APPLICATION OF SUPERVISORY CONTROL FOR DOUBLY FED INDUCTION GENERATOR BASED WIND ENERGY CONVERSION SYSTEM

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Abstract *- This paper proposes a supervisory control strategy for real power of doubly fed induction generator based wind energy conversion system. A doubly fed induction generator based wind energy conversion system is designed, modelled and parameters were estimated using different non linear optimization techniques such as piecewise linear approximation method, sigmoid network and wavelet network for both the partial and full load region. Suitable model is selected based on the model properties and is used as a reference input for the supervisory controllers. The parameters of Proportional Integral and Derivative controller were auto tuned and fed into the supervisory controllers. The error signal is also given as input to the supervisory controllers along with the constant controller parameters and the control signal is obtained as output by training the error signal with intelligent techniques such as fuzzy logic, neural network and adaptive neuro-fuzzy inference system. The performance of controllers is analyzed with performance parameters such as Integral Square Error and average power of doubly fed induction generator based wind energy conversion system. Adaptive neuro-fuzzy inference system tuned PID controller shows the better performance comparing to fuzzy tuned and neural network tuned PID controller.*

1   INTRODUCTION

In the recent years, wind energy has been a topic of consideration and attracted intensified interest due to the progress experienced in last decades. It plays the major role in the effort to increase the share of the renewable energy sources [1] and [2]. It helps to satisfy the global energy demand offering the best opportunity to unlock the new era of environmental protection [3].

Doubly Fed Induction Generator (DFIG) in a Wind Energy Conversion System (WECS) offers many advantages such as reduction of inverter cost, the potential to control torque and a slight increase in efficiency of wind energy extraction [4]. The WECS has strongly coupled variables which create nonlinearity and the stochastic variations of the input power and the presence of physical constraints on the system's variable render the control design task more difficult [5]. Coordinated tuning of the damping controller in DFIG based wind power system is discussed in [6]. The implementation of the Tagaki-Sugeno fuzzy controller for the active power and the DC capacitor voltage control of the Doubly Fed Induction Generator (DFIG) based wind generator is described in [7]. Vector control, direct torque control and direct power control are reviewed and their performances are analysed for DFIG based WECS in [8]. Different control strategies techniques were discussed for the WECS in the partial load region [9]–[14]. The proportional integral (PI) controllers for DFIG based WECS is described in [10],

[11], and [14]. A gain-scheduling linear quadratic Gaussian (LQG) controller is proposed in [12]. Second order sliding mode design, to control the DFIG based wind turbine according to the references given by maximum power point tracking is given in [15]. The power transfer matrix model and multivariable control method for a doubly-fed induction generator (DFIG) wind energy system [16]. Coordinated control strategy for DFIG system with series grid side converter is described in [17]. Recent studies indicate that when wind speed fluctuates around its rated value, undesirable drive train transient loads and power overshoots can occur [18].

This paper concentrates in developing the supervisory intelligent controllers for both the partial load region and full load region. Hammerstein Weiner (HW) model is developed and this model is used as reference input for intelligent controllers of DFIG based WECS. The ideal power curve of DFIG based WECS is given in [19]. A DFIG based WECS shown in Figure 1 is designed with several interconnected subsystems such as aerodynamic system, drive train system, DFIG system, back to back voltage source converter system with Rotor Side Converter (RSC) and Grid Side Converter (GSC) connected to direct current (dc) link. Partial and full load region are divided into low wind speed region, medium wind speed region and high wind speed region [5] as shown in Table.1. Description of subsystems of DFIG based WECS are discussed in [19].
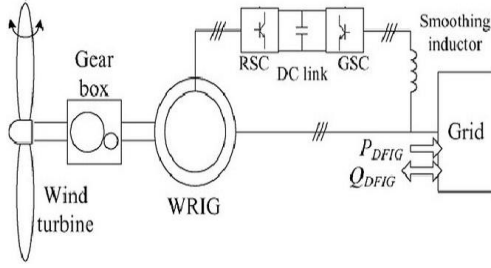
Figure 1. DFIG based WECS

Table 1. Classification of partial load region and full load region

Load Region		Wind Speed range (m/sec)	
		Minimum	Maximum
Partial Load Region	Low Wind speed	4	8.7
	Medium Wind Speed	8.7	11
Full Load Region	High Wind speed	11	26

2. Non linear Identification of DFIG based WECS:

DFIG based WECS is modeled with HW method and parameter estimation procedures are done by using System Identification Toolbox in Matlab [20]. Each sub systems of low wind speed region are designed individually and identified using HW model. The obtained model is analyzed using the model properties, which includes fit percentage, Akaike's FPE and Loss function [19].

3 CONTROLLER DESIGN

3.1 PID Controller

HW models developed for the wind speed regions mentioned in Table. 1 is given as reference input to the controller. The block diagram of DFIG based WECS with PID controller is shown in Figure 2.
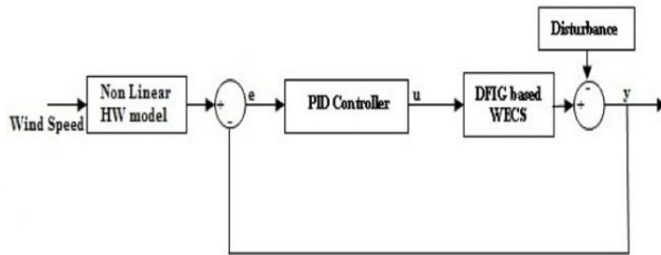

Figure 2. Block diagram of DFIG based WECS with PID controller

3.2 Supervisory Controllers

Generally, there are two approaches to deal with nonlinear problem in control system, i.e., gain scheduling and auto-tuning. Since auto-tuning can drastically reduce the effort required to build up the gain schedule [21], it is applied in the control structure, as shown in Figure 3. The Controller parameters are auto tuned and given to the supervisory controllers such as fuzzy logic, neural network and ANFIS. Supervisory controller further tunes the error signal and produces a control signal which in turn regulates the real power of DFIG based WECS. Continuous tuning of K_P, K_I and K_D with the error signal until the power of the DFIG based WECS can meet the desired output. Otherwise, it is very hard to analyze the performance of control system and to adjust the whole control [22]. The proposed strategy uses neural networks and fuzzy logic controllers to control the power transfer between the machine and the grid using the vector control techniques. This transfer is ensured by controlling the rotor via two identical converters. The first converter is connected to the RSC (rotor side) and the second is connected to the GSC (grid side) via a filter. This control strategy is used to control the rotor side currents and to protect the generator by limiting the output current (or voltage) [23]
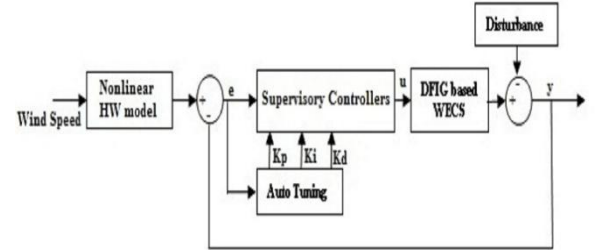

Figure 3. Block diagram of DFIG based WECS with supervisory controllers

The control signal is given to the DFIG based WECS is obtained [22] through equations 1- 8.

$$u(nT)_{cmd} - u(nT-T)_{cmd} = K_p e(nT) - K_I \frac{T}{2} e(nT) + 2K_I \frac{T}{2} e(nT) - (K_p e(nT-T)$$

$$- K_I \frac{T}{2} e(nT-T)) + K_D (\dot{e}(nT) - \dot{e}(nT-T)) \quad (1)$$

where $n = 0, 1, 2, \ldots, e(nT)$ is the tracking error signal between the desired and the actual power output, and K_P, K_I and K_D are constant proportional, integral and derivative control gains, respectively. Let

$$\tilde{K}_P = K_P - \frac{TK_I}{2} \quad (2)$$

$$\tilde{K}_I = K_I T \quad (3)$$

$$\tilde{K}_D = K_D \quad (4)$$

so that Eq. (1) can be expressed as equation(5)

$$\Delta u_{cmd} = K_I e(nT) + K_p (e(nT) - e(nT-T)) + \tilde{K}_D (\dot{e}(nT) - \dot{e}(nT-T)) \quad (5)$$

$$e_I = \tilde{K}_I e(nT) \Delta u_{cmd} = e_I + e_P + e_D \quad (6)$$

$$e_P = \tilde{K}_P(e(nT) - e(nT - T)) \qquad (7)$$

$$e_D = \tilde{K}_D(\dot{e}(nT) - \dot{e}(nT - T)) \qquad (8)$$

Equations 6-8 represent the tracking error, change in error and change in error rate, respectively. Eq. (5) is then written as

$$\Delta u_{cmd} = e_I + e_P + e_D \qquad (9)$$

e_I, e_P and e_D are the input signals to the supervisory PID controllers.

3.2.1 Fuzzy Logic

For the DFIG based WECS, the membership function used for the error terms given in equation (6-8) in the fuzzification process are the same, as shown in Figure 4. The output membership functions are shown in Figure 5.
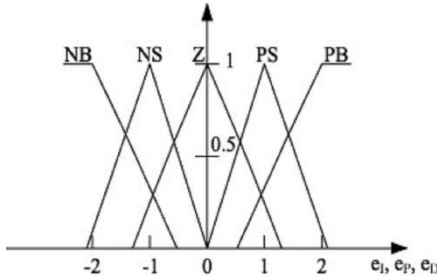

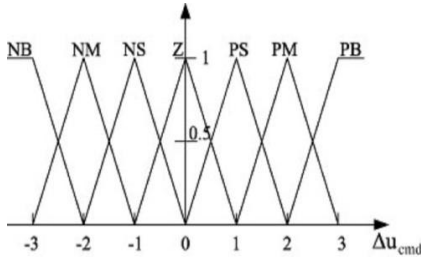**Figure 4. The input membership functions**

Figure 5. The output membership functions

There are three inputs, each having five membership functions. Hence one hundred and twenty five fuzzy control rules are framed. One of the fuzzy rules is given as follows

If e_p is NS and e_I is PS and e_D is NS **Then** Δu_{cmd} is NS.

Then the precise incremental control output is from the method of the centre of the gravity. In this proposed fuzzy logic control structure [24], e_P, e_I and e_D are related to K_P, K_I and K_D, as presented in equations (2-7). However, K_P, K_I and K_D in the control system are constant, while DFIG based WECS are highly nonlinear.

3.2.2 Neural network tuned PID controller

It is well known that neural networks can be utilized to describe the nonlinear systems. The neural network is of the feed forward hierarchical type constructed with three layers is shown in Figure 6 [25]. The activation function used is binary sigmoidal function. The Back Propagation (BP) algorithm is used to train network, which ensures the minimisation of a regulation error $e(t)$. The BP algorithm has three phases which includes feed forward phase, back propagation of error and Weight and bias updation [26].
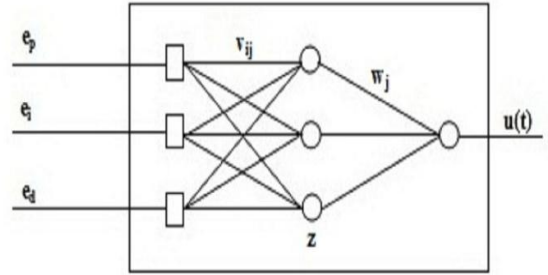

Figure 6. Neural network control structure

3.2.3 Adaptive Neuro-Fuzzy Inference System (ANFIS) tuned PID controller

ANFIS is the implementation of Fuzzy Inference System (FIS) to adaptive networks for developing fuzzy rules with suitable membership functions to have required inputs and outputs. FIS is a popular and cardinal computing tool to which fuzzy if-then rules and fuzzy reasoning compose bases that performs mapping from a given input knowledge to desired output using fuzzy theory. FIS basically consist of five subcomponents, a rule base, a database, a decision making unit, fuzzification inference and defuzzification inference. The first two subcomponents generally referred knowledge base and the last three are referred to as reasoning mechanism. An adaptive network is a feed-forward multi-layer Artificial Neural Network (ANN) with; partially or completely, adaptive nodes in which the outputs are predicated on the parameters of the adaptive nodes and the adjustment of parameters due to error term is specified by the learning rules. Generally learning type in adaptive ANFIS is hybrid learning [27]. Structure of the ANFIS is illustrated in Figure 7 [28].
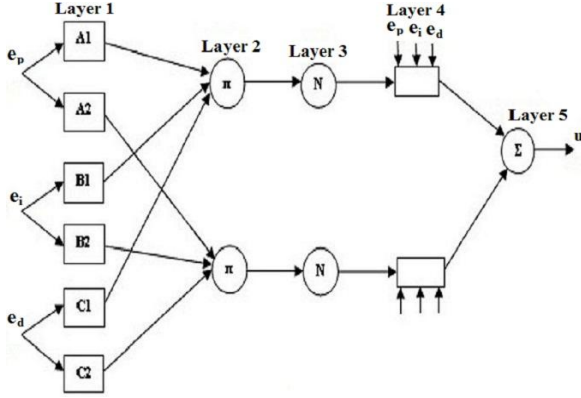
Figure 7. ANFIS structure

ANFIS model can design and determine the fuzzy system parameters based on the sample of the input and output of the system. In the first layer, five triangular membership functions of the three inputs are determined. ANFIS inputs and output are trained with these modified points. The inputs are the proportional error, integral error and the derivative error. In the layer 1, every node i in this layer is a square node with a node function

$$O_i^1 = \mu_{Ai}(e) \qquad (10)$$

where e_p, e_i, e_d are the input to node 0, and A, B, C are the linguistic labels associated with this node function. Five triangular membership functions are chosen with maximum equal to 1 and minimum equal to 0. Every node in layer 2 is a circle node labeled H, which multiplies the incoming signals and sends the product out. For instance,

$$w = \mu_{Ai}(e_p) * \mu_{Bi}(e_i) * \mu_{ci}(e_d); \qquad (11)$$

where i=1,2,3

Each node output represents the firing strength of a rule. Every node in layer 3 is a circle node labeled N.

The i-th node calculates the ratio of the i-th rule's firing strength to the sum of all rules' firing strengths.

$$\overline{w_i} = \frac{w_1}{w_1 + w_2 + w_3} ; \text{ where i=1,2,3.} \qquad (12)$$

The outputs of this layer will be called normalized firing strengths. Every node layer 4 is a square node with a node function

$$O_i^4 = \overline{w_i} f_i = w_i(pix + qiy + ri) \qquad (13)$$

where, $\overline{w_i}$ is the output of layer 3 and {pi, qi, ri} is the parameter set.

Parameters in this layer will be referred to as consequent parameters. The single node in layer 5 is a circle node labelled E that computes the overall output as the summation of all incoming, signals [29],as given in equation (14).

$$O_i^5 = \sum \overline{w_i} f_i = \frac{\sum w_i f_i}{\sum i f_i} \qquad (14)$$

4. RESULTS AND DISCUSSION

In this section, DFIG based wind energy conversion system with 2MW capacity is identified, modeled and controlled using the PID and supervisory controllers. Model properties of real power of DFIG based WECS in both the partial and full load region is given in Table. 2. In the low and high wind speed regions HW model produced by the sigmoid estimation method has best fit percentage of 60.05% and 80.05%. In the medium wind speed region HW model produced by piecewise linear estimation method has best fit percentage of 85.73%. Models with best fit percentage are selected and given as reference input to the designed intelligent controllers.

Table.2: Model properties of real power of DFIG based WECS

Load Region	Model properties of Estimation Approaches								
	Piecewise Linear			Sigmoid			Wavelet Network		
Low wind speed	Fit %	FPE	Loss Fcn	Fit %	FPE	Loss Fcn	Fit %	FPE	Loss Fcn
	47.89	0.012	0.006	*60.05*	*0.0054*	*0.0023*	52.17	0.00479	0.003291
Medium wind speed	*85.73*	*0.00041*	*0.00021*	60.32	0.01388	0.0059	85.66	0.00027	0.00016
High wind speed	62.76	0.01077	0.00552	*80.05*	*0.002*	*0.00084*	73.81	0.0021	0.0015

The parameters of PID controller obtained by autotuning are given in Table 3. The controller parameters and the error signal are given to the supervisory controllers as input. The supervisory controller keeps the controller parameters constant and tunes the error signal. The tuned error signal combined with constant PID controller parameters produce the control signal which regulates the real power of DFIG based WECS. The performance of supervisory controller with PID controller is analyzed with performance parameters like Integral Square Error (ISE) and average power of DFIG based WECS (P_{avg}).

$$ISE = \int_0^\alpha e^2(t)dt \qquad (37)$$

Table 3. Controller parameters of PID for different wind speeds

PID Controller Parameters	Range of Wind Speed		
	Low Wind Speed	Medium Wind Speed	High Wind Speed
K_p	0.0018924	0.0019	0.0018924
K_i	0.41806	220.911	0.41806
K_d	1.407e-006	7.4365e-04	1.407e-006

6.1 Low wind speed

Low wind speed HW model is simulated with the wind speed range between **4 to 8.7 m/sec**. Figure 8 shows the low wind speed input. The power output of DFIG based WECS for supervisory controllers are shown in Figure 9. The ISE values and P_{avg} of PID and supervisory controllers are shown in Table. 4.
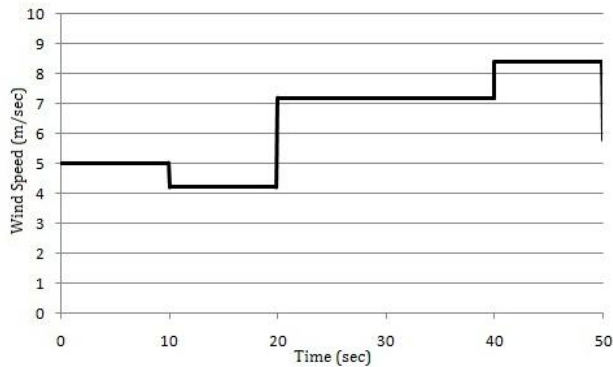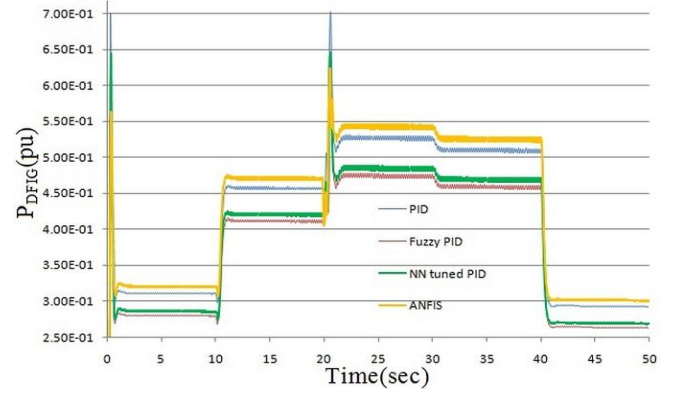

Figure 8. Low wind speed

Figure 9. Power output of low wind speed DFIG based WECS

Table 4. ISE and Pavg values of PID and supervisory controllers for low wind speed

Performance Parameter	PI	PID	FL tuned PID	NN tuned PID	ANFIS tuned PID
ISE	0.00123	0.00084	0.000793	0.00078	0.00078
P_{avg} (pu)	0.4176	0.4197	0.4278	0.4316	0.4396

6.2 Medium wind speed

DFIG based WECS for medium wind speed is simulated with the wind speed range between **8.7 to 11 m/sec**. Medium wind speed given as input to the DFIG based WECS is shown in Figure 10. The power output of DFIG based WECS for supervisory controllers are shown in Figure 11. The values of ISE and P_{avg} of PI and PID controller are shown in Table. 5.
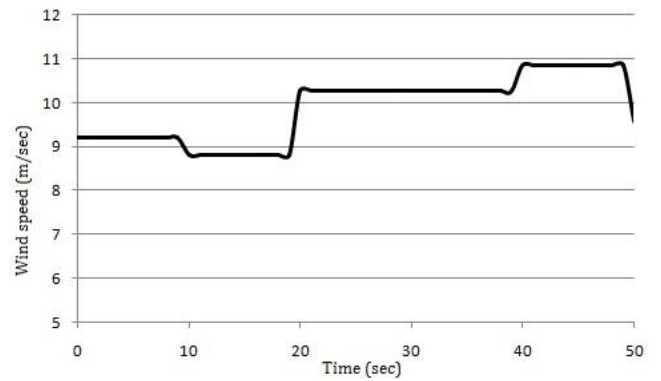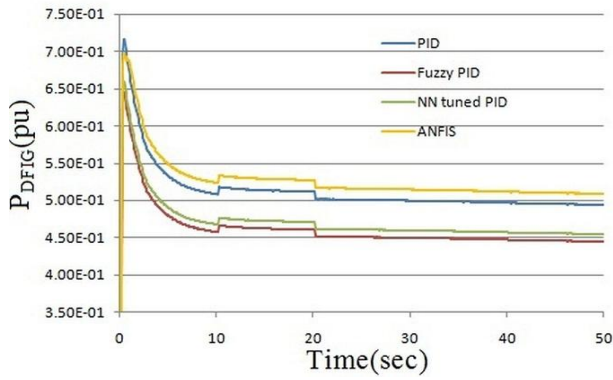

Figure 10. Medium wind speed

Figure 11. Power output of medium wind speed DFIG based WECS

Table 5. ISE and Pavg values of PID and supervisory controller for medium wind speed

Perform ance Parameter	PI	PID	FL tuned PID	NN tuned PID	ANFIS tuned PID
ISE	0.00191	0.001028	0.00098	0.0009	0.0008467
P_{avg}	0.5069	0.510076	0.5201	0.525	0.535047

6.3 High wind speed

DFIG based WECS for high wind speed is simulated with the wind speed range between **11 to 26 m/sec**. High wind speed given as input is shown in Figure 12. The power output of DFIG based WECS for High wind speed is shown in Figure 13. The ISE values and P_{avg} of PID and supervisory controller are shown in Table. 6.
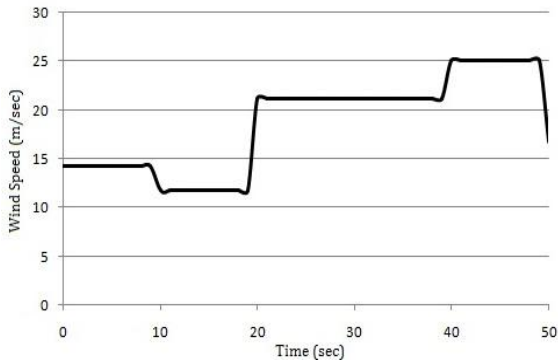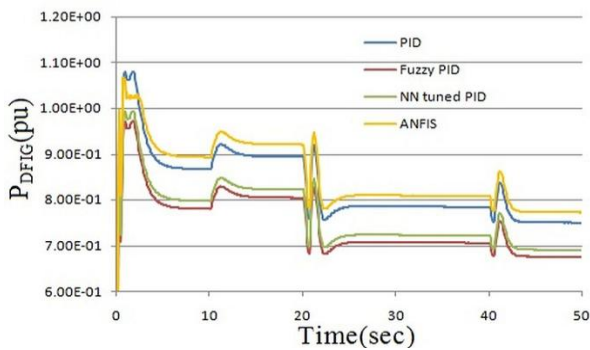

Figure 12. High wind speed

Figure 13. Power output of high wind speed DFIG based WECS

Table 6. ISE and Pavg values of PID and supervisory controller for high wind speed.

Perform ance Parameter	PI	PID	FL tuned PID	NN tuned PID	ANFIS tuned PID
ISE	0.0027	0.00173	0.000956	0.000894	0.0007865
P_{avg}	0.824	0.8271	0.84104	0.8478	0.8623

Classical and supervisory controller for DFIG based WECS are designed and simulated in matlab environment. The nonlinear WECS is well controlled by supervisory and classical controllers. The supervisory controllers work well in both the partial and full load region. The intelligent techniques adopted in supervisory controllers are fuzzy logic, neural network and ANFIS. Among them, ANFIS tuned PID controller produces the satisfactory results compared to the other designed controllers. Overshoot is less in ANFIS compared to the other designed controllers. Disturbance also has a very little effect on the power of DFIG. ISE values of ANFIS controller is also found to be low compared to the other controllers.

7 CONCLUSION

The DFIG based WECS is designed identified and Hammerstein Wiener model is developed. Parameter estimation of the HW model is carried out with piecewise linear, sigmoid network and wavelet network approximation methods. Suitable model selected based on model properties, is given as reference input to the controller. In the designed intelligent controllers, the parameters are kept constant and given as input to the controllers and the control signal is obtained by tuning the error signal. The designed controllers are tested in both the partial and full load region. The real power of the DFIG based WECS is better controlled by supervisory controllers. The performance of supervisory controllers with auto tuned constant PID parameters is analyzed with performance parameters such as ISE and average power of DFIG based WECS. ANFIS tuned PID controller produces the better results compared to other controllers.

APPENDIX
Ratings and specifications
Wind Turbine/Drive Train/Pitch System
System rated power= 2MW, Rated turbine speed=23rpm, Min/Max turbine speed=9.5/25 rpm, Radius of the rotor blades=35m, $v_{ci}/v_{cr}/v_{co}$ = 4/11/26m/sec, Gear ratio (i) = 74.38, Turbine inertia constant=3s, Generator inertia constant =0.5s , Shaft stiffness= 0.5 pu, Shaft damping=0.01pu
DFIG system
Rated generator apparent power =2/0.9MVA,
f_o =60Hz, P=3, r_s =0.00706p.u, L_{ls} =0.171pu,
r_r =0.005pu, L_{lr} =0.156pu, L_m =2.9pu, r_f =0.15/100pu,
L_f = 0.15pu C=1000μF, Rated dc link voltage = 1200V

REFERENCES

[1] José Luis Domínguez-García, Oriol Gomis-Bellmunt,Lluís Trilla-Romeroa, AdriàJunyent-Ferré, *"Indirect vector control of a squirrel cage induction generator wind turbine"* Computers and Mathematics with Applications Vol. 64 (2012)102–114.

[2] Whei-Min Lin, Chih-Ming Hong, Fu-Sheng Cheng, *"On-line designed hybrid controller with adaptive observer for variable-speed wind generation system"* Energy, Vol. 35 (2010), 3022-3030.

[3] G.Tsourakisa, B.M.Nomikosb, C.D.Vournasa, *"Effect of wind parks with doubly fed asynchronous generators on small-signal stability"* Electric Power Systems Research, Vol. 79 (2009) 190–200.

[4] K.Kerrouche, A.Mezouar, Kh.Belgacema, *"Decoupled Control of Doubly Fed Induction Generator by Vector Control for Wind Energy Conversion System"* Energy Procedia Vol. 42 (2013) 239 – 248.

[5] Mostafa Soliman, O. P. Malik, and David T. Westwick, *"Multiple Model Predictive Control for Wind Turbines with Doubly Fed Induction Generators"*, IEEE Transactions on Sustainable Energy, Vol. 2,(2011) 215-225.

[6] Y. Mishra, S. Mishra, M. Tripathy, N. Senroy, and Z. Y. Dong, *"Improving Stability of a DFIG-Based Wind Power System With Tuned Damping Controller"*, IEEE Transactions on Energy Conversion, Vol.24, (2009) 650 – 660.

[7] S. Mishra, Y. Mishra, Fangxing Li, Z. Y. Dong, *"TS-fuzzy controlled DFIG based Wind Energy Conversion Systems"*, IEEE Power and Energy Society General Meeting, (2009).

[8] Etienne Tremblay, Sergio Atayde, and Ambrish Chandra, *"Comparative Study of Control Strategies for the Doubly Fed Induction Generator in Wind Energy Conversion Systems: A DSP-Based Implementation Approach"*, IEEE Transactions on Sustainable Energy, Vol. 2, (2011), 288-299.

[9] F. D. Bianchi, H. Battista, and R. J. Mantz, *"Wind Turbine Control Systems:Principles, Modelling and Gain Scheduling Design"*, London: Springer-Verlag, 2007.

[10] H. Camblong, I.M. de Alegria, M. Rodriguez, and G. Abad, *"Experimental evaluation of wind turbines maximum power point tracking controllers"*, Energy Conversion and Management, Vol. 47(2006), 2846–2858.

[11] A. D. Hansen, P. Sorensen, F. Lov, and F. Blaabjerg, *"Control of variable speed wind turbines with doubly-fed induction generators"*, Wind Eng., Vol. 28 (2004), 411–443.

[12] I. Munteanu, N. A. Cutululis, A. I. Bratcu, and E. Ceanga, *"Optimization of variable speed wind power systems based on a LQG approach"*, Control Eng. Pract., Vol. 13 (2005), 903–912.

[13] F. D. Bianchi, R. J.Mantz, and C.F.Christiansen, *"Control of variable speed wind turbines by LPV gain scheduling"*, Wind Energy, Vol. 7(2004), 1–8.

[14] E. A. Bossanyi, *"The design of closed loop controllers for wind turbines"*, Wind Energy, Vol. 3(2000), 149–163.

[15] Brice Beltran, Mohamed El Hachemi Benbouzid, and Tarek Ahmed-Ali, *"Second-Order Sliding Mode Control of a Doubly Fed Induction Generator Driven Wind Turbine"*, IEEE Transactions on Energy Conversion, Vol. 27(2012), 261-269.

[16] Esmaeil Rezaei, Ahmadreza Tabesh, and Mohammad Ebrahimi *"Dynamic Model and Control of DFIG Wind Energy Systems Based on Power Transfer Matrix"*, IEEE Transactions on Power Delivery, Vol. 27(2012) 1485-1493.

[17] Jun Yao, Hui Li, Zhe Chen et al, *"Enhanced Control of a DFIG-Based Wind-Power Generation System With Series Grid-Side Converter Under Unbalanced Grid Voltage Conditions"* IEEE Transactions on Power Electronics Vol. 28(2013), 3167 – 3181.

[18] M. Soliman, O.P. Malik, D.T. Westwick, *"Multiple model Mulitple output predictive control for variable speed variable pitch wind energy conversion systems"*, IET Renewable Power Generation, Vol.5 (2011), 124-136, 2011.

[19] M. Vijayalaxmi, Dr. N. Shanmuga Vadivoo, "Application of Classical Controllers in the Doubly Fed Induction Generator Based Wind Energy Conversion System Using System Identification Approach", International Review of Electrical Engineering, Vol. 9 (2014), 431-439.

[20] Zulfatman and M. F. Rahmat, *"Application of Self-Tuning Fuzzy PID Controller on Industrial Hydraulic Actuator Using System Identification Approach"*, International Journal on Smart Sensing and Intelligent Systems, Vol. 2, (2009), 246-261.

[21] K.J. Astrom, T. Hagglund, *"The future of PID control"*, Control Engineering Practice, Vol. 9 (2001), 1163–1175.

[22] Zhijun Sun, Rentao Xing, Chunsheng Zhao, Weiqing Huang, "*Fuzzy auto-tuning PID control of multiple joint robot driven by ultrasonic motors*" Ultrasonics Vol. 46, (2007), 303–312.

[23] Ahmed Medjber, Abderrezak Guessoum, Hocine Belmili, Adel Mellit, "*New neural network and fuzzy logic controllers to monitor maximum power for wind energy conversion system*" Energy Vol. 106 (2016), 137-146.

[24] James Carvajal, Guanrong Chen, HalukOgmen, "*Fuzzy PID controller: Design, performance evaluation, and stability analysis*" Information Sciences, Vol. 123 (2000), 249–270.

[25] A. Noriega Ponce, A. Aguado Behar, A. Ordaz Hernández, V. Rauch Sitar, "*Neural Networks for Self-tuning Control Systems*", Acta Polytechnica Vol. 44 (2004),

[26] Laurene V. Fausett, "*Fundamentals of Neural Networks: Architectures, Algorithms and Applications*", Pearson Education India, 2006.

[27] Payam Solatian, Seyed Hamidreza Abbasi, Fereidoon Shabaninia, " *Simulation Study of Flow Control Based On PID ANFIS Controller for Non-Linear Process Plants*", American Journal of Intelligent Systems, Vol. 2 (2012), 104-110.

[28] G. Shahgholian and A. Movahedi, "*Modeling and Controller Design Using ANFIS Method for Non-Linear Liquid Level System*", International Journal of Information and Electronics Engineering, Vol. 1 (2011),

[29] T.P.Mote, Dr.S.D.Lokhande, "*Temperature Control System Using ANFIS*", International Journal of Soft Computing and Engineering, Vol.2, (2012).