach is known as pitch angle management.

Variable-speed Fixed-pitch (VS-FP)

Numerous benefits of variable-speed operation include better energy capture, less dynamic loads, and enhanced power quality. The necessity for higher penetration rates of wind energy coupled with the desire for better power quality has influenced the adoption of variable-speed systems. When the blade angle and tip speed ratio are both 0, the conversion is at its most efficient. As a result, both the pitch angle and the tip-speed ratio must stay constant at these values in order to maximise energy capture below rated power. The rotor speed must alter appropriately to wind speed under the condition.

Variable-speed Variable-pitch (VS-VP)

In this system, the turbine is set up to operate at variable speed, fixed pitch while the wind speed is below the rating, and variable pitch when the wind speed is above the rating. Other feasible approaches include pitch-to-stall and pitch-to-feather techniques. While variable-pitch operation enables efficient power regulation at higher-than-rated wind speeds, variable-speed operation maximises energy capture at low wind speeds. It should be emphasised that this control strategy yields the ideal power curve as well. Transient loads are also reduced by variable-pitch operation. Particularly for large-scale wind turbines, this is a considerable advantage of this control method over VS-FP schemes.

2.2 Control Design of our System

At the control design stage, the linear model has already been built and tested. This is a controller with full-state feedback. When the wind disturbance is ignored, the state estimate results are achieved. We're assuming that the measurements are generator and rotor speed.

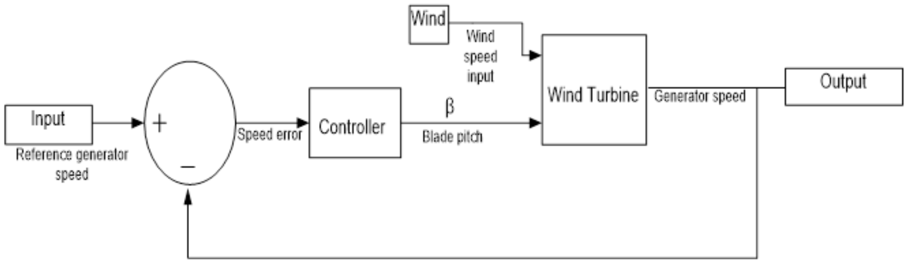

Figure 1. Block Diagram of Controller

3. Model Linearization

LINEAR MODELS:

Linear models for a wind turbine system can be expressed as

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} + \Gamma \underline{u_D}$$

$$\underline{y} = C\underline{x} + D\underline{u} + E\underline{u_D} \qquad (1)$$

Each of the linear models that we developed were expressed in state-space form as:

$M\dot{x}$ = Ax+Bu

y = Cx

Where, x = state vector

u = control input

y = measured outputs

M = mass matrix

A = state matrix

B = gain matrix

C = measured single related the y to the turbine states

Rotor blade collective pitch is now the primary control input for conventional wind turbines. The main system states are rotor or generator speed (or both), blade flap displacement and velocity, tower displacement and velocity, and others. Wind is the disturbance. Numerous factors, such as generator or rotor speed (or both), blade displacement as well as velocity and acceleration, tower displacement as well as velocity and acceleration, etc., can all be used to measure control signals. An ideal system should be able to provide control with the fewest number of measurements. Increasing operational, O&M, or both costs will result from making the regulated system more complex.

3.1 1-STATE MODEL

The rotor speed state is the sole thing included in the simplest linear model evaluated. For this model, it is assumed that the control input is a change in the rotor collective pitch angle $\delta\beta$ (the pitch angle of each blade is same in rotor collective pitch), and the disturbance input is a change in the uniform component of wind speed over the rotor disc δw. It's also believed that the observed control signal is rotor speed. This model is shown in Figure 2.

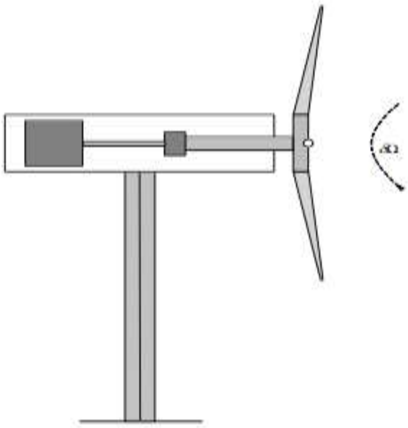

Figure 2. Depiction of the 1-state linear model

The state-space equation for this model with perturbed rotor rotational speed x_1 is

$$\dot{x_1} = \frac{\gamma}{I_{rot}} x_1 + \frac{\zeta}{I_{rot}} \delta\beta + \frac{\alpha}{I_{rot}} \delta w$$
$$y = x_1 \quad (2)$$

Comparing this with the general state-space form in Equation 1,

$\underline{x} = x_1$ -perturbed rotor speed,

$\underline{y} = x_1$ -measured perturbed rotor speed,

$\underline{u} = \delta\beta$ -perturbed rotor collective pitch,

$\underline{u_D} = \delta w$ -perturbed wind disturbance (the uniform component over the rotor disk), and

$A = \frac{\gamma}{I_{rot}}$ is the state matrix.

I_{rot} is the total rotor rotational inertia about the spin axis.

The parameter γ is the partial derivative of rotor aerodynamic torque with respect to rotor speed $\frac{\partial T_{aero}}{\partial x_1}$

The control input gain matrix is $B = \frac{\zeta}{I_{rot}}$, in which ζ is the partial derivative of rotor aerodynamic torque with respect to rotor collective pitch angle, $\frac{\partial T_{aero}}{\partial \beta}$. The disturbance input gain matrix is $\Gamma = \frac{\alpha}{I_{rot}}$, in which α represents the partial derivative of rotor aerodynamic torque with respect to wind speed, $\frac{\partial T_{aero}}{\partial w}$.

3.2 3-STATE MODEL

Addition of Drive-Train Torsion

The addition of two states to the previous model allows modeling of the first drive-train torsion mode as well as rotor and generator speeds.

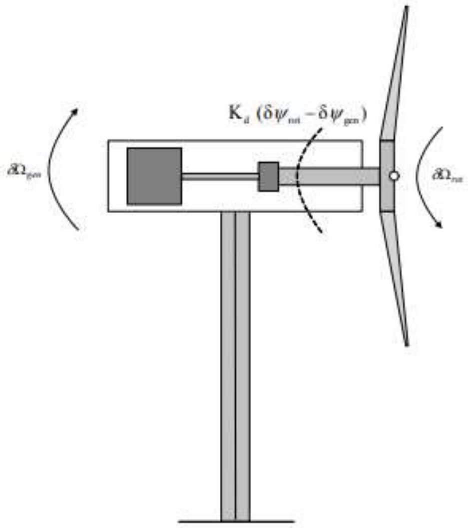

Figure 3. Depiction of the 3-state linear model

$x_1 = \delta\dot{q}_4$, perturbed rotor speed,

$x_2 = K_d(\delta q_4 - \delta q_{15})$, perturbed drive-train torsional spring force,

$x_3 = \delta\dot{q}_{15}$, perturbed generator speed.

The state-space equation is

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{(\gamma - C_d)}{I_{rot}} & \frac{-1}{I_{rot}} & \frac{C_d}{I_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{I_{gen}} & \frac{1}{I_{gen}} & \frac{-C_d}{I_{gen}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{\zeta}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \delta\beta + \begin{bmatrix} \frac{\alpha}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \delta w$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (3)$$

This is a first-order state-space equation, with $\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$ and $\underline{y} = x_3$. We have the same control input, $\underline{u} = \delta\beta$, and disturbance input, $\underline{u_D} = \delta w$.

For this state-space equation,

$$A = \begin{bmatrix} \frac{(\gamma - C_d)}{I_{rot}} & \frac{-1}{I_{rot}} & \frac{C_d}{I_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{I_{gen}} & \frac{1}{I_{gen}} & \frac{-C_d}{I_{gen}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{\zeta}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \qquad \Gamma = \begin{bmatrix} \frac{\alpha}{I_{rot}} \\ 0 \\ 0 \end{bmatrix}$$

While $C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$.

Here, K_d is the drive-train torsional spring constant, while C_d is the torsional damping constant (described in Equation 2). I_{rot} and I_{gen} represent the rotational inertia of the rotor and generator about the spin axis, respectively. The torsional spring/damper connects the rotor to the generator, modeled as lumped mass rotational inertia,

It is interesting to note that the rotor speed and the generator speed are coupled because of terms such as $\frac{C_d}{I_{rot}}$, K_d, $\frac{C_d}{I_{gen}}$, etc. In addition, the pitch input and wind disturbance gain matrices for this system now have three rows, instead of just one. Because they immediately affect the rotor speed state and rotor aerodynamic torque, the control input (rotor collective pitch) and wind disturbance input enter the system through the first-row elements of B and. Due to their coupling to the rotor speed state, the other system states are affected.

3.3 7-STATE MODEL

Addition of Blade Flap

To add the first flap mode for each blade on a two-bladed rotor, four additional states (two for each blade) are required. States to simulate the rotor's first symmetric flap mode, first drive train torsional mode, generator speed, and tower's first fore aft bending mode were included in the most sophisticated linear model employed in this work. This model may be expressed as the 7th order wind turbine in 7 states. X_1, X_2, X_3, X_4, X_5, X_6, X_7.

Where,

X_1 = rotor symmetric flap mode displacement,

X_2 = rotor symmetric flap mode velocity,

X_3 = rotor speed,

X_4 = drive train torsional spring force,

X_5 = generator speed,

X_6 = tower first fore-aft mode displacement, and

X_7 = tower first fore-aft mode velocity

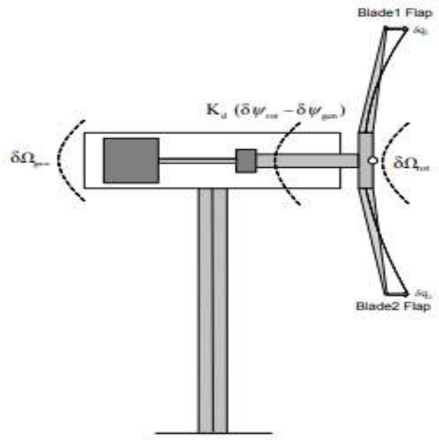

Figure 4. Depiction of the 7-state linear model

The final state equation for this model is

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{11} & M_{14} & 0 & 0 & 0 & M_{17} \\ 0 & 2M_{14} & I_{rot} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{gen} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 2M_{71} & 0 & 0 & 0 & 0 & M_{77} \end{bmatrix} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \\ \dot{x_5} \\ \dot{x_6} \\ \dot{x_7} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -K_{11} & -C_{11} & -C_{14} & 0 & 0 & -K_{17} & -C_{17} \\ 0 & -2C_{41} & \gamma - C_d & -1 & C_d & -K_{47} & -C_{47} \\ 0 & 0 & K_d & 0 & -K_d & 0 & 0 \\ 0 & 0 & C_d & 1 & -C_d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -2K_{71} & -2C_{71} & -C_{74} & 0 & 0 & -K_{77} & -C_{77} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} 0 \\ \zeta_b \\ \zeta \\ 0 \\ 0 \\ 0 \\ \zeta_t \end{bmatrix} u + \begin{bmatrix} 0 \\ \alpha_b \\ \alpha \\ 0 \\ 0 \\ 0 \\ \alpha_t \end{bmatrix} u_d$$

Please note that the mass matrix equation is not symmetric due to the selection of the states in this system. For example, x_2, which is associated with rotor first symmetric flap (which is a linear combination of blades one and two flap) (row two), couples to the tower fore-aft motion (x_7) through M_{17} while x_7 (row seven) couples to x_2 through 2 M_{71}.

Elements in A consist of various combinations of damping and stiffness terms for the turbine. The elements of B show how the control input enters the system. For the seven-state model shown above, the only nonzero elements in B are the second, third, and seventh rows. These quantities represent the partial derivatives of the blade flap normal force, rotor aerodynamic torque, and rotor thrust force with respect to pitch angle. These values reflect the capability to control the rotor symmetric flap mode, the rotor aerodynamic torque, and tower first fore-aft mode using rotor collective pitch. Because rotor collective pitch is the only control input in this study, the vector u has dimension 1×1, represented by perturbations in rotor collective pitch δβ.

The dimension of U_d is 1×1 and is used to represent the perturbations in windspeed δw. This disturbance is considered to contain only one component of wind speed, the component normal to and uniform across the rotor disk. The only nonzero elements in Γ are the second, third, and seventh rows (for the seven-state model). Those elements are the partial derivatives of the blade flap normal force, rotor aerodynamic torque, and rotor thrust force with respect to wind speed. These values reflect the influence of uniform wind-speed fluctuations on the rotor symmetric flap mode, rotor aerodynamic torque, and rotor thrust By removing the appropriate rows and columns, it is possible to derive models from this equation that have fewer states. Only generator speed was recorded for the models without tower motion.

3.4 Mathematical Equations of 7 State Space Model

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -205.689 & -9.28789 & -20.9296 & 0.0000303452 & 0 & 103.137 & -15.5651 \\ 1.07776 & 0.0115592 & -0.0348779 & -3.26681 \times 10^{-6} & 0 & -0.54041 & -0.0047153 \\ 0 & 0 & 2.691 \times 10^{7} & 0 & -2.69 \times 10^{7} & 0 & 0 \\ 0 & 0 & 0 & 0.0000156006 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 2.25453 & 0.0447976 & 0.152178 & -3.33549 \times 10^{-7} & 0 & -35.5138 & 0.0033466 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ -1150.67 \\ 2.57338 \\ 0 \\ 0 \\ 0 \\ 4.49326 \end{bmatrix} \qquad C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

4. Proportional-Integral-Derivative (PID) Control

The most common control used is PID Control. In this control the values of proportional, integral and derivative are tuned to get accurate results or efficient output. The general structure of the PID controller is shown below.

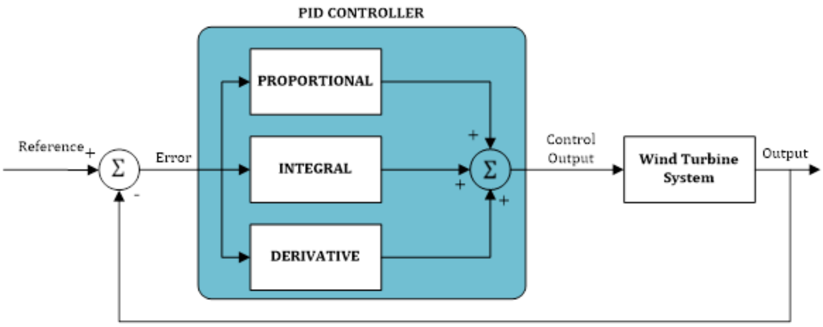

Figure5. GeneralStructure of PID Controller

PID control action is a mixture of proportional, integral, and derivative control actions. PID controllers are widely employed to control the time-domain behavior of a wide range of dynamic plants. These controllers are particularly popular due to their ability to give strong closed-loop response. Although PD control solves the overshoot and rising difficulties associated with proportional control, it does not solve the steady-state error problem. As a result, in addition to the benefits of PD controllers, PID controllers are employed to minimize steady-state error.

The PID controller is a common feedback loop component in industrial control applications. To enable the system data to approach or stay at the reference value, the controller compares the collected data to a reference value and uses the difference to produce a new input value.The PID controller may modify the input value based on previous data and the rate of difference appearance, making the system more precise and reliable. It is made up of three parts: a proportional controller, an integral controller, and a derivate controller. A proportional controller functions similarly to a gain amplifier. It can reduce steady-state error and improve system accuracy, but it reduces system stability. The use of an integral controller will accelerate the system's approach to the specified value and reduce steady-state error. A derivative controller can help with system settling and stability. The PID controller transfer function utilized in this paper is stated as follows:

$$G_{PID}(S) = K_p + \frac{K_I}{s} + K_D * \frac{N}{(1 + N_S)}$$

Where**,**

$\frac{N}{(1+N_S)}$ is a low-pass filter, it can effectively reduce high frequency noise component.

K_p = Proportional gain

K_i = Integral gain

K_d = Derivate gain

PID	**Rotor speed**	**Generator speed**

Table 1: Gain values of PID Controller

	Beta	Wind	Beta	Wind
K_p	-0.2709	12.5332	-0.2135	11.1057
K_i	-0.0419	2.0518	-0.0259	1.6057
K_d	0.0897	-4.0528	0.1550	-5.1785
N	2.9263	3.0924	1.2922	1.9989

It is critical to identify optimum parameters to ensure system stability and performance. PID settings may be tuned using a variety of techniques. However, in this study, MATLAB is used to calculate the three parameters of the PID controller values.

5. Linear Quadratic Regulator (LQR) Control

Linear quadratic regulator (LQR) is an optimum and state space feedback controller for linear systems that aims to discover the ideal controller that minimizes a specified cost function (performance index). This cost function is defined by two matrices, Q and R, which weight the state vector and the system input, respectively. The LQR design is based on the designer's expertise, which is provided through the selection process of the weight matrices (Q and R) in the typical LQR controller. These weighting matrices govern the penalty for state variable and control signal excursions. One feasible approach is to make Q and R diagonal matrices. The value of the items in Q and R is proportional to their contribution to the cost function. Linear quadratic regulator design is a well-known approach in current optimal control theory and has been widely employed in a variety of applications. The benefits of using LQR are that it is simple to build and that it improves the accuracy of state variables by estimating the state. The Linear Quadratic Regulator seeks to minimize a quadratic cost that is dependent on the system states m(f) and the system inputs (u). The goal of LQR is to minimize the control error e(t).

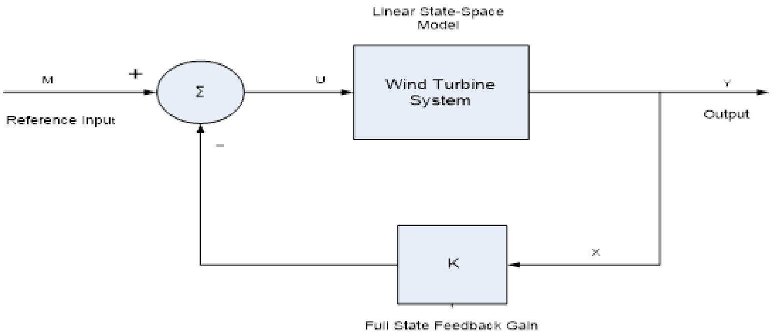

Figure 6. General Structure of LQR Controller

The LQR is the main approach for developing state-feedback control problems in modern optimal control theory. This is how the states participate in a reduction process. And the cost function considers how much the control signals are worth. The approach improves performance when the weighting matrices are right, however the main difficulty is the weighting matrices after repair. The Q and R weighting matrices are tuned using the hit-and-trial approach, which is a typical LQR control mechanism. Because the higher-order method is a time-consuming technique, these acts are unfeasible.

In current optimal control theory, the LQR is the most prominent approach for constructing state-feedback control problems. This is the minimization procedure, in which the states and control signals are weighted by the cost function using the appropriate weighting matrices. The This strategy improves performance; however, the key issue is the modification to assess the weighting matrices. The hit-and-trial methodology is used to calibrate the Q and R weighting matrices in the standard LQR control method. This method is not viable with the higher - level system since it is time intensive.

LQR is a control approach that offers the best performance in relation to a specific performance metric. Making a state feedback controller K that minimize the objective function J is the aim of the LQR design problem. This method develops a feedback gain matrix that minimize the target function to find a balance between the amount of control effort, the magnitude, and the reaction time that would result in a stable system. For a continuous-time linear system described by

$$\dot{x} = Ax + Bu$$

With a cost functional defined as

$$J = \int_{0}^{\infty} (\underline{x}^T Q \underline{x} + \underline{u}^T R \underline{u}) dt$$

Q = diagonal ([1 1 0.1 10^-9 10 1 1]);

R = diagonal ([10,10]);

Where Q and R are the weight matrices, Q must be a positive definite or positive semi-definite symmetry matrix, and R must be a positive definite symmetry matrix. One feasible way is to make Q and R diagonal matrices. The worth of the items in Q and R is proportional to their contribution to the cost function J.

6. Simulation & Results

The results of the system with using PID and Optimal LQR Controller are shown here. In this report we are considering only two states Rotor speed and Generator speed, X_3 and X_5 respectively.

6.1 ROTOR SPEED

Rotational speed of a wind turbine rotor about its axis and the rated speed of rotor in a wind turbine is 42 rpm.

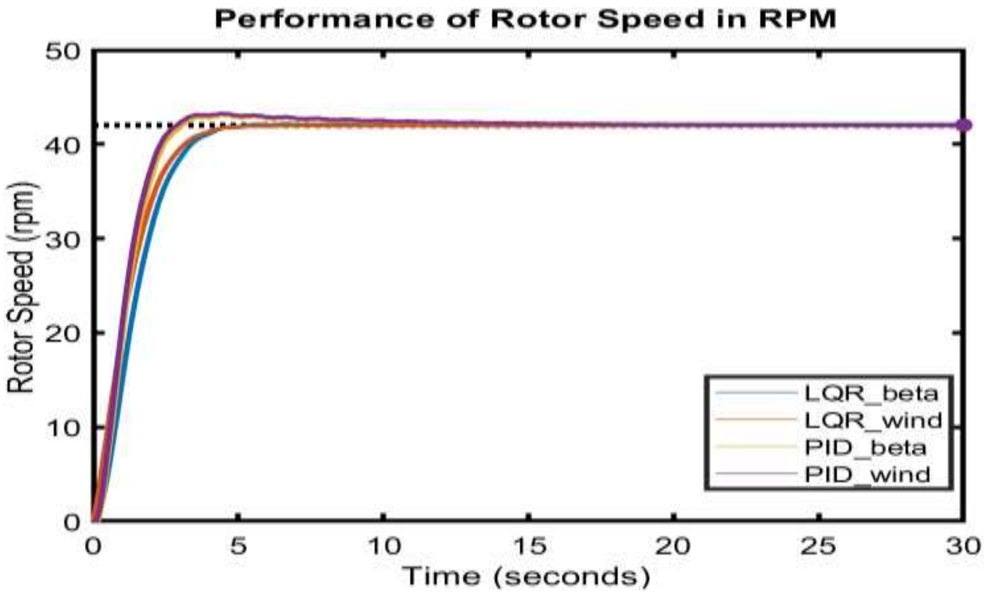

Figure 7. Simulation graph of Rotor Speed

Rotor Speed X_3		**Rise Time(t_r)**	**Peak Time(t_p)**	**Settling Time(t_s)**	**Peak overshoot M_p (%)**	**Steady state(e_{ss})**
PID	**Beta**	1.73	4.43	5.86	2.72	42
	Wind	0.67	4.42	6.78	3	42
LQR	**Beta**	2.41	6.66	4.08	0.143	42
	Wind	2.31	6.54	3.75	0.111	42

Table 2: *Comparison of results of PID and LQR controller of Rotor speed X_3*

6.2 GENERATOR SPEED

Wind power is generated by the force wind exerts on the blades of a turbine, causing the turbine's shaft to rotate at a speed of 10 to 20 revolutions per minute (rpm). The rotor shaft is connected to a generator that converts mechanical energy into electrical energy. And the rated speed of generator is 1500 rpm.

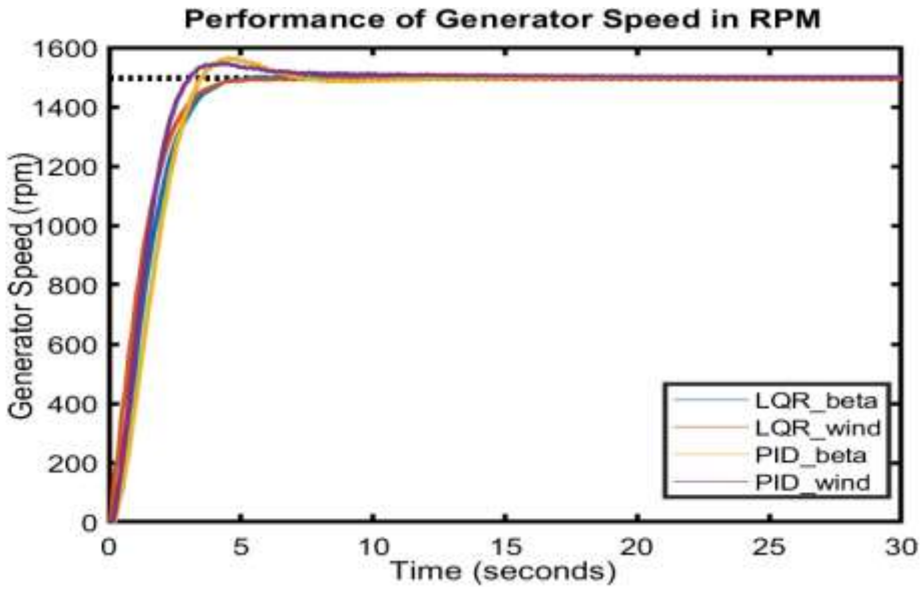

Figure 8. Simulation graph of Generator Speed

Generator Speed X_5		Rise Time(t_r)	Peak Time(t_p)	Settling Time(t_s)	Peak overshoot M_p (%)	Steady state(e_{ss})
PID	**Beta**	2.24	4.55	5.97	4.42	1500
	Wind	1.88	4.25	5.64	3.09	1500
LQR	**Beta**	2.34	6.66	4.08	0.154	1500
	Wind	2.4	6.54	3.75	0.118	1500

Table 3: Comparison of results of PID and LQR controller of Generator speed X_5

7. Conclusion

While LQR controllers can handle several wind turbines states simultaneously, PID controllers cannot. While PID regulation has a larger overshoot, pitch angle fluctuated for a moment, which is harmful for pitch actuator. So as to enhance control performance of large wind turbine a LQR pitch control algorithm based on disturbance correction is better according to LQR control theory. This control method could reduce pitch actuators movement and had good control performance on generator and rotor speed. The simulation results showed that LQR method has good performance and it is simple and effective. So, it has the great potential to be applied into engineering.

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