CONTROLLER DESIGN OF DFIG-BASED WIND TURBINE BY USING DE-OPTIMIZATION TECHNIQUES

PROFESSOR & GUIDE: **DR. G. SAMBASIVA RAO**

K. JENNIFER[1], A.NAGARAJU[2], CH. RENUKSWARARAO[3], CH. RAKESH[4], G. BALA BHARGAV[5]

[1]STUDENT, [2]STUDENT, [3]STUDENT, [4]STUDENT, [5]STUDENT,

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING,

R.V.R & J.C. COLLEGE OF ENGINEERING, GUNTUR, ANDHRA PRADESH, INDIA.

ABSTRACT

This paper involves the design of a controller for a doubly fed induction generator-based variable-speed wind turbine using evolutionary technique. It is based on exploiting efficient swarm intelligence-based evolutionary soft computational method, namely Differential Evolution Optimization (DEO), to design the controller for the low damping plant of the DFIG. This paper appropriately discusses an overview of wind energy and the components of a DFIG-based wind turbine, along with their operating principles. The controller design for the DFIG-based wind turbine using the DEO technique, along with its fitness functions, is depicted. The responses of the DFIG system concerning terminal voltage, active-reactive power, and DC-Link voltage have slightly improved with the DEO-based controller. Finally, the obtained output is verified with experimental setup.

Keywords: DFIG, Wind turbine, PID controller, DEO technique, Fitness function.

I.INTRODUCTION:

Up to the present, the principal stream of electrical energy has been generated from conventional vestige sources, which are predominantly non-renewable sources such as gas, oil, and coal. This type of energy conversion emits an enormous amount of carbon dioxide to the surroundings, which results in global warming. Among these advanced electricity generation technologies, the renewable energy converters are admirably glowing on their smaller size, lower cost per unit along with being more environmentally friendly. Alternatively, refers to fuel sources limitations and the insane price of thermal plants generated electricity per kW connected with the variable cost of fuel cause a global trend to replace limited energy sources with plentiful alternatives. Wind power is the best renewable energy sources which have been extensively developed in recent years; Wind power has several advantages such as no pollution, comparatively low capital cost involved and the short gestation period [1]. Induction generators, mainly doubly fed induction generators are attractive more and more popular in renewable source employment [2]. The induction generators have a few weaknesses such as reactive power utilization and unregulated voltage profile during variable rotor speed. These problems can be solved by execution of DFIG along with power electronic converters. The DFIG is wound rotor induction machines can operate in super-synchronous as well as sub-synchronous behaviour. The profit of the DFIG as compared with fixed speed generators are to improve power quality, reduce mechanical stress and fluctuations also excellent power imprisons [3]. The control of DFIG presents a dual dilemma to balance the velocity changes and reactive power. In meaningful use, DFIGs should be cut off from the network while the voltage inequity is more than 6% [3]. It has described that the torque. Pulsation could concentrate using injected recompense current in the DFIG rotor, although using their method torque pulsation could not eliminate. However, Z. Wang and Y. Sun presented magnitude along with frequency control of network linked DFIG based on a coordinated model meant intended for wind power generation [4]. In this paper, it has been provided that an alternate technique to design a controller for the DFIG system considered by KO et al. and Bharti et al. [5, 6] using the Bioinspired Technologies. The obtained results have compared with the existing solutions. However, Perdana Carlson, and Persson [7] presented that dynamic response of a wind turbine with DFIG associated to the power system for the study of system response during grid disturbances. On the other hand, the implementation of DFIG for voltage regulation at a remote location is described in [8].

II.AN OVERVIEW OF WIND ENERGY:

Renewable resources, widely available globally, offer stability in energy markets, mitigating fuel price fluctuations. Increased reliance on renewables reduces the economic burden of fossil fuels and the risk of supply interruptions. Transitioning to renewables yields financial benefits and promotes a cleaner environment, with wind power being highlighted since the 1970s oil crisis, reflecting a global shift towards clean energy integration.[1]

Wind Turbine Systems:

Wind turbines can operate at either a fixed speed, typically within a narrow range of about 1%, or at variable speeds. The mechanical power extracted by a wind turbine from the wind can be calculated using the formula provided in reference [9]:as follows

$$Pm = \frac{1}{2}\rho v_w^3 C_P(\lambda,\beta) \qquad (1)$$

Here ρ is the air density in kg $/m^3$;A = πR^2 is the area in m^2 swept by the rotor blades.

However, $C\rho$ is the power coefficient, which is a function of both tip-speed-ratio λ and the blade pitch angle β of WT. the tip speed ratio λ is defined as $\lambda = \frac{w_t r}{v_w}$ (2))

Now from above r is the blade length in m, ww_t is the wind turbine rotational velocity in rad/s, and $v_w is$ the wind speed in m/s. For the given power coefficient c_P,

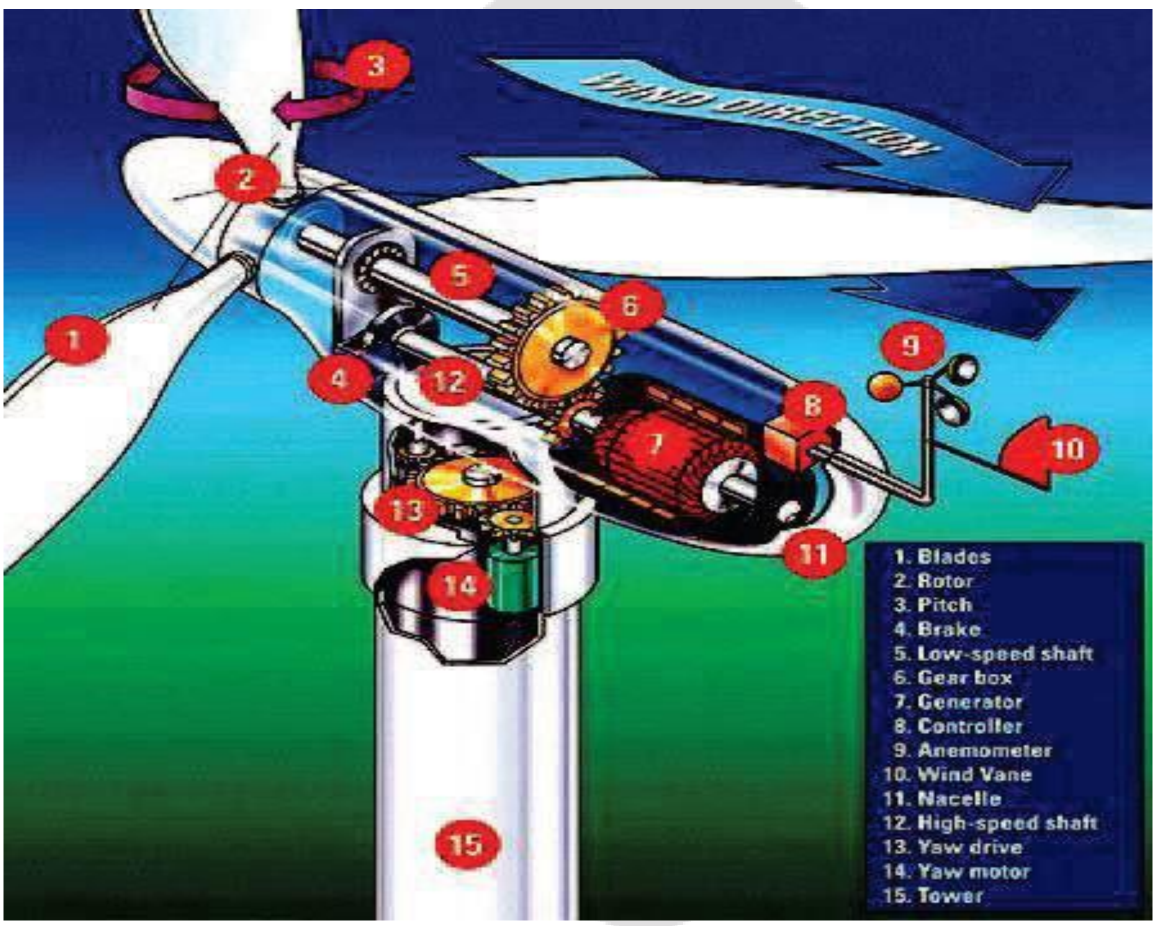
$$c_\rho(\lambda, \beta) = 0.22\left[\frac{116}{\lambda_i} - 0.4\beta - 5\right] e\frac{-12.5}{\lambda_i} \quad (3)$$

Here $$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (4)$$

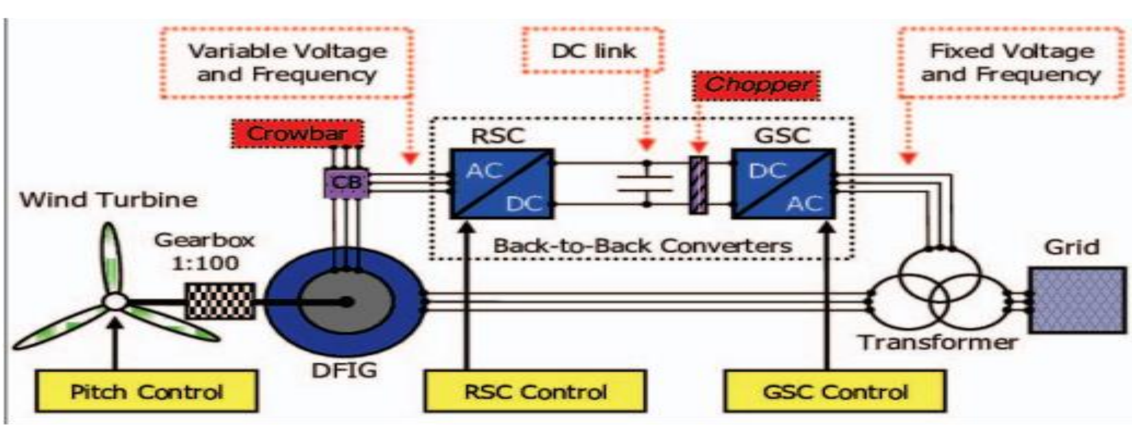
These equations are used to determine the mechanical power extracted by wind turbines and the corresponding power coefficient based on various parameters such as air density, wind speed, rotor blade length, and tip-speed ratio.

DFIG OVERVIEW AND WORKING PRINCIPLE

The key components of doubly fed induction generator (DFIG) based wind turbines are detailed in reference [13], with a standard DFIG-based wind turbine system depicted in Figure 1.



The wound rotor induction generator, known as DFIG, is notably prevalent in the wind energy industry, recognized for its effectiveness in converting wind energy, as illustrated in Figure 2.



DFIGs comprise a wound rotor induction generator with its rotor circuit often regulated by power electronic devices to enable variable speed operation. The stator winding of the DFIG is directly linked to the grid via a power transformer, typically ranging from a few kilowatts to several megawatts in capacity. The rotor converter typically accounts for approximately 30% of the total converter capacity. Variable speed DFIGs can harness more electrical energy during low wind speeds compared to fixed-speed wind generators [13].

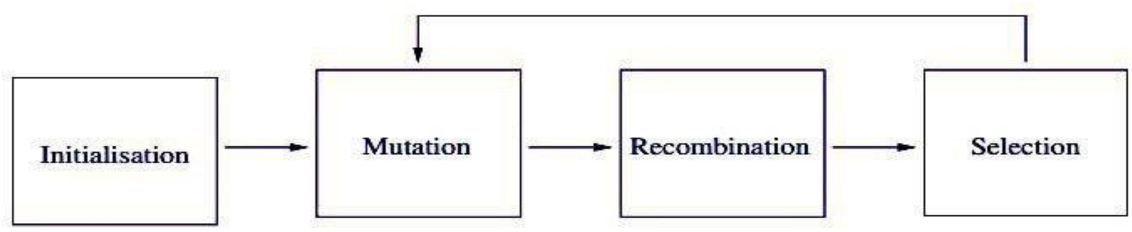
DFIGs function in two modes: (i) in super-synchronous mode, when the rotor speed (Nr) exceeds the stator rotating magnetic field speed (Ns) and slip (S) is negative, both stator and rotor windings supply power to the grid; and (ii) in sub-synchronous mode, when Nr is lower than Ns and S is positive, the stator winding supplies power to both the network and the rotor winding. Here, Nr represents the rotor's rotational speed, Ns denotes the stator's rotating magnetic field speed, and S represents slip, with positive and negative signs indicating direction.

DIFFERENTIAL EVOLUTION ALGORITHM:

Differential Evolution (DE) is a meta-heuristic that doesn't assume much about the problem it's solving and can explore vast solution spaces. However, it doesn't guarantee finding the optimal solution. DE operates on extended real-valued functions without needing the problem to be differentiable, unlike traditional methods like gradient descent. This makes DE suitable for non-continuous, noisy, or dynamic optimization problems. It optimizes by maintaining a population of candidate solutions and creating new ones based on simple formulas, treating the problem as a black box without requiring the gradient.[10]

Flowchart for differential evolution algorithm:

The first variant of the DE algorithm operates by maintaining a population of candidate solutions, or agents, which navigate the search-space using simple mathematical formulas. If a new agent's position improves, it's accepted into the population; otherwise, it's discarded. This process iterates with the aim, though not guaranteed, of finding a satisfactory solution.



Formally, the algorithm minimizes a fitness function f without considering its gradient. The objective is to find a solution m for which f(m) < f (p) for all p in the search-space, indicating

m as the global minimum. Maximization can be achieved by considering the function g = -f.

Each candidate solution x is represented as a vector of real numbers. Parameters like **crossover probability** (CR) and **differential weight** (F) are chosen by the practitioner, typically within the ranges [0, 11 and [O, 2] respectively, along with a population size greater than 4.

Termination:

The termination of the algorithm ideally occurs upon achieving the global optimum, but this isn't always guaranteed. Typically, the user defines the termination criteria, often limiting the number of iterations. Another method is reaching the objective, especially if the optimal value is known, as with benchmark functions. Additionally, feedback from the objective function, such as repeated values indicating optimization stall, can trigger termination. Personal monitoring can also determine when optimization is complete.[11]

Variants:

Variants of the DE algorithm is continuously evolving to improve optimization performance. Various schemes for crossover and mutation of agents are possible, and advanced variants often involve perturbing or adapting DE parameters during optimization. Additionally, hybrid optimization methods combining DE with other optimizers are being developed.

Setting Control Parameters:

The values of population size (NP), crossover constant (CR), and mutation scale factor (F) are typically determined empirically based on specific heuristics. Proper tuning of these parameters is crucial for the algorithm's reliable performance. The mutation scale factor, F, controls the search speed and robustness, with lower values promoting faster convergence but risking trapping in local optima. Similarly, CR and NP affect convergence, with higher values favouring increased diversity in the population and potential for finding optimal solutions but at the expense of longer computation time.

Selecting control parameters is challenging due to their interdependence and sensitivity to objective functions. Traditionally, parameters remain fixed during execution, with rule-of-thumb values suggested by Storn and Price (1997) typically falling between 0.5 and 1.0 for F and between 0.8 and 1.0 for CR. They also recommend NP to be between 5×D and 10×D, where D is the problem dimension, with a minimum of 4 to ensure mutation operations. Adjustments to NP may be needed if mis-convergence occurs, but beyond a certain limit, it may not significantly improve performance. While these suggestions are practical, finding optimal parameters often requires numerous trial runs for each problem setting.[12]

The concept of Fitness Function for the Design:

For our design case, we aim to optimize the three parameters of the PID controller (KP, KI, KD) to achieve the best output results. This involves defining a three-dimensional search space where each point represents a specific combination of PID parameters. The performance of these combinations is evaluated using a fitness function composed of several component functions, such as steady-state error, peak overshoot, rise time, and settling time.[12]

In the MATLAB library, we have defined a fitness function which has PID parameters as input values, and it returns the fitness value of the PID based controlled model as its output.

III.PROBLEM STATEMENT:

The manuscript is objected to design a PID controller for a low damping plant. The low damping plants are the higher order plants which exhibit sluggish behaviour. It means that the plant has considerable settling time, large peak overshoot which is undesirable for better performance. We have the 6th order transfer function model of the DFIG plant in [5, 6, 13, 14], as follows.

$$G(S)=\frac{0.000324s^6-1.75s^5-2366s^4+7.9e6s^3+7.5e9s^2+5e12s+2.18e14}{s^6+2340s^5+8.67e6s^4+4.79e9s^3+2.7e12s^2+1.27e14s+9.6e14}$$

The fitness function is: -

F = (1-exp (-)) (Mp +Ess) + (exp (-β)) (Ts-Tr)

Where;

M_{p} Peak Overshoot

T_{s} Settling Time

T_{r} : Rise Time

β: Scaling Factor (Depends upon designer)

Function [F] = fitness (KD, KP, KI)

This fitness function will take the PID parameters as input and return calculated value of fitness function for different cases. We need to minimize it as possible by providing different values of PID parameters.

We make a function that will take value from the output of evolutionary algorithm techniques as (KP, KI, KD), and give us the evaluated value of the fitness function. In this function, we make a PID controller that will use these parameters, and then we take the closed loop performance parameters like Peak Overshoot, Settling Time, Rise Time, Scaling factor and put these parameters into the fitness function equation [15].

IV.CONFINING THE SEARCH SPACE:

To refine our search and expedite convergence, we restrict our search space, running the algorithm numerous times within this defined space to attain optimal values for Kp, Ki, and Kd. Prior to execution, we conduct trial and error exercises to delimit the search space. Our experimentation reveals that utilizing a derivative controller renders our closed-loop system unstable. Consequently, we opt for a PI controller in this study. Additionally, we establish that KP should range between 0 and 20, while Ki should fall within 0 and 200; values beyond these ranges lead to impractical responses and system instability. [15]

To derive PID controller gains using the DE algorithm, we refer to sections 4.5, 4.6, and 4.7.

Table: 1 Gains of the DE-based controller

Parameters	k_p	k_i	k_d
Gains	14.7769	137.9634	0

V.SIMULATION RESULTS:

Simulink response of DFIG system

In this section, the simulation response of a Doubly Fed Induction Generator (DFIG) system is presented. The system comprises a 9 MW wind farm with six 1.5 MW wind turbines connected to a 25 kV distribution system, which exports power to a 120 kV grid via a 30 km feeder. The wind velocity is held constant at 15 m/s. [15]

The control system employs a torque controller to maintain the turbine speed at 1.2 per unit (Pu) and regulates reactive power production at 0 Mvar. Initially, the DFIG wind farm generates 9 MW with corresponding turbine speed and generator speed at 1.2 Pu. The DC voltage is stabilized at 1150 V, and reactive power is maintained at 0 Mvar.

At t=0.03 s, there is a rapid drop in positive-sequence voltage to 0.5 Pu, leading to oscillations in the DC bus voltage and DFIG output power. The control system intervenes to stabilize the DC voltage and reactive power at their set points, resulting in system recovery in about four cycles.

The response of the DFIG-based wind turbine with Fast Fourier Transform Algorithm (FFA)-based controller gain and Differential Evolution (DE)-based controller is analysed in terms of voltage, current at the terminals, active power generated, reactive power requirements, DC capacitor voltage, and generator speed, as depicted in Figures 5 to 7, respectively.

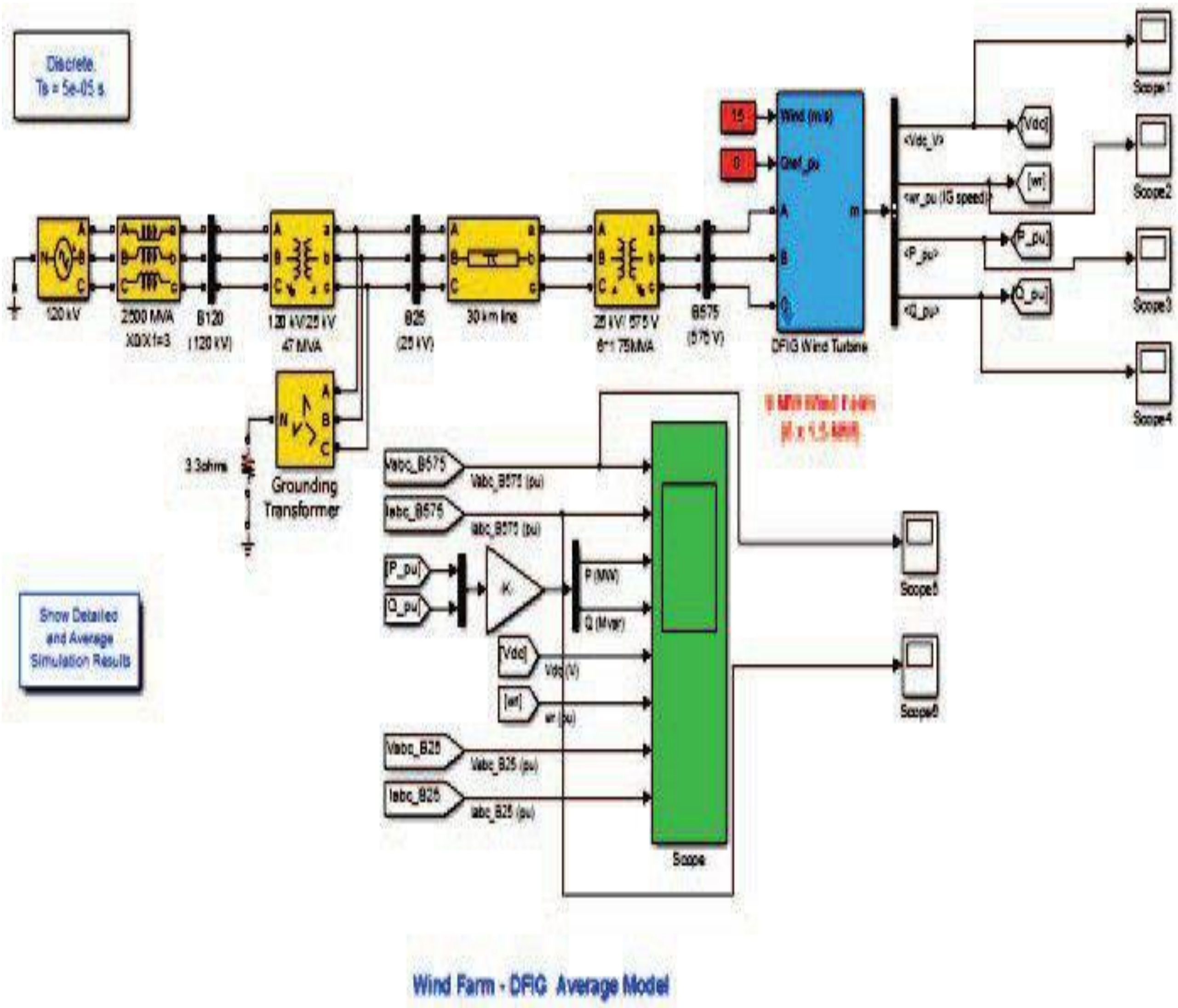


Figure 4: DFIG based wind turbine MATLAB Simulink

Model diagram

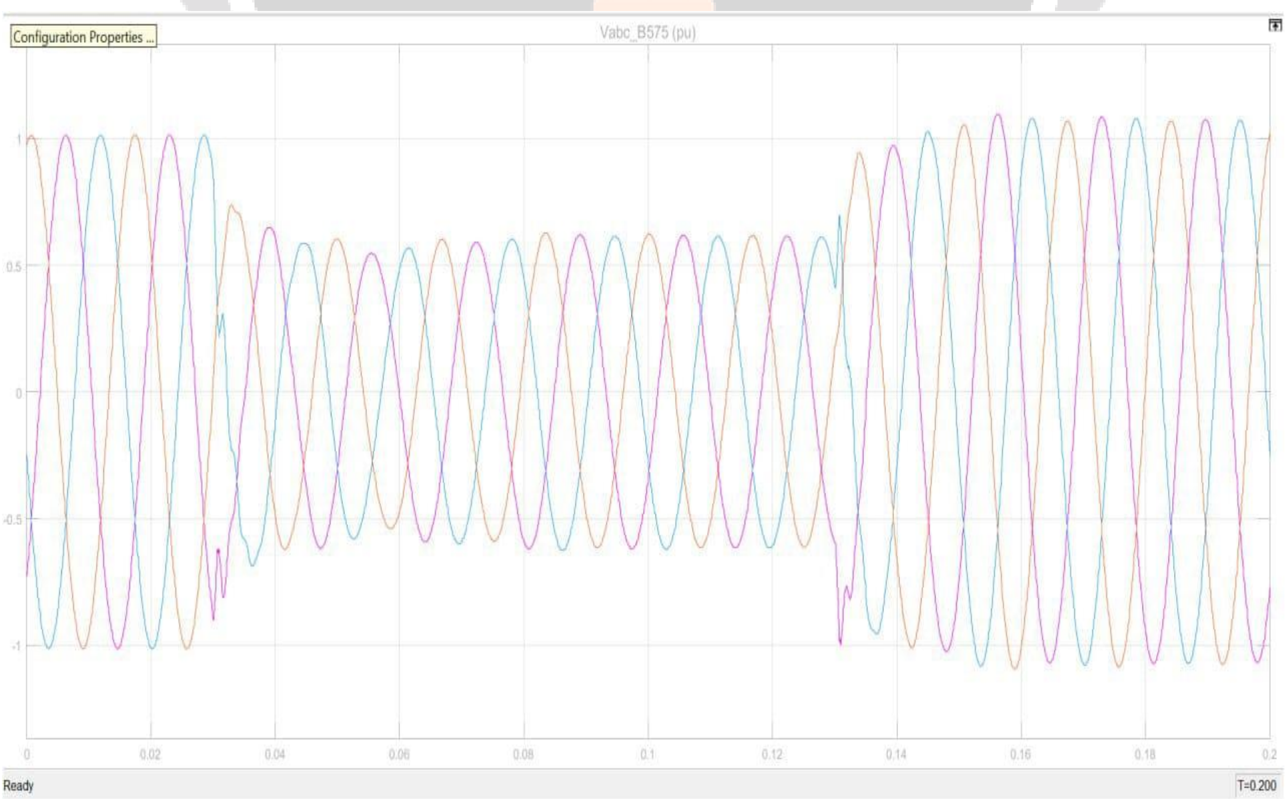


Figure 5(a) Voltage at the DFIG terminals in pu (DE-based controller)

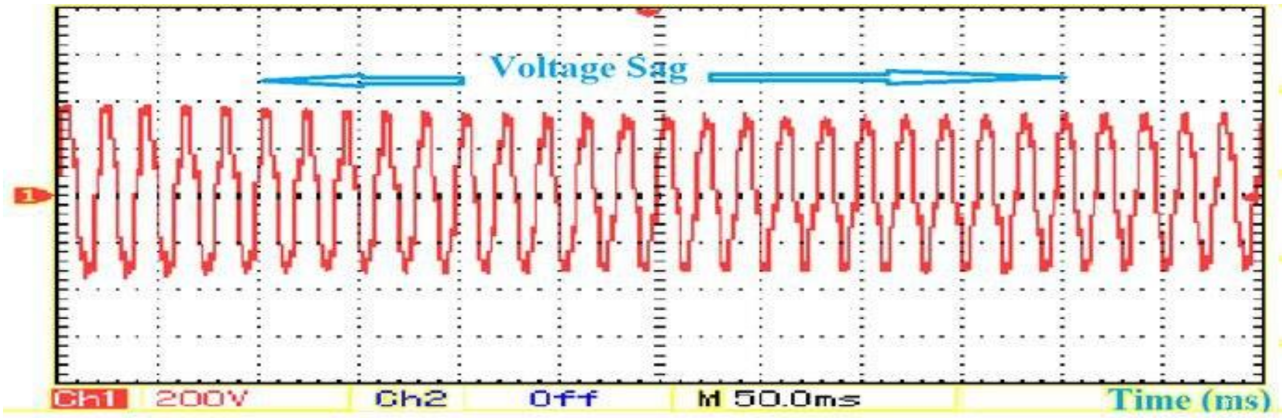


Figure 5(b): Voltages at the DFIG terminals in pu (Experimentally done)

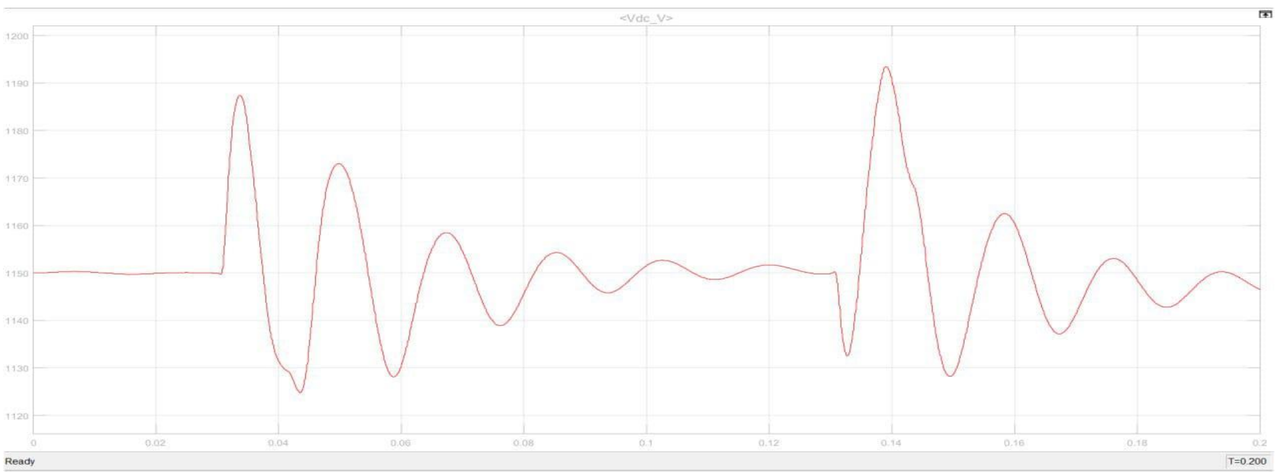


Figure 6(a): DC link voltage at common link capacitor (DE-based controller)

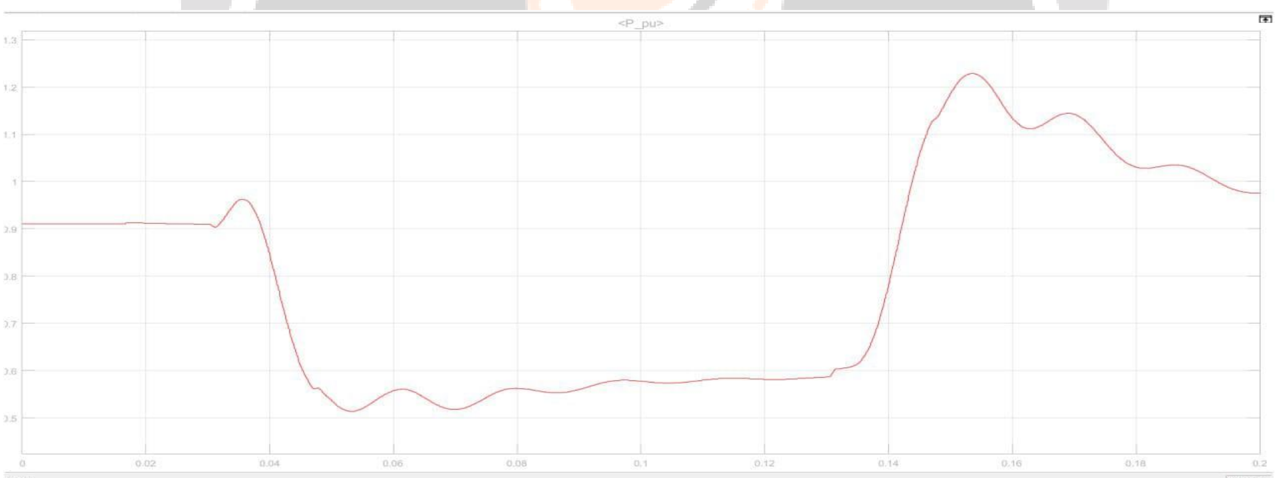


Figure 6(b): Active power given to the DFIG in pu (DE based controller)

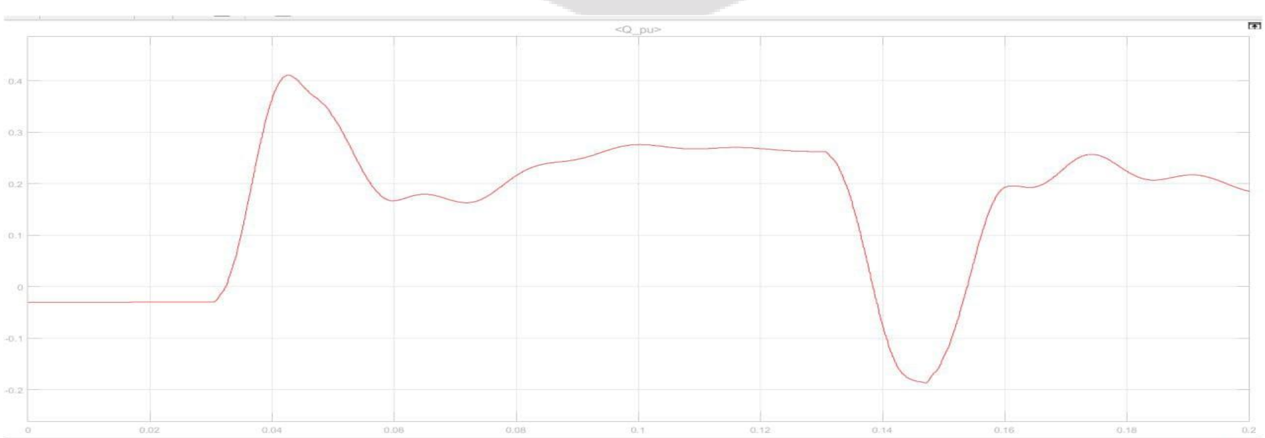


Figure 7(a): Active power requirement of DFIG in PU (DE-based controller)

Here figure 5-7 concluded that the response of the DFIG system regarding terminal voltage, active-reactive power and DC-Link voltage slightly improved with a DE-based controller instead of a GA-based controller.

DE-based DFIG Control Response by PID Controller: The response of the DE-based PID controller intended in [5, 6, 13, 14], is as publicized in Figure 7(a) . However, the step response of DE- based PID-controller for closed-loop in [5, 6, 13, 14], is shown in Figure 7(b)

Open-loop step response of the DFIG system:

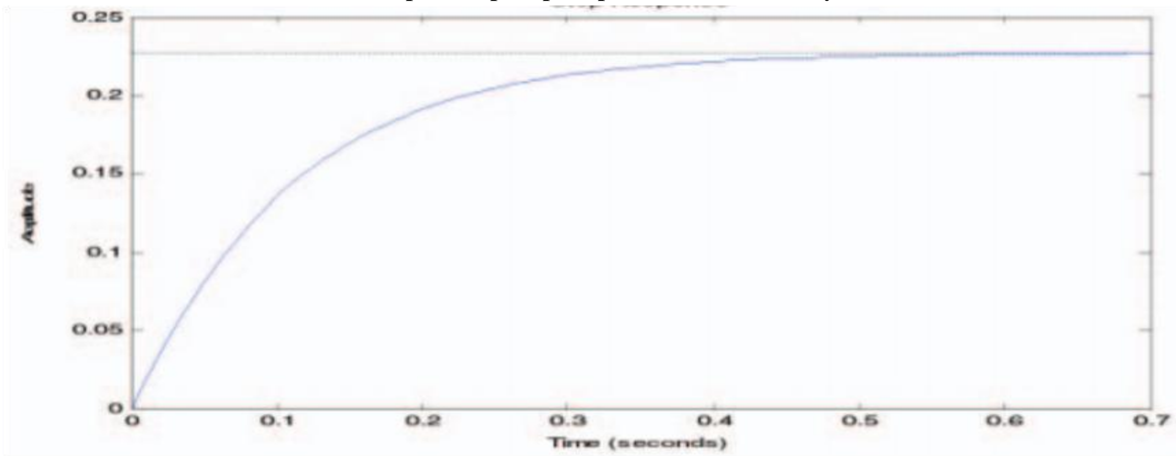


Fig 8(a) : step response of DFIG(open loop)

Table 3: Step response of DFIG (open loop)

Observations of fig 8(a):

Rise time	Settling time	Over shoot	Under shoot	Peak	Peak time
0.2359sec	0.4197sec	0.0%	0.0%	0.2269	0.7780sec

Close loop step response of DFIG

A system of DE controller :

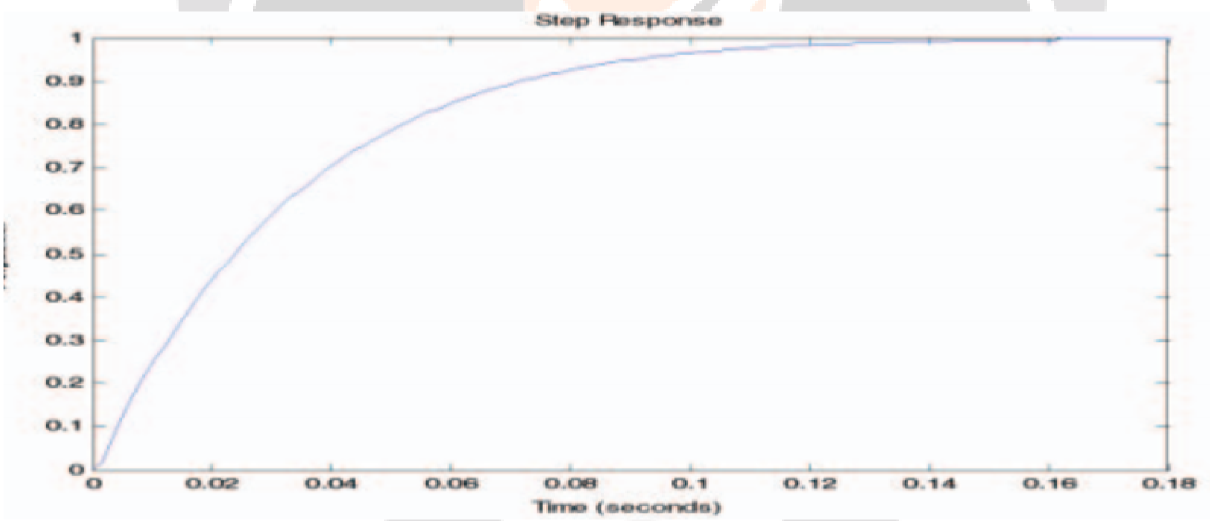


Fig 8(b): step response of DFIG (closed loop)

Observation of de:

TABLE 4: Step response of DFIG (closed loop)

Observation of the fig 9(b)

Rise time	Settling time	Over shoot	Under shoot	Peak	Peak time
0.0675sec	0.1145sec	0.0%	0.0%	0.9992	0.2115sec

6.4. VALUES OF DE RESPONSE:

Table 6: Values for DE-based method

Controllers	Peak time	Overshoot	Peak
DE-based PID	0.2115sec	0%	0.9992

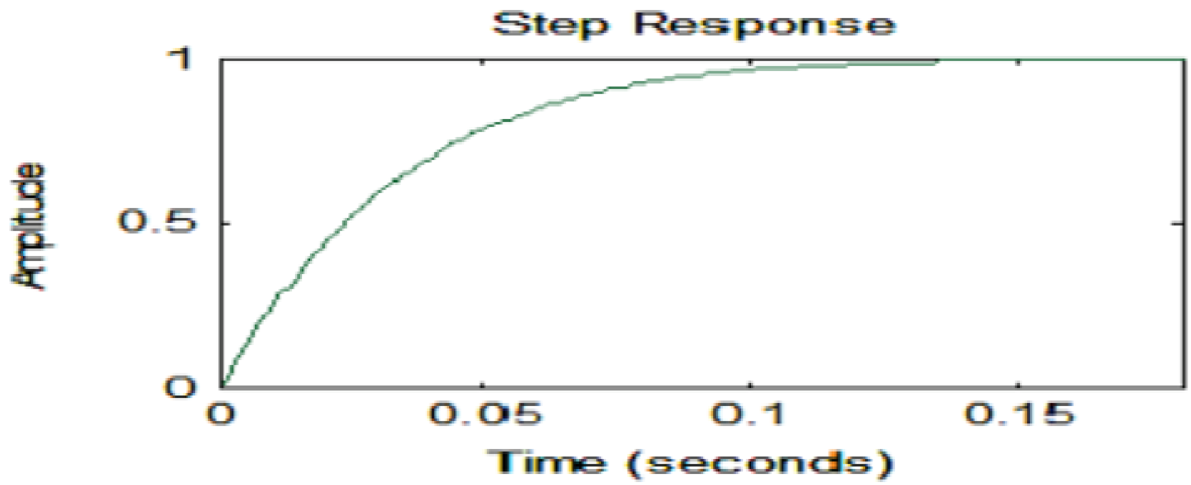


fig 9(b): Step response of de-based method

VI.CONCLUSION:

The DE-based PID controller significantly enhances system responses. The DE-based controller not only improves system response but also eliminates percentage overshoot entirely. Experimental results demonstrate that the system with the DE-based controller settles faster, achieving a reduced settling time of approximately 0.0395 seconds and zero percentage overshoot. The DE-based control technique presents a reliable and effective option for designing controllers in DFIG-based wind turbine systems for wind energy conversion applications. It's worth noting that the experiments validating the effectiveness of the DE-based controller have already been conducted.

VII.ACKNOWLEDGEMENTS:

The authors recognize the monetary help from the Power Plant Engineering works, Visakhapatnam, Andhra Pradesh, India" through research project no: 11/2019-20.

VIII.REFERENCES:

1] Fang Yao, R.C. Bansal, Z.Y. Dong, R.K. Saket and J.S. Shakya (2011); "Wind Energy Resources: Theory, Design, and Applications, "Handbook of Renewable Energy Technology, pp: 03-20, World Scientific Publishing House, Singapore, 2011

[2] Tazil M, Kumar V, Bansal RC, Kong S, Dong ZY, Freitas W, et al., "Three-phase doubly fed induction generators: an overview." IET Electric Power Applications 2010; 4:75-89.

[3] T. Brekken and N. Mohan, "Control ef a doubly fed induction wind generator under unbalanced grid voltage conditions," IEEE Trans. Energy Conv. 22 (1), pp: 129-135, 2007.

[4] Z. Wang, Y.Sun, G. Li, and B.T.Ooi, "magnitude and frequency control of grid-connected doubly fed induction generator based on a synchronized model for wind power generation," IET Renew. Power Generation, 4 (3), pp: 232-241, 2010.

[5] Hee-Sang KO, Gi-Gab Yoon, Nam-Ho Kyung, and Won-Pyo Hong, "Modelling and control of DFIG-based variable speed wind-turbine," Electric power system Research 78, pp. 1841-1849, 2008.

[6] Om Prakash Bharti, R.K.Saket, S.K.Nagar. "Controller Design For DFIG Driven By Variable Speed Wind Turbine Using Static Output Feedback Technique," Engineering, Technology &Applied Science Research Vol. 6, No. 4, pp-1056-1061, (2016) .

[7] Saidur R, Rahim NA, Islam MR, Solangi KH., "Environmental impact of wind energy. Renewable and Sustainable Energy Reviews 2011;15:2423-30.

[8] Naidu, Bhim Singh," Experimental Implementation of a Doubly Fed Induction Generator Used for Voltage Regulation at a Remote Location," IEEE Transactions on Industry Applications, vol. 52, no. 6, pp-5065-5072, November/December 2016.

[9] Nolan D.Caliao, "Dynamic modelling and control of fully rated converter wind turbines." Renewable Energy 36, p 2287-2297,2011.

[10] Price, R. M.Lampinen, J. A. "Differential Evolution: A Practical Approach to Global Optimization" Pringer. ISBN: 978-3-540-20950-8, 2005.

[11] Fogel, D. B., "Evolutionary computation: toward a [new philosophy of machine Intelligence," John Wiley and Sons, 2006.

[12] Rocca, P.; Oliveri, G.; Massa, A. "Differential Evolution as Applied to Electromagnetics," IEE Antennas and Propagation Magazine, 2011.

[13] Om Prakash Bharti, R. K. Saket, S.K. Nagar, "Controller Design for Doubly Fed Induction Generator Using Particle Swarm Optimization Technique." Renewable Energy, Science Direct, Elsevier 114 (Part B), 2017, 1394-1406, 2017.

[14] Om Prakash Bharti, R. K. Saket, S.K. Nagar, "Controller Design of DFIG Based Wind Turbine by Using Evolutionary Soft Computational Techniques." Engineering. Technology & Applied Science Research, Vol.7, No. 3, 2017, 1732-1736-1736.

[15] Matlab documentation. [16] S. Rajasekaran, G. A. Vijayalakshmi Pai, "Neural Networks, Fuzzy Logic and Genetic Algorithms: Synthesis and Applications," 2003.

[16] S. Rajasekaran, G. A. Vijayalakshmi Pai, "Neural Networks, Fuzzy Logic and Genetic Algorithms: Synthesis and Applications," 2003.