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GA based Optimal LQG Controller Design for Pitch Regulated Variable Speed Wind Turbine

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Abstract: This work focuses on developing an optimal controller for pitch-regulated speed control of a variable-speed wind turbine operating under above-rated wind conditions. As power generation from wind is inherently variable, effective control strategies are essential to reduce power fluctuations and ensure stable grid integration. A pitch control mechanism is employed in the full-load region to regulate rotor speed by adjusting blade angles, thereby maintaining power output within desired limits. A simplified two-mass mechanical model of the turbine, based on the Controls Advanced Research Turbine (CART) from NREL, is developed and linearized around an operating point (wind speed of 18 m/s and rotor speed of 42 rpm). Initial open-loop simulations reveal the need for a closed-loop controller. A conventional PID-based pitch controller is first implemented in MATLAB-SIMULINK, followed by the design of a more advanced Linear Quadratic Gaussian (LQG) controller, which integrates a Linear Quadratic Regulator with a Kalman filter for optimal state estimation. As manual tuning of LQG weighting matrices is time-consuming and suboptimal, a Genetic Algorithm is proposed for their optimal selection. The objective of this work is to enhance power quality by minimizing fluctuations in the generated wind power.

I. INTRODUCTION

Wind turbine plays an important role to convert wind kinetic energy to electricity. They are relatively simple machines when compared with complex electrical power plants. However, the stochastic nature of the wind introduces a degree of complexity which is not usually associated with other regulated power-producing services.

If the energy price from WTs in the coming years is to be competitive with other power production methods, an optimal balance must be made between maximum power capture on one side, and load-reduction capability on the other side. To be able to obtain this, a well-defined control-design is needed to improve energy capture and reduce dynamic loads. Control can be divided into two main categories: control for below rated wind and above rated wind conditions. For below rated wind condition, objective is to optimize energy capture whereas for above rated wind condition, the objectives are to keep generator speed at its rated value to avoid over-speed and mitigate the effect of loads acting on turbine blades. This paper is focussed on controller design for above rated wind conditions.

II. PROBLEM DEFINITION

When a WT is operating at rated speed, a rise in the mean wind speed may necessarily cause the force on the rotor blades to increase, and hence the torque to rise as well. If the generator is allowed to accelerate this will result in increased rotor speed, if no control is utilized to counteract the change in wind speed. This is not a desired situation since the generated power will deviate from the rated value and when the matter of fatigue is concerned, these variations in torque will give stress cycles, which in turn will reduce the lifetime of the WT components. Hence, the design of a control system capable of mitigating the effect of wind loads through pitch regulated speed control is essential for above rated wind speed condition.

III. LITERATURE SURVEY

In 2004, Alan D. Wright [3] presented a control approach based on the Disturbance Accommodating Control (DAC) method and provides accountability for wind-speed fluctuations. Simulation of simple classical PI control for the CART resulted in unstable closed-loop behaviour in the flexible system, these results highlighted the need for modern control methods.

In 2006, Tomonobu Senjyu, Ryosei Sakamoto, Naomitsu Urasaki, Toshihisa Funabashni and Hideomi Sekine [4] proposed the output power leveling of wind turbine generator for all operating regions by pitch angle control. The proposed method presents a control strategy based on the average wind speed and the pitch angle control using generalized predictive control in all operating regions or WTG.

In 2013, Fredric Sandquist, Michael Muskulus and O. A. Lara [13] discussed two different approaches for individual pitch control of wind turbines. The first one is a gain scheduled decentralised control design and the second one is a robust H∞ loop shaping control design. Both controllers work well in whole region 3

In 2013, S. A. Tahera, M. Farshadnia and M. R. Mozdianfard [14] presented an optimal gain scheduling power controller for a variable-pitch variable-speed wind energy conversion system. For this purpose a set of linear quadratic Gaussian (LQG) controllers are optimally designed using differential evolution (DE) optimization algorithm.

in 2014, Hua Geng and Geng Yng [15] discussed the nonlinear property of the real wind turbine and compared the typical linear and nonlinear strategies employed in wind turbine pitch control. They have analyzed the performance of linear PI controller, gain scheduled PI and nonlinear adaptive controller.

In 2014, Raja M. Imran , D. M. Akbar Hussain and Zhe Chen [16] presented a LQG controller for collective pitch regulation of turbine rotor blades in high wind speed region. They have considered 3 state model of the wind turbine system and compared the perfor- mance of the controller with the conventional PID controller. Here the weighting matrices are selected by trial and error procedure which is a highly tedious process.

In 2015, Tan Luong Van, T.H.Nguyen and D.C.Lee [17] proposed an advanced pitch angle control strategy based on the fuzzy logic where the generator output power and speed are used as control input variables for the fuzzy logic controller. The pitch angle reference is produced by the FLC which can compensate for the nonlinear characterestic of the pitch angle to the wind speed.

In 2015, Omid Bagherieh and Ryozo Nagamune [18] presented an application of gain- scheduling control techniques to a floating offshore wind turbine on a barge platform for above rated wind speed cases. Special emphasis is placed on the dynamics variation of the wind turbine system caused by plant nonlinearity with respect to wind speed.

In 2016, Yaxing Ren, Liuying Li, Joseph Brindley and Lin Jiang [19] proposed a non- linear PI based pitch angle controller by designing an extended order state and perturbation observer to estimate unknown time varying nonlinearities and disturbances. The proposed PI does not require actual model and uses only one set of PI parameters to provide a global optimal performance under wind speed changes.

In 2016, Richie Gao and Zhiwei Gao [20] introduced a novel pitch control approach is developed by integrating optimization, delay-perturbation estimation, and signal com- pensation techniques. Specifically, an optimal PI controller is designed by applying direct search optimization to ideal delay-free pitch model.

IV. SYSTEM DESCRIPTION AND MODELLING

Wind Turbine System

A wind turbine is a device for extracting energy from the wind. Figure 1 shows the basic components, including the blades, hub, low and high speed shaft, gearbox, generator, nacelle, and tower. The generator is coupled to the utility grid either directly or via a frequency-conversion system. In the latter case, the rotor speed is variable ; in the former case, it is fixed by the frequency of the grid. The aerodynamic torque is transferred to the generator via the drive train. This transmission consists of a low-speed and high- speed shaft, separated by the gearbox. The rotational speed of the generator is typically 1500 revolutions per minute (rpm), whereas the rotor rotates at 20-50 rpm.

Blade-pitch regulation provides means for initiating rotation, varying rotational speed to extract power at low wind speeds, and maintaining power production at a maximum level. Controllers must be designed to meet each of these objectives, but this study pertains only to constant power production stage.

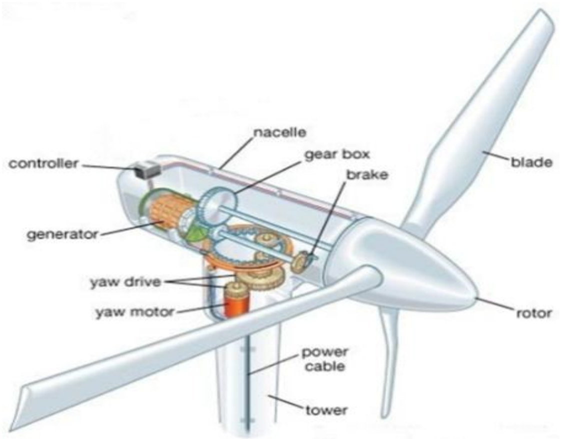

Figure 1: Wind turbine system

Wind Energy Conversion Principles

Simply the working principle of a wind turbine can be explained as, when wind blows over the turbine blades the rotor will rotate. This will cause the rotation of the generator rotor connected by the gear trains and hence generates power. The power in the wind (Pwt) in steady state can be described mathematically according to the following equation

$$Pwt = (\tfrac{1}{2})\,\rho\pi R^2 V^3$$

Collective Blade Pitch Control

A pitch regulated WECS have an active control system to vary the pitch angle (turn the blade around its axis) as shown in figure 2.

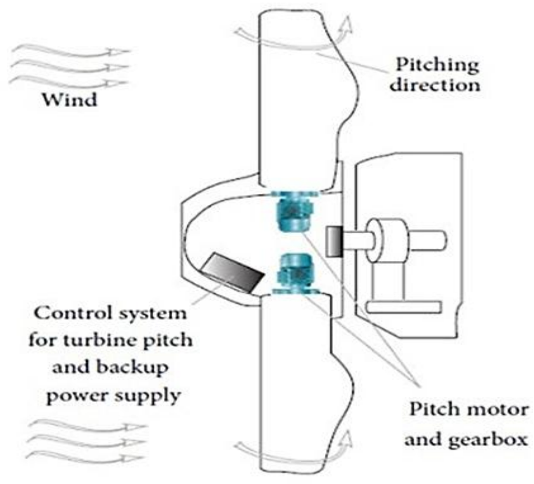

Figure 2: Configuration of pitch regulation subsystem in the WT

Figure 3 describes the implementation of the pitch control scheme. Pitch control subsystem is composed of pitch angle controller, actuator and the turbine mechanical subsystem. During high wind speed events the extracted wind power has to be limited via blade pitching, which is realised by means of a pitch regulated speed controller that regulates the generator speed, ωg to its rated value $\omega g,ref$. The pitch controller is thus active only when the wind speed exceeds rated speed.

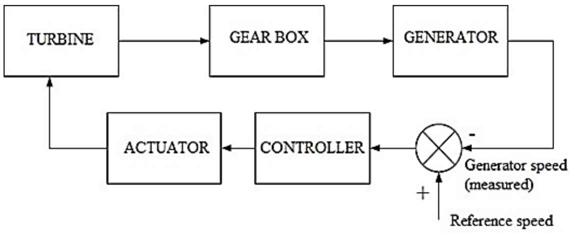

Figure 3: Pitch control scheme

Wind Turbine Modelling

Modelling of Blade Aerodynamics

The wind turbine rotor transforms the absorbed kinetic energy of the air into mechanical power. The energy available in the air is

$$Pwt = (\tfrac{1}{2})\,\rho\pi R^2 V^3$$

where ρ is the air density, R is the radius of the swept area of the blades, and V is the wind speed. But the turbine mechanical power which a wind turbine can extract depends on the power coefficient Cp and is given by

$$Pmec = (\tfrac{1}{2})\,Cp\rho\pi R^2 V^3$$

The power coefficient Cp is a function of pitch angle β and tip-speed ratio λ. The general expression of power coefficient is as

$$Cp = C1\left(\frac{C2}{\lambda i} - C3\beta - C4\right)e^{\frac{-C5}{\lambda i}} + C6\,\lambda$$

The aerodynamic torque developed by the turbine is

$$Tr = (\tfrac{1}{2})\,Cq\rho\pi R^3 V^2$$

By adjusting β the aerodynamic torque developed by the turbine and hence the rotor speed can be effectively controlled. This is the basic principle behind wind turbine pitch control mechanism.

Two Mass Drive Train Model

The wind turbine is a combination of subsystems such as aerodynamic rotor, drive train and generator. Here the wind turbine is modelled as a two mass inertia system, where two inertias are connected with a tortional spring and a tortional damper as shown in figure 4.

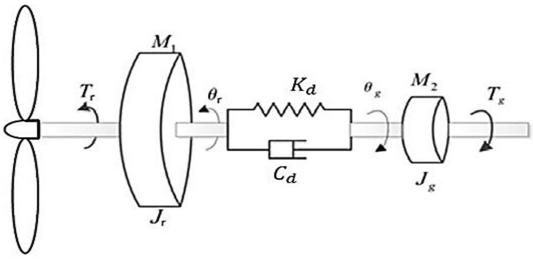

Figure 4: Two mass model of wind turbine

The wind turbine dynamics can be described by the following equation,

Tsh = Cd(ωr − ωg) + Kd(θr − θg)

The two mass drive train model developed so far represents a highly non linear system, due to the expression of the aerodynamic torque.

Actuator Model

The actuator is used to realise the rotation of the blades around the longitudinal axis. Hydraulic or electromechanical devices are widely used for the pitch actuator in the high wind speed range of the turbine. There is a lag time between what the controller requests for the commanded pitch and the actual pitch delivered to the blade by the actuator. This pitch actuator lag must be accounted for.The pitch actuator can be modelled with a simple first-order model. The actuator transfer function is described by

Act(s) $=\frac{1}{\tau s+1}$, where τ is the time constant of the actuator.

V. CONTROLLER DESIGN AND METHODOLOGY

A control system is an interconnection of components forming a system configuration that will provide a desired system response.

PID Controller

A Proportional-Integral-Derivative (PID) controller is a conventional contol loop feed- back mechanism commonly used in industrial control systems. A PID controller continuously calculates an error value (e(t)) as the difference between a desired setpoint and a measured process variable. The controller attempts to minimize the error over time by adjustment of control variables. The block diagram of the PID controller is shown in figure 5, where the PID produces a control signal u(t) such that,

ut = kpe(t) + ki∫e(t)dt + kd $\frac{de(t)}{dt}$

where, kp=Proportional gain, ki=Integral gain, kd=Derivative gain

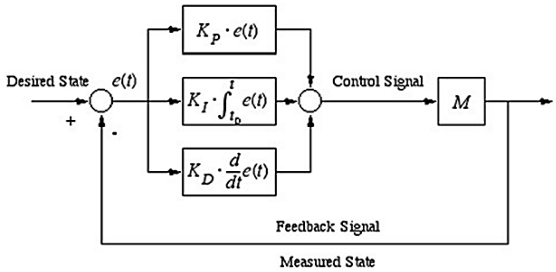

Figure 5: Block diagram of PID controller

LQG Controller

Linear Quadratic Gaussian (LQG) controller is an optimization controller based on state space model of a linear system with quadratic objective function. LQG design problem is rooted in optimal stochastic control theory.

The LQG controller is simply the combination of a Kalman filter with a regular, LQR controller. The separation principle guarantees that these two can be designed and computed independently. The state space equations of the open loop plant for a standard LQG problem is

x˙ = Ax + Bu + Gw

y = Cx + Du + v

where x is the state vector, u is the control input vector, y is the measured output vector, w and v are stochastic white noise associated with the plant and the measurement, respectively. The matrices A(state transition matrix), B(control input matrix), G(plant noise gain matrix), C(measured state matrix) are all Linear Time Invariant (LTI).

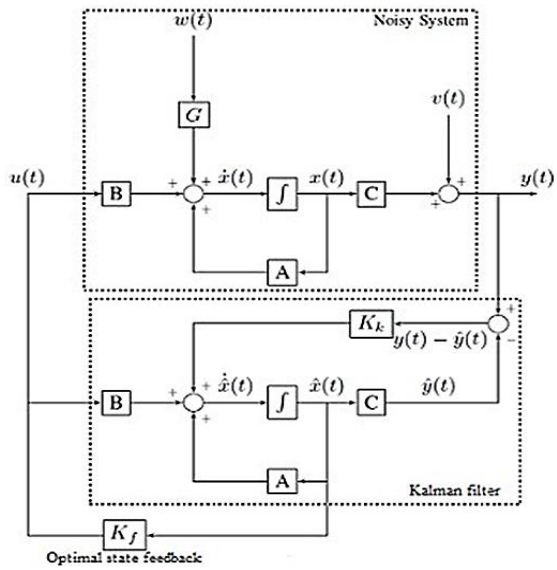

Figure 6: LQG regulator block diagram

Both w and v are assumed to be white gaussian noises with zero mean and have covariances Ξ and Θ respectively and the cross covariance is assumed to be zero (w and v are uncorrelated) in order to simplify many expressions and derivations. In real world control design problems, it is rarely possible to have access to all states of the system which are needed for full state feedback in LQR design. Instead, access is only possible to specific measured outputs of the system. If these measurements carry enough information about the states of the system, then a state observer using Kalman Filter could be implemented to estimate all states of the system. The main inputs to the observer are the control input u and the system output y.

From Fig.6 it should be noticed that LQG is formed by connecting the system and the Kalman Filter through the optimal state estimation gain Kk and then creating full state feedback by using the estimated states xˆ which passed through the optimal feedback gain Kf. Because of the stochastic separation principle, the previously mentioned gains could be designed individually.

The design process starts with checking controllability and observability of the pairs (A, B) and (A, C) respectively. These criterias are necessary for the existence of the solutions for the equations used to find the optimal gains. Then, the optimal kalman gain Kk is calculated where Pk is the solution of the Filter Algebraic Riccati Equation (FARE).This solution ensures a minimum value of the kalman filter performance index. After that, the optimal state feedback gain Kf is calculated where P is the solution of the Control Algebraic Riccati Equation (CARE). This solution ensures a minimum value of LQR performance index.

CARE requires two weighting matrices: Q (symmetric positive semi-definite) and R (symmetric positive definite). These weighing matrices provide a means to trade-off opposing objectives: state regulation and control usage. After finding the optimal gains, the closed loop system could be created by augmenting the system with Kalman Filter resulting in the new model as shown in figure 3.4. In order to eliminate any steady-state offset that may occur, an integrating controller can be added to the controlled system. Integral control is a method of output feedback, which integrates the error between any reference signal and the output and adds it to the state feedback control effort to eliminate steady-state error.

From the above mentioned LQG design procedure it is evident that it is necessary to select the weighting matrices Q and R in order to solve the CARE to get the state feedback gain matrix Kf . There are infinite number of possible selections for the weighting matrices. The trial and error method is typically used in the choice of elements of the weighting matrices to meet the required specifications. But trial and error method does not ensure optimal selection of weighting matrices and usually several iterations must be performed to find matrices that meet the specified requirements. Therefore the tedious manual selection procedure has to be replaced by Evolutionary algorithms to automate the search for the best values of weighting matrices that meets design specifications. In this work Genetic Algorithm is proposed to automate the search for optimal values of weighting matrices.

VI. GA OPTIMIZATION OF LQG CONTROLLER

As discussed in the previous chapter for a LQG controller the control performance depends on the selection of optimal values for the weighting matrices Q and R. In this work Genetic Algorithm is proposed to automate the search for the optimal values of the tuning parameters.

Genetic Algorithm

Genetic Algorithms are the heuristic search and optimization technique that mimic the process of natural evolution. GAs encode the decision variables of a search problem into finite-length strings of alphabets of certain cardinality. The strings which are candidate solutions to the search problem are referred to as chromosomes and the alphabets are referred to as genes. To evolve good solutions and to implement natural selection, we need a measure for distinguishing good solutions from bad solutions. The measure could be a fitness function that is a mathematical model or a computer simulation. This fitness function must determine a candidate solutions relative fitness, which will subsequently be used by the GA to guide the evolution of good solutions. We can start to evolve solutions to the search problem using the following steps:

1.Initialization: Start the process by randomly generating individuals of the initial population, where each individual is a candidate solution of the problem.

2.Fitness evaluation: Once the population is initialized calculate the fitness value of each individual in the generation. A fitness function value quantifies the optimality of a solution. The fitness value is assigned to each solution depending on how close it is actually to the optimal solution of the problem. It is used to rank a particular solution against all the other solutions

3.New generation: The initial population should be improved through several iterations. Hence a new generation can be generated through the application of genetic operators like selection, crossover and mutation in the search space of the optimal solution.

•Selection: This is a process that determines which solutions are to be preserved and allowed to reproduce and which ones deserve to die out. Selection allocates more copies of those solutions with higher fitness values and thus imposes the survival-of-the- fittest mechanism on the candidate solutions.

•Crossover: The crossover operation is to generate new individuals from the ones chosen by selection operator. A crossover between two individuals is performed by selecting two points on the chromosomes of the two individuals and swapping the chromosomes between those points.

•Mutation: In this stage, the mutation operator modifies the chromosomes of the individual to generate a new individual where an element of the chromosome is randomly chosen to change. Mutation operator occasionally introduces new features in to the solution strings of the population pool to maintain diversity in the population.

4.Stopping criteria: Now calculate the value of the fitness function for each individual in the new generation to evaluate whether the GA search process is converging to an optimal solution. The optimization process is over until a convergence criterion is reached, or the desired number of generations is accomplished. If the convergence criterion is not satisfied, the iterative process returns to step 3 and produces the next generation and repeat the iteration until the required convergence criterion is met.

LQG-GA Optimization

The performance of the LQG controller depends on the optimal selection of weighting matrices Q and R. The trial and error method is typically used in the choice the elements of the weighting matrices to get good performance and robustness. But this method does not ensure the optimal selection of weighting matrices and usually several iterations must be performed to find matrices that meet the specified requirements. Hence in this work a methodology based on Genetic Algorithms is proposed to automate the search for the best values of the weighting matrix elements.

To implement GA, a genetic representation of feasible solution, namely individual and the fitness function to evaluate the candidate solutions are required. The algorithm begins by establishing an initial population of individuals. The individual contains information about the weighting matrices and represent a LQG controller. Here the genetic representation of a LQG controller is defined by selecting the diagonal elements of weighting matrix Q and the value of R is chosen to be 1. Therefore an individual is composed by three elements, namely chromosomes that correspond to the diagonal elements of the matrix Q. Once the population is defined each solution has to be evaluated to measure its quality by assigning a value equivalent to the performance according to the fitness function.

The most crucial step in applying GA is the choice of the performance indices that are used to evaluate the fitness of each individual. Here the fitness function chosen is based on the linearized system response to step input, and two optimal performance indices are used for that purpose, Integral of Absolute Error (IAE) and Integral of the Squared Error (ISE). These performance indices are defined by equations

$$\mathrm{IAE} = \int |e(t)|dt$$

$$\mathrm{ISE} = \int (e(t))^2 dt$$

where e(t) is the error signal in the step response in time domain. Fitness function is defined as the reciprocal of the performance index. The initial population should be improved through several iterations. In each iteration, three operators, selection, crossover, and mutation, are performed to generate a new population. The iterations will continue until a convergence criterion is reached or the desired number of iterations are performed.

VII. RESULTS AND DISCUSSION

The non-linear mathematical model of the Wind Turbine System has been developed and it has been linearized around an operating point. Then a conventional PID controller has been designed for the pitch regulated speed control of the wind turbine. Later LQG controller has been designed for the speed control. Since LQG controller design with trial and error values of weighting matrices does not ensure optimal performance Genetic Algorithm based optimal LQG controller is developed with performance indices IAE and ISE. Simulations are performed using MATLAB in order to validate the performance of the developed control laws.

CART Description

The numerical example of wind turbine that has been used in this work is based on a linear model of the Controls Advanced Research Turbine (CART) which is used by the National Wind Technology Centre (NWTC) that is operated by the National Renewable Energy Laboratory (NREL) and located at Boulder, Colorado. CART is a two-bladed, teetered, upwind, active-yaw wind turbine. This machine is used as a test bed for studying a number of aspects of wind turbine controls technology on medium- to large-scale machines. General specifications of the CART machine are given as

Turbine Type: Horizontal axis, upwind rotor, teetering hub.
Number of Blades: 2

Rotor Speed (region 3): 42 rpm

Yaw Configuration: Active yaw drive Rotor Diameter: .43.3 m

Height: 36.6 m hub-height Coning: 0 pre-cone

Tilt: 4 shaft tilt

Actuator time constant: 0.2

In this work 3 state model of the CART linearized by FAST code at the control design point 18 m/s for wind speed, 12 degrees for rotor collective pitch and 42 rpm for rotor speed is considered for simulation and is shown below.

PID Controller

A conventional PID controller is implemented for the pitch regulated speed control of wind turbine system. The tuned values of the PID parameters are obtained as
Kp = 0.084, Ki = 0.014, Kd = −0.138

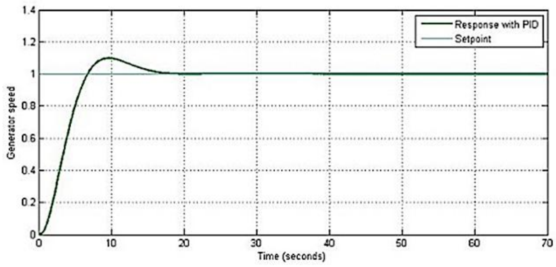

Figure 7 Step response of the system with PID controller

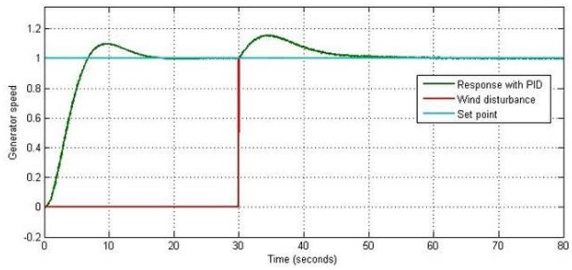

Figure 8 System response of PID control with step wind disturbance

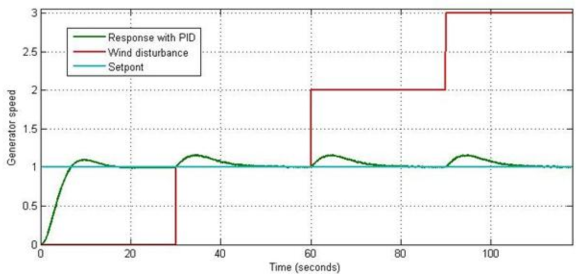

Figure 9 System response of PID control with wind disturbance as sequential stair signal

The simulation result of the wind turbine system with PID controller without considering wind disturbance is shown in figure 7. From the result it can be observed that the generator speed settles to its desired set value in 17 seconds with 10% peak overshoot. Figure 8 represents the system response when a step wind disturbance is introduced into the system steady state (t=30 seconds). The figure 9 represents the system response with wind disturbance as a sequential stair signal with sample time 30 seconds. From the simulation results it is observed that a step change in wind speed causes the system out- put to overshoot upto15% of the reference value and it takes 30 seconds to settle back to steady state value. Hence to improve the disturbance rejection capability advanced optimal controllers are to be considered.

5.3 LQG Controller

In order to ensure better speed regulation and disturbance rejection an optimal LQG controller has been designed. To apply LQG controller the system should be both controllable and observable.

Performance of LQG controller depends on the optimal selection of weighting matrices. Firstly the controller performance is evaluated by trial and error method of selection of the elements of the weighting matrices. Later Genetic Algorithm is used for the optimal selection.

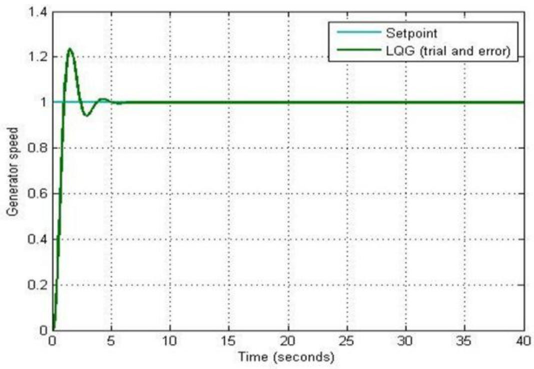

Figure 10: Step response of the system with LQG control (trial and error)

The simulation result of the step response of the system with LQG controller with trial and error values of weighting matrices are shown in figure 5.4. From the simulation result it is observed that the system output reaches the desired set point value in 5 seconds. Compared to PID control, settling time has been reduced but peak overshoot is increased to 23.5% which is not in the desired limits. Hence to improve the system response controller parameters has to be optimized.

GA based LQG Controller

To achieve optimal performance of the LQG controller Genetic Algorithm is used to automate the search for the optimal values of weighting matrices. The specifications associated with GA optimization are

Population size: 50 Cross over rate: 80% No. of generations: 300 Function tolerance: 10−6

Here, two performance indices are considered: Integral of Absolute Error (IAE) and Integral of the Squared Error (ISE). When the performance index is choosen as IAE the simulation result of the GA search process for the best individual is given in figure 11.

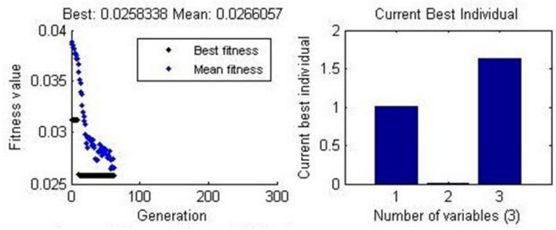

Figure 11: Simulation result of GA optimization (IAE)

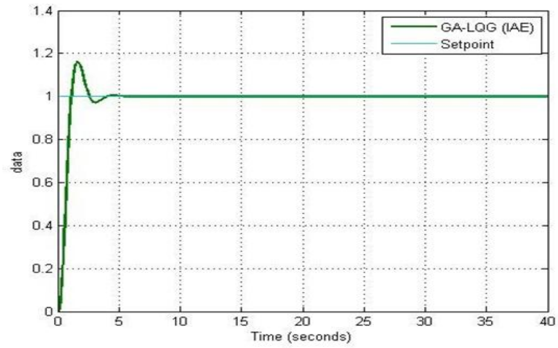

Figure 12: System response with GA-LQG (IAE) control

The Figure 12 represents the step response of the system with performance index IAE. From the figure we can observe that the peak overshoot has been reduced to 16.2%

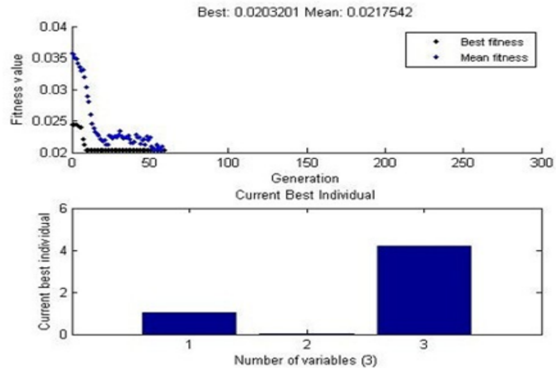

Figure 13: Simulation result of GA optimization (ISE)

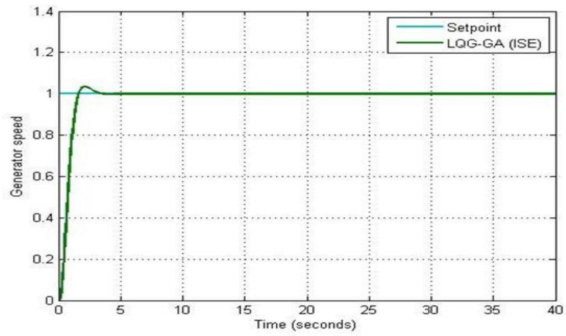

Figure 14: System response with GA-LQG (ISE) control

When the performance index is chosen as ISE the simulation result of the GA search process for the best individual is given in figure 13.

The step response of the system with performance index ISE is shown in figure 14. From the result it can be observed that, when ISE is chosen as the performance index more optimised response is obtained compared IAE. With performance index ISE the peak overshoot and settling time of the system response has been reduced to 3.5% and 3 seconds respectively. So GA optimisation with performance index ISE yields optimized response.

Comparison of results are tabulated in table 1

Table 1: Result analysis

Controller	% overshoot (M_p)	Settling time (sec)
PID Controller	10	17
LQG (Trial & Error)	23.5	5
GA-LQG (IAE)	16.2	4
GA-LQG (ISE)	3.5	3

VIII. CONCLUSIONS

In this paper a GA optimized LQG controller is proposed for pitch regulated speed control of a variable speed wind turbine in above rated wind speed conditions. Mathematical model of the wind turbine system has been developed based on two mass model of the system. The nonlinear system model has been linearized around an operating point and the linear state space model has been developed.

Initially a PID controller has been designed for speed regulation of wind turbine and it is observed that the controller performance is not satisfactory in the case of wind disturbance rejection. Hence an optimal LQG controller is developed. Performance of a LQG controller depends on the optimal selection of weighting matrices. Therefore instead of trial and error procedure Genetic Algorithm is proposed to automate the search for the optimal values of weighting matrix elements. In Genetic Algorithm search process two performance indices are considered, Integral of Absolute Error (IAE) and Integral of Squared Error (ISE). From the simulation results it can be observed that, GA optimized LQG controller yields system response with reduced overshoot and settling time compared to trial and error procedure. It is also observed that with GA optimization with the performance index ISE, more promising response is obtained when compared to IAE. The disturbance rejection capability of the proposed controller has been evaluated by introducing wind disturbances in the form of step, sequential stair and Gaussian noise signals. From the results it can be observed that the GA optimized LQG controller with performance index ISE yields optimal speed regulation with better wind disturbance rejection.

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