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Development of Utilizing Magnetic Brake in Small Wind Turbine Speed Control using Fuzzy Logic Controller

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Abstract

The objective of this work is to determine the performance of magnetic brakes in small wind turbines for various speeds. Finally, the quality of electric power produce can be enhanced by exact control of turbine`s rotor speed given by the magnetic brakes. **Findings:** Simulations have done using the various controllers comprising Proportional Integral Derivative (PID) Controller, Proportional Integral Controller, Fuzzy Logic (FL) Controller and Non Linear Controller in Mat lab Simulink. A comparative study is then made for the above simulations and obtained a conclusion that PID is the best choice. Besides this, a turning is made for PID controller using bacterial Fragmentation Algorithm and the best fit results are obtained. With such a controller inserted in our system, the system can have its optimum performance even at stall conditions. **Applications/Improvements:** With such a controller inserted in our system, the system can have its optimum performance even at stall conditions.

Keywords: Control System, Fuzzy Logic Controller, Magnetic Brake, Torque, Wind Turbine

1. Introduction

Small wind turbines have been optimized for fabricating greatest power output at the most credible speed of wind is around 10m/s, 15m/s or 20m/s (stall condition). It could be extravagant for designing them to function along the availability of doubtful elevated wind speeds. Restricting the power output in high wind conditions are mandatory even on a small wind turbine; or else a runaway turbine would overload its rotors, mechanical power train, its electrical generator as well resulting in catastrophic failure. Figure 1 shows a wind turbine system consisting of Hub, Gear transmission system, Brake, Generator, Blade, Nacelle, and a high speed shaft. The wind turbine system functioning mechanism is as follows: The blades spin by blowing wind gets on a wind turbine. The blades have been closely placed to a hub which moves over a turning shaft, and the shaft works along a gear transmission box by the rise in turning speed. The transmission has been fixed to a high speed shaft turning a generator for producing electricity. On high wind, the turbine possesses a brake for preventing turning of the blades and getting smashed up. The subsystems corresponding to detailed system are discussed below.

The wind turbine holds chiefly four subsystems[1]. The blade and pitch system, generator and converter system,

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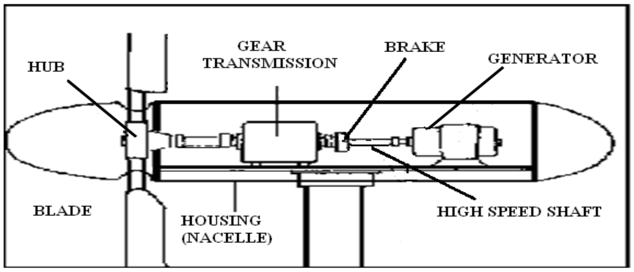

Figure 1. Wind Turbine System.

drive train system and the control system. Blade and Pitch System, this system could be entered at this targets the wind turbine system. Input has been provided by the wind to the wind turbine and to the blade and pitch system. Drive Train System is composed of shaft that rotates in low speed, another shaft rotating at high-speed and gear system involved for generating a torque and rotational force demanded by generator and converter system for producing electrical power. The drive train functioning standard highly depends on a speed transmission mechanism. Generator and Converter System, this system makes the most of the rotational energy relocated from the drive train system converting the transferred energy into electrical energy. In this system the generator helps in attaining this point whereas the converter tends to show up a constant power output. Finally Control System, The control system which could be designed as either an active or passive system is used to monitor and regulate the operation of the wind turbine. Monitoring the systems provides knowledge of faults when a component fails to satisfy its original function design.

Regulating the system entails the processes design to ensure that the system delivers the expected output at all times. Typically, the control strategy adopted for this purpose is divided into two modes of operation; the partial load mode and the full load mode. Under low wind conditions, from velocities 3m/s to 12.3m/s of the wind speed denoted as V_w, the control system utilizes the partial mode region which seeks to maximize the electric power Pg, measured in Watts, by capturing the maximum amount of energy of the wind. The most excellent negotiation is to supplement controllers for improving the available sources of energy. Wind turbines have been understood to be highly add-on energy sources for enriching the quantity of power resulting in demand of designing wind turbines and inhibited hence their interfaces of output along the previously present electrical power grids, in electrical industry.

1.1 Objectives

- To choose and design the controller.
- Simulation of the system using PID controller at various wind speeds performed in Simulink environment.
- Simulation of the system using nonlinear and fuzzy controllers at various wind speeds performed in Simulink environment.
- Comparison of the various controllers used for speed control of wind turbine system.
- Fabrication of magnetic brake system
- Ascertain the performance of magnetic brakes in small wind turbines by measuring the torque of the rotor against speed of revolution.

1.2 Motivation

Conventional brakes cause numerous troubles, particularly in vehicles that are hybrid and in wind turbine systems causing remarkable wear, complex and slow actuation, lack of failsafe features, fading, improved consumption of fuel because of assistance of power and prerequisite to restrict anti-lock. In the idea of solving these troubles, a brake that is contactless and magnetic is supposed to be developed. This brake is less-sensitive to temperature than friction brakes, has fast and simple actuation, wear-free and possesses a condensed sensitivity for wheel-lock and can provide significant braking torque in small wind turbines.

In[2] presented the simulation of a magnetic field that is rotational with ferromagnetic rotor that is solid. Conductor's finite element simulation passing in a magnetic field at greater range of speeds gives oscillatory responses. In this paper, the huge convection terms are eliminated by adding artificial diffusion. Adaptive mesh refinement optimization approach is utilized for accurate results. [3]Holds two types of eddy current brakes along the magnets that are permanent. One of it is segmented with an iron core assembly and another holds permanent magnet only. The eddy current braking system with dc-excited magnet intrinsically requires the supply of power and possesses the consequential losses of power. If the dc-excited magnetic poles have been restored along permanent magnet the braking system could be acquired a greater efficiency because of no losses of power and a greater power/weight ratio a finite element technique is put in place for computing the magneto static field. In addition Galerkin FEM along linear interpolation performance might oscillate among the nodes that are adjacent for estimating attraction force and braking. Gain with Halbach array is later weighed against iron core Permanent magnet assembly. The Halbach array brings up elevated braking force due to the well-built flux density. In addition it possesses the property of self-shielding. [4]Analyses the electro dynamical performance of conversion system for wind energy later on a grid loss. An advanced technique of electrical braking could be functional using the induction generator operation in a mode that is self-excited. EDB reduces 60% of the rated speed, thus minimizing the wear of brake pad and tear of brake pad and puts down the expense towards maintenance considerably, while common outage of grid exists. Main drawback associated with the electrical braking is that cyclically braking end up the blades for slowing down, that rises the stalling effect, dropping the blades efficiency. [5]Exhibits a research of an electromagnetic device optimization utilized in measuring water flow into a heater in the idea of increasing its torque of braking. Simulations that are dynamic were executed using the transient motion solver showing 2D and 3D belonging to the Finite Element (FE) program Magnet which is commercial. Caudal meter's torque which is the output has been calculated and assessed against measurements. Purpose of the current research is the device configuration optimization for maximizing the brought up braking torque. Proposes[6] a brake consists of rotating discs numerous in numbers immersed in a magneto rheological fluid and a covered electromagnet. Practical design criteria namely choice of material, sealing, surface area of work, generation of viscous torque, implemented current density, and choice of MR fluid have been preferred for choosing a fundamental automotive MR brake configuration. A finite element model, which is two-dimensional of the MRB has been formed for simulating the magnetic flux flow in steady- state among the MRB domain utilizing the module COMSOL Electromagnetic and the magnetic field intensity distribution solving. The chief disadvantage connected with the projected MRB configuration was the incapability of generating adequate braking torque for stopping a vehicle. [7]Expresses an electrically actuated proportional brake design which contributes a predominant enhanced torque to- weight ratio corresponding to an MPB on maintaining (or improving) response time and dynamic range. The suggested device could be designed in two configurations which is locked and unlocked that provide a superior amount of optioning in designing a provided application. Brake prototype exhibited herein contributes a torque that is resistive just about magnitude of three orders greater than the motor torque. Disc wear is one of the difficulties of the WDB, even though it gets lessen with the usage of discs with greater wear-resistant, named stainless steel or ceramic. The WDB too show torque ripple that is elevated relative to the MPB. [8]Talk about the torque of brake control from the brake of mechanical disc in a wind turbine. Brake torque is estimated by coefficients of friction and clamp force. A pressure controller has been executed over the test system that is laboratory-sized and utilizes a disturbance estimator for rejecting trouble in the idea of tracking a reference curve. Estimator is competent of determining both input equivalent disturbances and disturbances generated by irregularities of brake disc. Controller could discard disturbances of input equivalent and an approach to cancel the brake disc disturbance has been projected. [9]Presents eddy current brakes, which were controlled electrically and exhibits inadequate produced braking torque at least speeds by non-contact actuators. For overcoming this, the ac magnetic fields holding frequencies that are fixed and variable in dissimilar waveforms have been researched at high and low speeds. This method develops an exact electromagnetic FEM which could be utilized for simulating and analysing the conductor disk exposing to the numerous kinds of time changing fields to generate varying fields to improve braking performance at low speeds. A 60% rise in the torque of braking could be acquired with the FM assessed against the DC field braking.

The main drawback associated with this paper is that is away from heat is the critical issue with circular brakes, where the eddy currents are continuously circulating in the identical piece of metal and hence require periodic maintenance or replacement of the brake. Due to this reason, circular eddy current brakes demand some kind of cooling system.

In this work, a comparative study has been made for different kinds of brakes including friction brakes, hydraulic brakes, electromagnetic brakes and eddy current brakes. From the literature survey, it is understood that all these conventional brake system has the disadvantage of wear and tear, noisy operation, fading etc. which affects the braking performance of wind turbine system. To overcome these effects, a new magnetic brake has to be developed that is discussed in the next section.

2. Methodology

Small wind turbine Braking performed by generator's dumping energy into a resistive bank (electrical braking) or using disk brakes or drum brakes to slow down a turbine (mechanical braking). Often these require periodical maintenance as they are subjected to friction, fading etc. To overcome these effects a magnetic brake can be used. Here dumping of magnetic field is done by means of an actuator.

Figure 2 shows the block diagram for projected speed control system. For the projected work, solenoid actuator as actuating device and as system controller PID controller is chosen.

2.1 Magnetic Brake Modelling

Magnetic braking tends to happen only on an occasion of a moving conductor being exposed to a magnetic field. By Faraday's law; the rate of change of flux linkage calculates the magnitude of voltage generated around a closed loop[10].

$$\oint E.dl = \oint \frac{F}{q}.dl = -\frac{d}{dt}\int B.n.da$$

According to Lorent'z law, the electric force of moving charges is equal to the magnetic Lorent'z force exerted on the particles[11].

$$E.\, q = q.\, (v \times B)$$

The electric field which is induced is at right angle to magnetic field strength and velocity. At the same time the electric field indicate radially towards the brake disc centre until the innovative persistence of excitation field. Electric field leads to the charges movement and generating current produce a field that is opposing as per the Lenz's law and by superposition include to a magnetic force which repels, resulting in slow down of conductor. This principle is employed in the magnetic brake for speed control in the wind turbine system.

For obtaining the functioning capability of magnetic brake analytically, we need to calculate the power and hence torque of rotor against the speed of revolution.

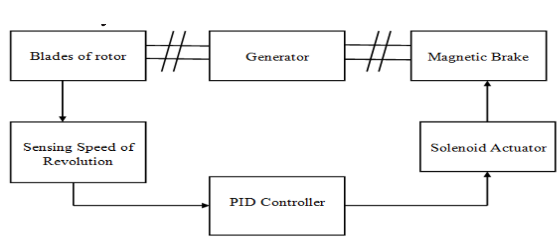

Figure 2. Block diagram of the proposed system.

Figure 3 shows the magnetic brake bench that is going to be designed.

2.2 Wind Turbine Modelling

Model of wind turbine plant has been separated into two predominant parts. Wind turbine being initial part includes a rotor of turbine on a shaft of low-speed, shaft of high-speed and a gearbox. Wind speed and blade pitch angle are the inputs of this part of the plant providing the outputs, the angular rotation of shafts of high-speed and mechanical power, Pm. Electric generator of the second part's input was only angular rotation that is to be constant from the plant of turbine showing electrical power as output.

The below mentioned six steps exhibit progression of events in the block diagram exposed in Figure 4.

- Wind and blade pitch angle have been taken as input for wind turbine plant ending up in the spin of rotor.
- The angular speed of low-speed shaft is looked up and weighed against the reference low speed shaft angular speed.

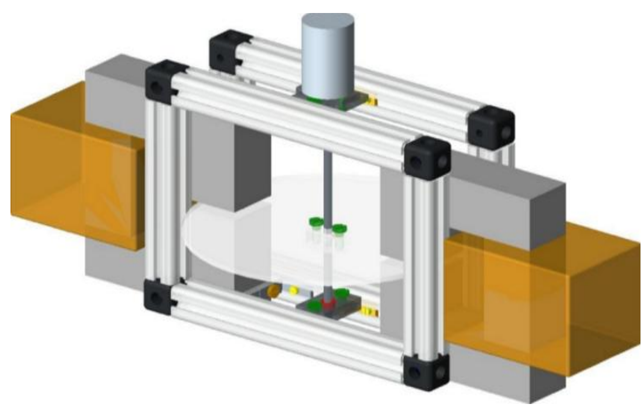

Figure 3. Magnetic brake bench.

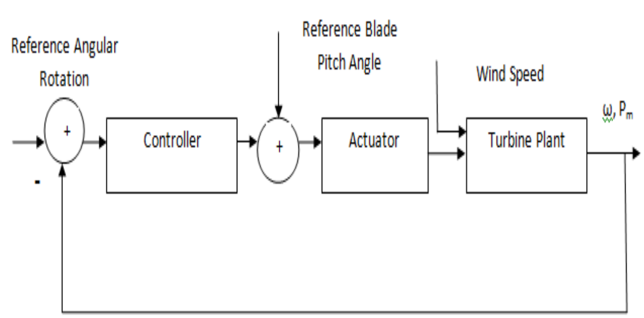

Figure 4. Block Diagram of Wind Turbine System Dynamics and Control.

- The angular speed error being the controller's input commanding a modification in blade-pitch angle.
- Pitch angle of a new blade has been functional to the actuator.
- The actuator alters the blade pitch angle.
- Input is the new wind speed for the plant of wind turbine repeating the six steps.
- Figure 4 demonstrates the general block diagram of the wind turbine system.

2.3 Overall Transfer Function for Turbine Plant, Actuator and Controller

The overall transfer function is achieved on cascading the actuator, plant and controller. The block diagram demonstrates a constant load output, controlling via rotational speed control.

Figure 5 expresses the system block diagram in the Laplace domain.

Figure 6 explains the block diagram of wind turbine along power of variable output. During load variations what will be the output power or how is it getting varied is described below.

This illustrates the entire system jointly along the system power output loop and is obtained from Equation.

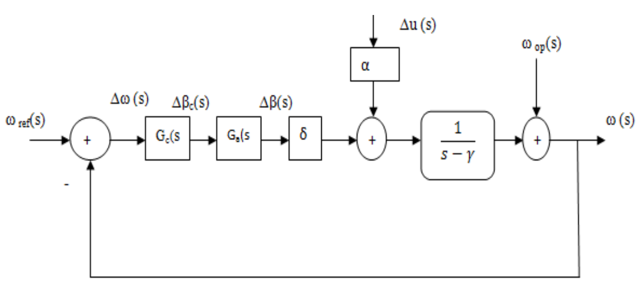

Figure 5. Block Diagram for the Turbine Plant with Actuator and Controller.

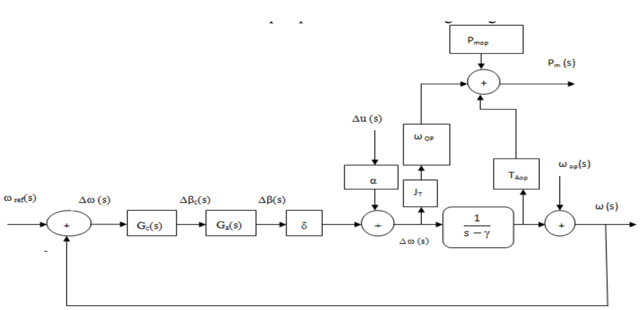

Figure 6. Wind Turbine Plant Block Diagram with Power Output Shown.

$$P_m = T_A\omega = P_{mop} + \frac{\partial Pm}{(\partial Ta)_{op}}\Delta T_A + \frac{\partial Pm}{(\partial \omega)_{op}}\Delta\omega$$

$$P_m = P_{mop\,+}\,\omega_{op}\Delta T_A + T_{Aop}\Delta\omega$$

Functions for transferring illustrates the relationships among the output ω(s) and the inputs of individual Δu(s), $\omega_{ref}(s)$ and $\omega_{OP}(s)$ for the actuator, the rotor speed and controller could be achieved. Corresponding to every input-output examination assumption of every inputs are zero and seeing three inputs and single output exists and also showing transfer functions three in number, corresponding to the relationships among the output and every inputs.

$$\frac{\omega(s)}{\Delta u(s)} = \frac{a\left(\frac{1}{s-\gamma}\right)}{\left(1 - Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)\right)}$$

$$\frac{\omega(s)}{\omega op(s)} = \frac{1}{\left(1 - Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)\right)}$$

$$\frac{\omega(s)}{\omega ref(s)} = \frac{Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)}{\left(1 - Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)\right)}$$

$$\omega(s) = \Delta u(s)\frac{a\left(\frac{1}{s-\gamma}\right)}{\left(1 - Gc(s)\delta\right)\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)} + \omega_{op}(s)\frac{1}{\left(1 - Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)\right)} + \omega_{ref}(s)\frac{Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)}{\left(1 - Gc(s)\delta\left(\frac{Ka}{s} + Ka\right)\left(\frac{1}{S-\gamma}\right)\right)}$$

The characteristic equation, CE for the closed loop all the transfer functions is illustrated in Equation.

$$CE = S^3 + (k_A - \gamma - k_A k_D \delta)S^2 + (-k_A\gamma - k_A kp\delta)\,S + (-k_A k_I \delta)$$

2.4 Wind Turbine Aerodynamic Data Specifications

Little key data points were there associating Cp, λ, and β, that are sound enough for determining the wind turbine functioning. Depending on the provided data, the linearized operating point has been selected for being $\beta_{OP} = 9o$, $\lambda_{OP} = 7$, $u_{OP} = 7.5$ ms-1 and $C_{pOP} = 0.2$. This point of operation has been selected since it depicts the functioning of operation at comparatively aerodynamically steady circumstances.

At the β = 3deg, the wind turbine works at utmost C_{pal} though it is very nearer to conditions of stalling (β < 3deg). Henceforth pitch angle of the blade is limited for lower operational blade pitch angles and it confines the control scheme.

At β = 12deg, pitch angle of the blade exhibits high that the wind turbine would not be able to obtain any power from the wind. Consequently the point of operation has been put up at β = 9deg. The performance coefficient, Cp has been determined at the pitch angle of line raised wind turbine operation blade, β, of 9deg.

A third-order polynomial has been utilized for fitting the data in the idea of achieving difference of the performance coefficient, Cp, with the pitch angle, β. The operation point constants, the derived Cp(λ, β) curves and the association among Cp and Cq have been utilized for estimating the wind turbine dynamic constants α, δ and γ.

Table 1 illustrates the data which are achieved involving these parameters. α value is positive since some rise in speed of wind end up the acceleration of the rotor. On the other hand, δ is negative since raising the pitch angle end up for decline in the speed of rotor.

For steady condition of the wind turbine plant, the value of γ has to be negative for making the wind turbine plant transfer function pole fall on the left hand side of the s-domain. The wind turbine linearization constants are given in Table 1.

Linearization is applicable for the wind turbine that has to be analysed involving linearization conditions has been noted. All the performance parameters of wind turbine fall on the derived Cp (λ, β) curves at some particular point of operation. Hence, the wind turbine dynamic model has been moderately accurate for simulations at or near the condition of operation.

Table 1. Wind Turbine Linearization Constants

Linearization Constant	Constant Value
α	$0.117s^{-2}$
δ	$-0.8582s^{-2}$
γ	$-0.0256\ s^{-2}$

3. Controller Design

When utility-scale wind turbines turn to be highly well-known the PID controller became the industry benchmark for controlling blade-pitch which standardizes the error, or variation among considered input and the required input. Value of error together with its derivative and integral corresponding to time gives up a signal to the actuator(s), influencing the plant that is controlled.

The PID controller seems to be linear, single-input single-output controller refrained to three gains. Frequently the gains that are three in number have been estimated depending upon intuition and experience. These values have been calculated via a range of process out of which only one could be selected and utilized. The suitable gains essential for the compulsory outputs would be estimated.

3.1 Routh Analysis

Routh analysis is involved in usage for the stability analysis for the PID controller. As per the Routh Hurwitz criterion, elements belonging to the first column of Routh array are bound to be positive; making all the roots lie on left half of s plane or else the system become sum balanced. The amount of sign variation belongs to numerous roots lying on right half of s plane.

The transfer function for turbine plant dynamics that is achieved has been provided using the gains of controller k_P, k_I and k_D. The equation's denominator is a third order polynomial. 2 is chosen as the actuator gain, k_A , making the understanding that the actual pitch rate is to be dual of the pitch rate needed for correcting the blade pitch in single time step.

In the operating point, $\beta_{OP} = 9o$; $\lambda_{OP} = 7$; $u_{OP} = 7.5ms^{-1}$ and $\omega_{OP} = 11\ rads^{-1}$, $\gamma = -0.0256$ and $\delta = -0.858$. Note: $\gamma < 0$ and $\delta < 0$.Forexploring the values range corresponding to the constants for stabilizing the system, the Routh analysis has been developed and is illustrated in Table 2.

For steadiness, every term present in the first column of Table 2 is bound to be positive and the coefficients are bound to be positive which are placed in the denominator of the transfer function. Thus,

Table 2. Routh Analysis

S^3	1	$(-k_A\gamma k_A k_p\delta)$
S^2	$(k_A-\gamma-k_A k_D\delta)(-k_A\gamma k_A k_p\delta) + (k_A k_I\delta)/(k_A-\gamma-k_A k_D\delta)$	$(-k_A k_I\delta)$
S^1	$(k_A-\gamma-k_A k_D\delta)$	0
S^0	$(-k_A k_I\delta)$	0

S^2: $(k_A-\gamma - k_A k_D\delta) > 0 \longrightarrow k_A + |\gamma| + k_A k_D|\delta| > 0 k_D > -1.1$

S^1: $(k_A\gamma - k_A k_p\delta) > 0 \longrightarrow k_A |\gamma| + k_A k_p|\delta|) > 0 \longrightarrow k_p > -0.029$

S^1: $(k_A-\gamma - k_A k_D\delta)\ (k_A\gamma - k_A k_p\delta) > -\ (k_A k_I\delta)$

$(k_A + |\gamma| + k_A k_D|\delta|\ ((k_A |\gamma| + k_A k_p|\delta|) > (k_A k_I|\delta|)$

$(1.1 + k_D)\ (0.029 + k_p) > k_I$

S^0: $-\ (k_A k_I\delta) > 0\ (k_A k_I|\delta|) > 0 \longrightarrow k_I > 0$

The gain has to be adopted in the idea of maintaining stability:

$k_P > -0.029$ deg.rad^{-1}, $k_I > 0$ deg.rad^{-1}, $k_D > -1.1$ deg.rad^{-1}, and $(1.1 + k_D)(0.029 + k_p) > k_I$

Thus the linear approximation corresponding to control system of the wind turbine, steadiness could be preserved for an extensive choice of controller gain. Prediction by designer that the system retorting to a unit step input in the idea of selecting ideals corresponding to the three controller gains exists.

3.2 Controller Design Methodology

Controller design was a centred mostly Proportional-Integral-Derivative (PID) controller which gets implemented without difficulty in the field. Gain selections relative to these controllers are typically a process of trial-and-error depending on intuition and experience from the engineers of field control. A methodical move towards the gain assortment supplies to the control system, apparition of the potential functioning improvement. This research gives a tactic to choose values of gain for a controller of PID regulating speed of rotor, a turbine of wind with constant-speed by regulating the blade-pitch angle. Exploration of the model that is dynamic involved for explaining the turbine and its environment of operation has taken place. A conventional technique to PID the choice of controller gain has been established. Conventional move possesses linear zing the model of wind turbine relative to a point of operating. The retort regard to an input by means of step is investigated, and the gains have been modified waiting suitable behaviour of the system has been noticed and also depends deeply on trial-and-error.

Regime of controlling power has probed in only by the time turbine arrive at the design speed of rotor for needed power generation. Existing with these circumstances, the rotational speed is unnatural for a particular required value via the control of blade-pitch angle. Variation in wind speed has been accommodating for controlling great venture from the needed speed of rotation. Therefore, the power generation too has forced to a moderately stable range. Additional to uphold a steady rotational speed, the actuator association has to be controlled for putting off fatigue and overheating. The grouping of standardizing an invariable speed of rotation and diminishing the motion of actuator are the organizing purposes particular for the power control regime. Operating point assortment has been significant in maintaining aerodynamic steadiness in this system of wind turbine. At the operating point, ω_{OP}, has been particular to be the turbine's constant speed that is needed, 105 RPM (11 rad/s).

Utmost value of C_p against the complete surface happen at a pitch angle of β = 9o and 7 is a tip speed ratio. Implementing the rotational speed which is to be constant is of 11 rads^{-1}, relating tip speed ratio to a wind speed of 7.5 m/s. In this point particularly, maximum power might be created by the turbine. On the other hand, minor divergence out of this point targeting pitch angles which are in negative might end up in blades that are stalled, which noticeably declines the power generated. On altering to 9 deg, the pitch angle, the power coefficient magnitude has been condensed rather variation of around 7 is the tip-speed ratio that could effortlessly be endured. Stalled blades existing in low tip-speed-ratio condition is noticed.

3.3 Controller Design: Gain Selection

Major controller obligation for compensating the deviation of wind speed on varying the pitch angle, β, is to maintain constant the rotor angular speed, ω. A code using Matlab has written in the idea of estimating the most excellent association of the controller gains, k_D, k_I and k_P. Design has been depending on the parameters that are two which diminish. Primary parameter has been the root mean square (RMS) of the error among the actual rotational speed and the intended speed of rotation. Error's root mean square point out the potential of the controller for discarding the fluctuations of speed of wind.

The second parameter has been taken as the Actuator Duty Cycle (ADC) that has been proposed by Kendall, et al., (1997) for measuring actuator motion throughout a run of the simulation and is the total quantity of degrees having the pitched over blades with the simulating duration of time. In an idea of preventing over-heating of the fluid that is hydraulic, these values have got to stay put underneath a convinced value that manufacturer offers. This parameter has been correlated to the monetary controller cost.

Greater the controller gains, the greater the ADC and the fewer cost-effectively good-looking the controller. Henceforth, minimization of the controller gains has been utilized for keeping the ADC much low.

This section donates a means of wind turbine functionality estimation, linearization, control and modelling. The detailed assistances are:

- Wind turbine model has been achieved utilizing a Taylor series linearization approach joined with the rough calculation of the dynamics of wind turbine. It is said that there has not been willingly obtainable data for an uncomplicated data lessening process the technique built up has been utilized and it has been established for being victorious depending upon the output profiles which has been achieved relating all the simulations.
- The methodical move towards PID-controller design has been put in place sharing representing a visually noticing influence of gain modification on both actuator duty cycle and RMS speed error that has been joined with the gains size and the cost. This revelation of influence of gain allows choice of the foremost probable arrangement of parameters of controller devoid of demanding a process which is bound to be lengthy and is trial-and-error.
- The wind turbines operation rely much on the control strategy was noticed. It is much obvious when the reference angular speed has been completed to deviate right through the simulation which refers mentioning the identical turbine of wind could be brought up for functioning at dissimilar modes based on the control strategy.
- Controller design's priceless feature move has the capability for noticing the forceful character of the PID controller of PID in this steady-speed application of wind turbine.

4. Results and Discussion

In order to demonstrate the effectiveness of this method, some simulation has been carried out. Simulations are done in Simulink. For this work, mathematical model has developed and Simulation for the solenoid actuator as well as PID controller is also done.

4.1 Simulation Results

An effortless test that contributes helpful data with regard to the functionality of the system for applying a small step signal to the input and the response is monitored. In Simulink, achievement of this utilizing a 'scope' block for monitoring command and response signals. Simulation results for solenoid actuator with and without PID controller is obtained and a comparison is then made for the response with and without PID controller.

4.2 Comparison with PID and PI

The following Figure 7 shows a comparative action for the solenoid actuator with and without PID controller.

4.3 Output Response

The Figure 8 depicts the output response of the actuator with and without PID controller. For $K_p = 1$, $K_d = 0.002$, and $K_i = 0.01$, the output response is obtained as follows. From the response, settling time is obtained as 0.32 seconds and rise time as 3.87m/s when PID controller is

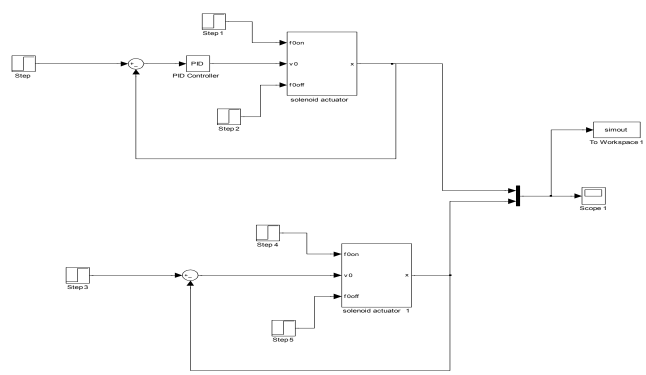

Figure 7. Simulink Model for Actuator with and without PID Controller.

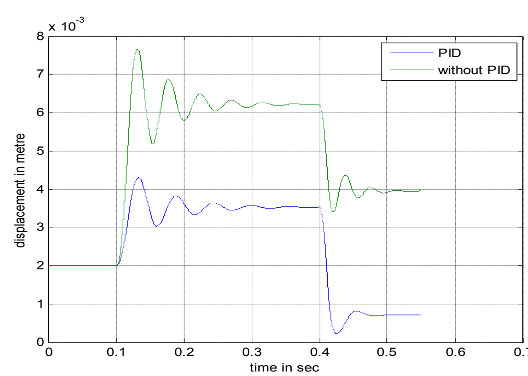

Figure 8. Output Response with and without PID.

used. I t is clear from the response that the steady state as well as transient characteristics are improved when PID controller was used.

The Table 3 shows the time domain specifications for the system with and without PID controller.

The comparison table clearly shows that with PID controller, the performance of the system is considerably increased.

4.4 Simulink Model for Speed Control System

The block diagram for control system of speed is illustrated in Figure 9. Blades keep rotating upon capturing the energy and its speed is being sensed by a speed sensor to check whether the speed of revolution of the blade exceeds the set value. The blade keeps a constant speed as the sensor continuously feeds information to the controller, which in turn controls the magnetic brake through a solenoid actuator. Braking force could be precisely restricted by the magnetic field regulation; which is governed by the solenoid actuator.

The Simulink block developed for speed control system is as illustrated in Figure 10.

According to the control problem as mentioned in section 3, we have to extract maximum output below rated speed; rotor speed gets reduced while wind speed exceeds the cut out limit and the power of output needs to be remain as constant if exceeding of wind speed occurs

Table 3. Comparison Table with PI and PID Controller

Time Domain Specifications	With PID Controller	With PI Controller
Rise Time	3.87ms	4.22ms
Peak Time	0.13s	0.11 s
Settling Time	0.32s	0.38 s
Peak Overshoot	19%	27%

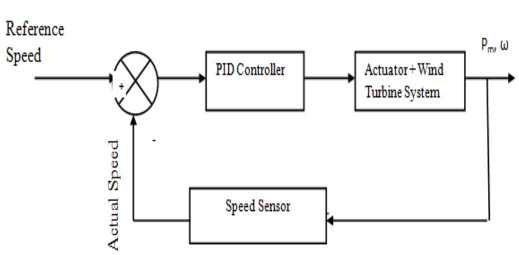

Figure 9. Block Diagram for Speed Control System.

the set value or rated speed. Considerations for this simulation are as follows:

- Wind speed is set as 7.5/s
- Reference angular speed is set as 11/s
- Controller parameters are chosen to reduce the rms value of error between actual and rotational speed.
- Steady state error has to be completely eliminated.
- The output response obtained for above rated speed is as follows in Figure 11.

It is clear from the response that output power remains constant when speed exceeds above the rated speed that is 7.5 ms^{-2}.The error curve obtained is shown in Figure 12.

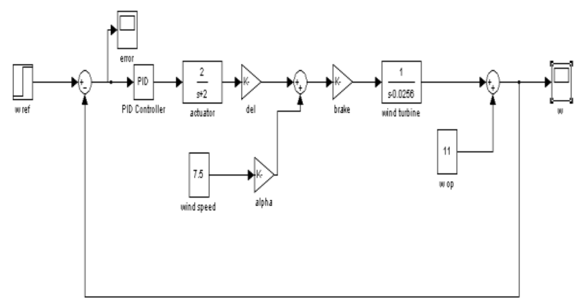

Figure 10. Simulink Model for Speed Control System.

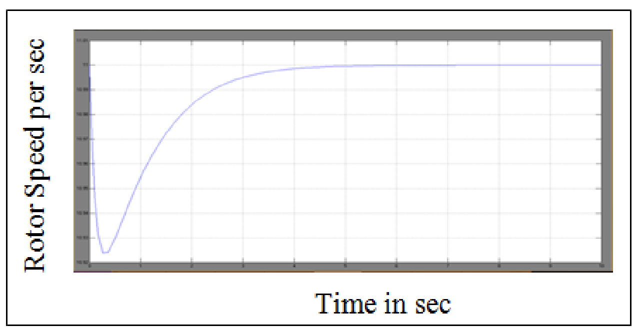

Figure 11. Constant Output Powers for above Rated Speed.

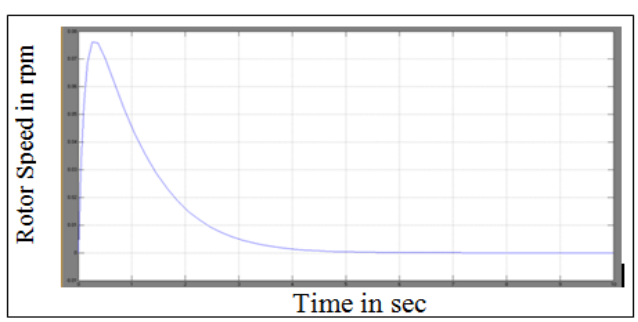

Figure 12. Error Curve.

It is observed from the response that the error increases initially and finally settles down to zero. Hence, we obtained zero steady state error. That means the PID controller has successfully achieved the requirement.

Simulation with PI controller

PI controllers are typically usual; hence the action of derivative is identified to be sensitive for measuring noise, while an integral term absence might put off the system from reaching its intended value because of the control action. An integral controller (Ki) diminishes the rise time, shoots up both the overshoot and the settling time, and gets rid off the error which is in steady-state.

Hence, PID controller is replaced with a PI controller whose simulation is also carried out which is shown in Figure 13.

The output response obtained when PI controller used is shown below in Figure 14.

The power output goes on increasing when wind speed exceeds the rated speed instead of keeping it a constant.

5. Simulation using Fuzzy Logic Controller

Fuzzy logic developed swiftly has become one of the most victorious technologies to contribute to the brought up of sophisticated control system. Quite a few research exhibits, both in simulations and experimental results, that Fuzzy Logic control contributes better outcomes with regard to those achieved by conventional control algorithms hence; in industrial electronics the FLC control has been formed as a striking solution to control the electrical drives with large parameter variations.

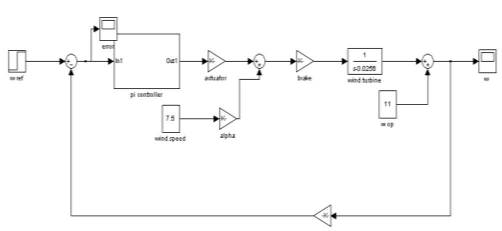

Figure 13. Simulink Model for System with PI Controller.

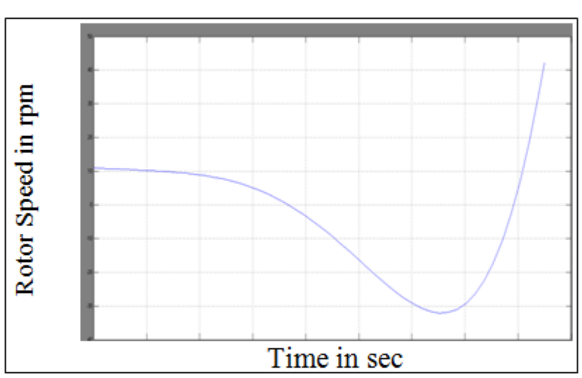

Figure 14. Output Responses with PI Controller.

5.1 Fuzzy Logic Controller (FLC)

Controller of Fuzzy logic could be preferred as a particular class of symbolic controller. In Fuzzy logic operational laws are expressed in linguistics terms as an alternative of mathematical equations. Numerous systems are highly intricate for modelling precisely and they deal with difficult mathematical equations; consequently traditional techniques turn into infeasible in available systems. On the other hand fuzzy logics linguistic terms contribute a feasible technique to define the functional features of such a system.

5.2 Structure of a Fuzzy Logic Controller

A fuzzy logic controller possessing three main components:

- Fuzzification
- Fuzzy inference
- Defuzzification

The structure for FLC is shown in Figure 15.

5.3 Design of a Fuzzy Logic Controller for the Actuator Figure 16

The inputs of the FLC are expressed in the following seven linguistic variables.

- Negative Big (NB)
- Negative Medium (NM)
- Negative Small (NS)
- Zero (ZE)
- Positive Big (PB)
- Positive Medium (PM)
- Positive Small(PS)

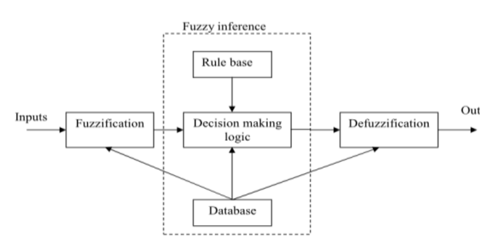

Figure 15. Structure of Fuzzy Logic Controller.

Every level is detailed by a fuzzy set.

The two input variables chosen are 'error' and 'change in error'. Error = $\omega_{ref} - \omega_{actual}$ where ω_{ref} is the reference speed and ω_{actual} is the speed that is actual and the change in error is $\frac{dE}{dt}$.

The triangular shaped functions have been selected as the membership functions because of the out coming best control performance and effortlessness. For all variables, fuzzy membership function with level of seven in number has been utilized. Figure 17 depicts the 7 × 7 rule base table that has been utilized in the system.

The simulation of the fuzzy logic controlled actuator for the speed control of wind turbine system is shown in Figure 18.

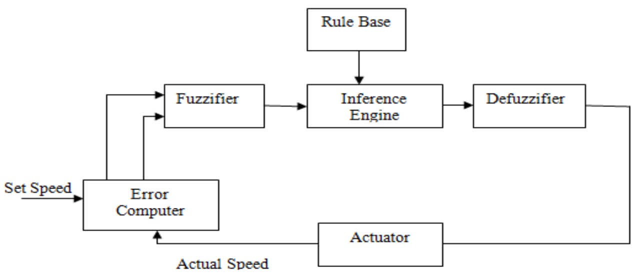

Figure 16. Structure of a Fuzzy Logic Controller for the Actuator.

e/ce	NB	NB	NB	NB	NB	NM	NS
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

Figure 17. Rule Base Table for the Fuzzy Logic Controlled Actuator.

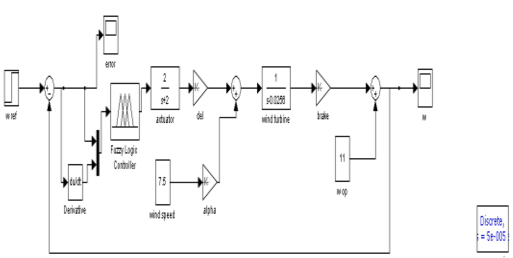

Figure 18. Simulink Model for the FLC Actuator for Wind Turbine.

The output response for the above system is shown as follows in Figure 19.

The FLC actuator is much time consuming and hence settling time is very high in this case. So we are going for a nonlinear controller for checking the system performance.

6. Simulation using Nonlinear Controller

Replacing again FLC with a nonlinear system (saturation nonlinearity). All systems exhibit the phenomenon of saturation due to their limitation in physical capabilities. The output is proportional to the input for a range of input signals. When this range exceeds, the output tends to become a constant. The Simulink model and response obtained is depicted in Figure 20.

The output response when nonlinear controller used is shown in Figure 21.

Here the speed of response is better but the steady state error is not minimised to zero. The comparison shown ~~below~~ Table 4 gives the steady sate error when various controllers are used.

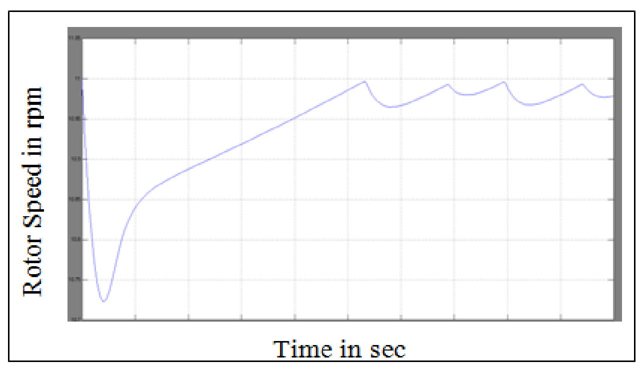

Figure 19. Output response for FLC Actuator.

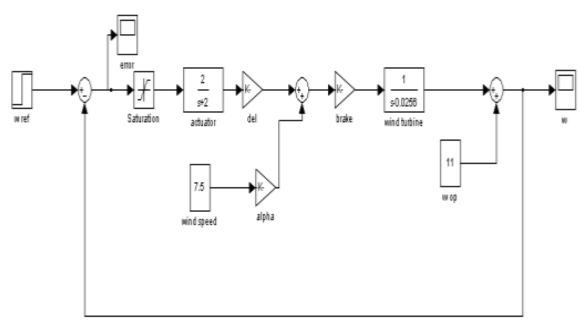

Figure 20. Simulink Model of the System with Non Linear Controller.

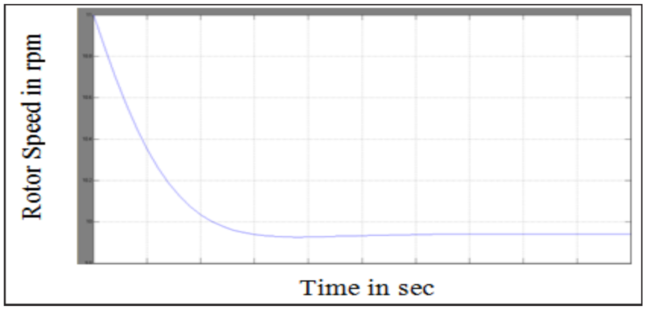

Figure 21. Output Response with Non Linear Controller.

Table 4. Comparison Using Various Controllers

Controllers	Non Linear	PI	FLC	PID
Steady State Error	1.135	0.8755	0.715	0.000

7. Bacteria Foraging Optimization

Continued existence of species corresponding to numerous expected evolutionary procedures relies on their suitability criteria, relying on their food probing and motile attitude. Law of evolution gives equivalent preference to those species possessing improved food probing aptitude and either get rid of or redesign those with deprived search ability. Those species genes were found to be the fittest moves propagating in the evolution chain as they owns capability for reproducing much enhanced species in upcoming generations. Hence a sound considerate and foraging behaviour modeling in some of the corresponding evolutionary species, end up in its request in any optimization algorithm that is of nonlinear system. Foraging strategy of Escherichia coli bacteria available in intestine of human could be detailed by four method specifically chemotaxis, swarming, reproduction, and elimination dispersal.

(i) Chemotaxis
Features of bacteria motion for need of food could be explained in both ways, i.e. tumbling and swimming mutually referred as chemotaxis. A bacterium referred as 'swimming' because of it movement in a well-known direction, and 'tumbling' when its movement is altogether in various directions.

(ii) Swarming
Intention of bacteria for reaching at the wealthiest food place is required since the bacterium that is optimum up to a time period in the idea to seek out period must put effort for exerting a pull on other bacteria hence that jointly they meet at the required location further speedily. For accomplishing this, a punishment function depend on the comparative distances of every bacterium from the suitable bacterium up to that investigating period, is supplemented to the unique cost purpose. Ultimately, if every bacteria were combined together to the solution point, this consequence function ends up in zero. Swarming influences bacteria gathering together as collections and shift as patterns that are concentric owing greatest density of bacteria.

(iii) Reproduction
Unique bacteria group, subsequent to attainment developed via quite a few chemo tactic stages arrive at the reproduction stage. At this time preeminent group of bacteria get separated into two groups. The well again half substitutes along the left out half of bacteria, is getting eradicated owing to their worse foraging capabilities making the bacteria inhabitants steady in the evolution progression.

(iv) Elimination and Dispersal
Involving the process of evolution, an unexpected action might persist, that might radically modify the smooth evolution method and end up in abolition of the group of bacteria and/or scatter them to innovative surroundings. Paradoxically as an alternative of troubling the usual chemo tactic bacteria group expansion, this unidentified occasion might put a latest group of bacteria closer to the food location.

(v) Tuning
The social foraging behaviour of Escherichia coli bacteria was utilized in solving optimization troubles. This is a hybrid move towards connecting genetic algorithms (GA) and bacterial foraging (BF) algorithms for performance optimization troubles. The planned algorithm has later been utilized for tuning a PID controller for the speed control system.

Initialize parameters S, D, N_S, N_C, Nre, Ned, Ped, C(i), Dattract, Wattract, Hrepellant and Wrepellant, where

S: Number of bacteria to be used for searching the total region (here s = 25)
D: Number of parameters to be optimized.
N_S: Swimming length after which tumbling of bacteria will be done in a chemotactic step (Ns = 3).
Nre: Maximum number of reproductions to be undertaken (N_{re}= 6).

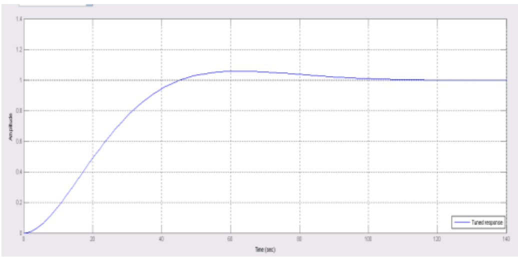

Figure 22. Tuned Response of PID Controller by BFO Algorithm.

Ned: Maximum number of elimination-dispersal events to be imposed over the bacteria (N_{ed} = 2).

Ped: Probability with which the elimination-dispersal will continue (P_{ed} = 0.25).

The location of each bacterium which is specified by random numbers on [0, 1]

C(i): This is chemotactic step size assumed constant for our design.

The tuning results are given below:

K_p = 0.1966, K_i = 0.127 and K_d = 0.8147.Hence, best fit controller parameters are obtained after PID tuning by BFO algorithm. Tuned result is shown in Figure 22.

Time in sec

8. Conclusion

In this work, various simulations are done in Matlab/ Simulink using various controllers including PI, non-linear, FLC, and BFO. Finally, a comparison made with all their responses with PID controller. It is concluded that PID gives optimum response when choosing it as the system controller. And with BFO optimization, the best fit values are obtained for PID. Also, the steady state error closely approaches to zero.

- The speed control of small wind turbines can be achieved using magnetic brake as well as PID controller.
- As magnetic brake is wear free and silent, it yields better response since the braking force is controlled by the regulation of magnetic field which is controlled by the actuator itself.
- PID controller is having improved speed of response and steady state characteristics and so brings the entire system in control by suitable action with actuator.
- With such a proposed system, better speed control can be achieved particularly at stall condition and output power is maintained constant.
- On comparing with the base paper, the proposed system is free from friction since dumping of magnetic field is used and braking torque is increased to a higher extent.
- Instead of using single magnetic brake, an array of magnetic brakes canbe used to obtain optimum results.
- Implementation of real time hardware for checking the system performance.
- More capacity of wind turbines can be done with proper drives.
- More controllers can be adopted.
- PC based control is also possible.

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