An Advanced Neuro-Fuzzy Tuned PID Controller for Pitch Control of Horizontal Axis Wind Turbines

Sachin Goyal[1†], **Vinay Kumar Deolia**[1], and **Sanjay Agrawal**[2], Non-members

ABSTRACT

Modern power systems comprise a variety of generating systems, including conventional thermal power stations and advanced renewable generating sources, one contender being a wind energy conversion system (WECS). Blade pitch control is an important part of the highly non-linear WECS. Many control strategies have been proposed by researchers around the globe. Current research work focuses on developing a control structure for a non-linear pitch control system using an advanced neuro-fuzzy tuned PID (NF-PID) controller. This approach utilizes the simplicity of a PID controller and the power of a soft computing technique like neuro-fuzzy to handle non-linearity. The model in this study is developed on the MATLAB Simulink platform and the obtained simulation results satisfy the requirements of constant output power even if the wind speed input changes abruptly.

Keywords: Wind Turbine Control, Pitch Controller, Neuro-Fuzzy Proportional Integral Differential Controller, Adaptive Neuro-Fuzzy Inference System, Wind Energy Conversion System, Permanent Magnet Synchronous Generator

1. INTRODUCTION

The continuous availability of resources is an important part of human existence and current supplies are not enough to meet the needs of future generations [1]. Therefore, researchers and scientists worldwide are striving for an alternate energy source and see wind power as a probable solution. This pattern is expected to rise in the next few years, along with increased capacities and larger wind turbines (WTs), owing to environmental concerns and the continuing quest for energy efficiency. Such devices develop from simplistic structures into complicated systems, built into large facilities known as "wind farms," with multi-MW power generation modules. The design of current wind turbine control systems is essential for ensuring the health and reliability of advanced wind turbine conversion systems and their efficient operation. Wind energy is connected to many technological fields, including aviation, electronics, and electrical engineering. According to the newest reports from the World Wind Energy Association (WWEA) 2018, China is the frontrunner with more than 216 GW of installed wind power capacity, adding only another 52 GW in 2019 [2], followed by the USA (96 GW) and Germany (59 GW) [3]. India added a total of 20 150 MW wind power installed capacity over a period of five years from 2013–2018 with a growth rate of 82% against global growth of 77% for the same period, becoming the fourth largest country for global installed wind power capacity equating to 36 625 MW [4]. Annual growth in globally installed wind power capacity and the trends of major contributors are presented in Fig. 1, while Fig. 2 shows their percentage contributions in 2020 [3, 5]. According

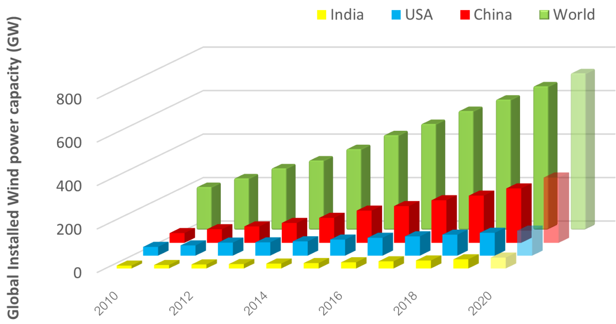

***Fig. 1**: Annual global installed wind power capacity of major nations.*

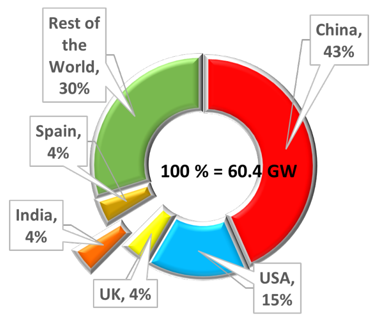

***Fig. 2**: Added capacity in 2019 and the share provided by the top five countries.*

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[1]The authors are with the G.L.A. University, Mathura, India.
[2]The author is with the School of Engineering and Technology, Indira Gandhi National Open University (IGNOU), New Delhi, India.
[†]Corresponding author: sachin.goyal@gla.ac.in

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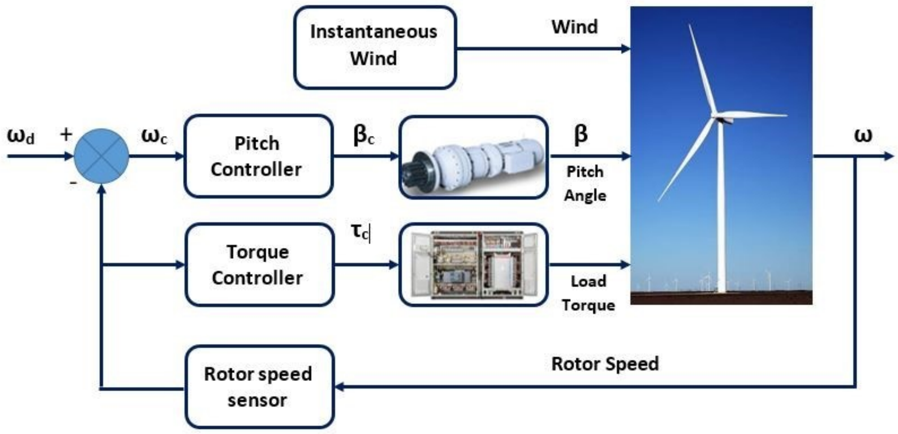


Fig. 3*: General structure of a pitch controller for a variable speed WT.*

to the GWEC 2016 report, India has the potential for around 302 GW of wind power at a height of 100 m AGL [6].

Over time, the scale and ability of wind turbines has increased tremendously, especially in the field of variable speed wind turbines (VSWTs). In addition, numerous wind turbine control techniques have been built and evaluated. Indeed, regarding continuous wind turbine systems (CSWTs), the VSWT wind power conversion method has some advantages and hence is the key competitor in the commercial wind turbine industry for two reasons. Firstly, the VSWT is more power-efficient than CSWT, generating around 10% more power annually, as opposed to constant speed wind turbines. Secondly, a VSWT can be smoothly controlled with modern control techniques [7]. A general structural diagram of a pitch-controlled VSWT is shown in Fig. 3.

Regulating the electrical power output of a wind turbine is the main task for a pitch control system in the above-rated wind speed regime. Torque control is another parameter of interest, generally executed at below-rated wind speeds to extract maximum power through the wind turbine. Output power regulation is achieved by adjusting the angle of attack from the wind over the turbine blades. The pitch angle control is a prominent method for regulating output torque and widely used. Here, the pitch angles of turbine blades are turned in or out according to the wind speed profile. The pitch angle controller is designed in two ways. In individual pitch control (IPC) systems, the pitch angle of each blade is separately scrutinized and controlled [8], while the collective pitch control strategy is employed to control the angle of all blades by the same amount [9]. The pitch controller is beneficial for controlling the power output at optimum levels and minimizing aerodynamic loads at strong wind speeds [10].

2. AERODYNAMIC CHARACTERISTICS OF A WIND TURBINE

In 1887, the very first wind turbine for the generation of electricity was built in Scotland by Prof. James Blyth. It was a 10 m high wind turbine, primarily designed for charging the batteries and accumulators.

2.1 Wind Power

A wind turbine transfers the kinetic energy available in the wind into the rotor of a generator through a gear mechanism also known as a transmission system. The kinetic energy (U) in the blowing wind is given by Eq. (1).

$$U = \frac{1}{2}(\rho A) V_w^3 t \tag{1}$$

where ρ is the density of air (in kg/m^3), A is the area of cross section offered by the wind turbine (or the swept area of the WT blades); V_w is the wind velocity (in m/s) and t is time (in s). The whole amount of this energy cannot be extracted, since only a fraction is available for extraction by the wind turbine. This constraint is also known as the Betz's limit. The power coefficient (C_p) is generally used to represent the fraction of power available as mechanical output from the wind turbine. The C_p is an empirical function of the tip speed ratio (λ) and blade pitch angle (β) as given in Eq. (2), while the tip speed ratio (TSR) of the wind turbine is defined as the speed ratio of the blade tip to the wind speed, as given in Eq. (3).

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} + C_3\beta + C_4\right)\exp\left\{\frac{C_5}{\lambda_i}\right\} + C_6\lambda \tag{2}$$

$$\lambda = \frac{\omega_r \cdot R}{V_w} \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + l_1\beta} - \frac{l_2}{\beta^3 + 1} \tag{4}$$

where ω_r is the turbine rotor speed, R is the radius of the swept area of the WT, C_1 to C_6 and l_1 to l_2 are constants

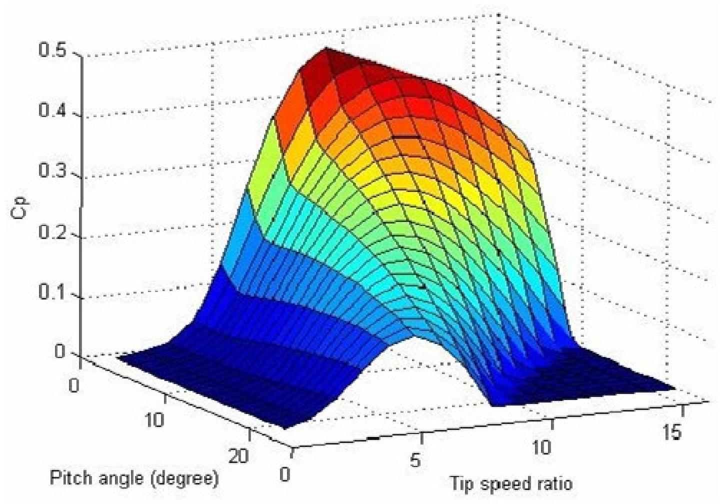


***Fig. 4**: Relationship between the power coefficient (C_p), pitch angle, and tip speed ratio.*

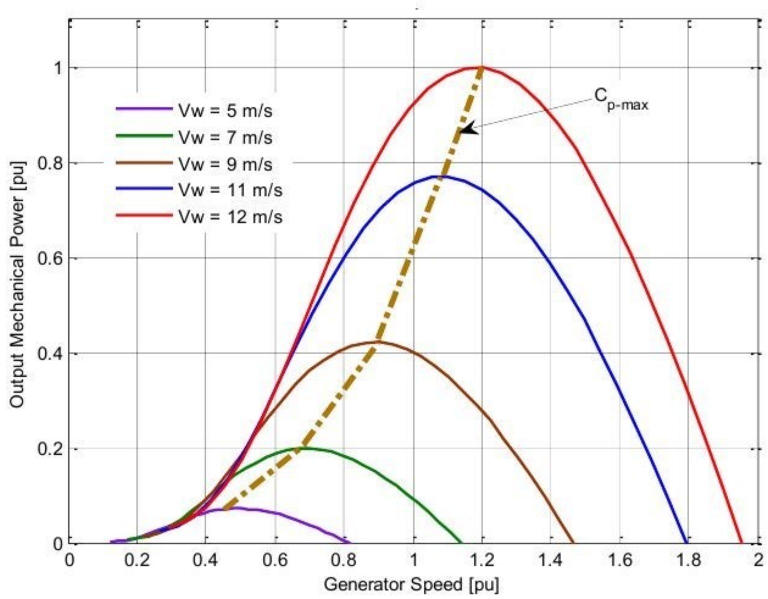


***Fig. 5**: Generator speed versus mechanical power characteristics of the horizontal axis wind turbine (HAWT).*

(C_1 = 0.52, C_2 = 116, C_3 = −0.4, C_4 = −5, C_5 = −21, C_6 = 0.0068, l_1 = 0.08, and l_2 = 0.035) [11].

2.2 Wind Turbine Characteristics

This section discusses the various characteristics associated with the wind turbine system. Fig. 4 presents a three-dimensional surface diagram involving the C_p, blade pitch angle (β) and TSR (λ). The optimum value of TSR (λ_{opt}) corresponding to the maximum value of the C_p (C_{pmax}) is helpful in determining the required pitch angle (β_{opt}). Any change in wind speed or wind turbine rotor updates the tip speed ratio and corresponding C_p for a fixed value of the pitch angle and this, in turn, changes the WT power output.

Fig. 5 shows that the mechanical power delivered by the wind turbine blades depends upon their rotational speed and the generated power reaching its maxima, corresponding to a particular rotor speed for various wind speeds.

Wind power shares a highly non-linear relationship with wind speed (V_w), as discussed in Eq. (1). Therefore, the characteristics of wind power versus wind speed can be divided into four zones: a) dead zone, b) MPPT zone, c) pitch control zone, and d) stalled zone, as presented in Fig. 6. The dead zone extends from 0 m/s wind speed to a cut in speed, while the MPPT zone is also known as the sub-synchronous speed zone with the pitch angle being $\beta = 0$ degrees to enable the turbine to extract the maximum possible power available from the wind. In the third zone, where the wind speed is above the rated value, the extra power is shredded off using the pitch control mechanism. Finally, in the fourth zone, the wind turbine

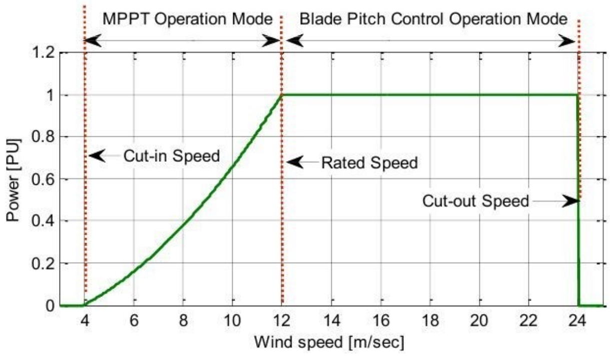


Fig. 6: *Regions operating wind turbines.*

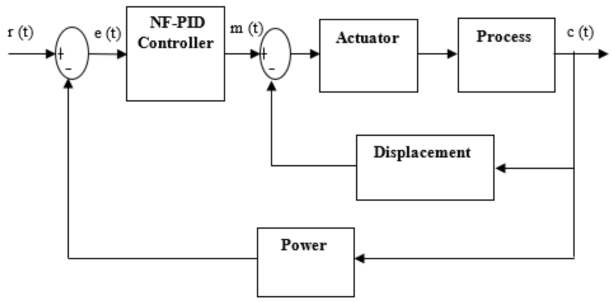


Fig. 7: *Closed-loop F-PID pitch control system.*

is protected from the mechanical stress caused by very high wind speeds by tilting the blade pitch angle to 90 degrees.

3. PITCH CONTROL METHODOLOGY

This research article focuses on developing a pitch angle controller for a horizontal axis wind turbine using the most sophisticated three-element PID controller. The PID gains are updated using an adaptive neuro-fuzzy model. Firstly, a PID controller is developed and its gains then updated using a fuzzy logic controller according to the parameter tuning algorithm. Finally, the fuzzy inference system (FIS) structure, as the heart of the fuzzy logic controller, is replaced by the FIS obtained from the ANFIS model.

3.1 PID Controller

Due to its basic configuration and high robustness, a three-element controller or simple proportional, integral and differential (PID) controllers are perhaps the most commonly used industrial devices [9]. The PID control action comprises a linear combination of additive, integral, and differential effects of the error signal as given in Eq. (5).

$$m(t) = k_p e(t) + k_i \int_0^T e(t)\,dt + k_d \frac{de(t)}{dt} \tag{5}$$

The performance of the control loop is largely dependent upon the values of gain parameter k_p, k_i, and k_d. To improve the control effect, the values of gain parameters are updated by the fuzzy logic controller.

The proportional component develops a control effect in direct proportion to the input into the controller $e(t)$, instantly impacting the performance. From the stability perspective, the steady state error reduces and the control performance improves with a rise in the 'P' component. The main drawback is that the steady state bias cannot be entirely removed. The machine experiences massive overshoots and becomes more oscillatory with relatively high k_p values. The system can even become unstable in certain extreme situations.

The integral effect is a powerful approach for removing the steady state error entirely, in contrast to the proportional controller, but the integral component inserts an additional pole into system transfer function and any improper design may lead the system to become unstable. The derivative control primarily affects the transient response of the system in relation to speed and stability but has no effect on its steady state behavior. A derivative controller is equivalent to an HPF filter and requires the proper selection of parameter k_d.

Fig. 7 shows a closed-loop F-PID system for pitch control.

3.2 Fuzzy Logic Controller

A fuzzy logic controller (FLC) is primarily developed using the fuzzy set theory, based on the non-crisp boundary approach. It has been proven to successfully handle the system's non-linearity. The fuzzy set theory consists of three stages: a) fuzzification, b) rules inference, and c) defuzzification [12]. A fuzzy logic controller is developed here to update the value of PID gain parameters (k_p, k_i, and k_d) according to the following expressions given in Eq. (6) [13, 14].

3.3 Updating Algorithm for PID Gains

The PID gain parameters are updated in real time every second. The change in gains, i.e., Δk_p, Δk_i, and Δk_d are given as:

$$\begin{aligned} \Delta k_p &= \frac{K_p(n+1) - K_p(n)}{K_p(n)} \\ \Delta k_i &= \frac{K_i(n+1) - K_i(n)}{K_i(n)} \\ \Delta k_d &= \frac{K_d(n+1) - K_d(n)}{K_d(n)} \end{aligned} \tag{6}$$

These gains in a conventional PID controller are fixed but in this research work, the parameters are updated using a fuzzy tuner structure [15]. Initial values are selected randomly, generally as unity which is recursively updated by the FLC structure. In this work, the error in blade pitch angle and rate of change in error

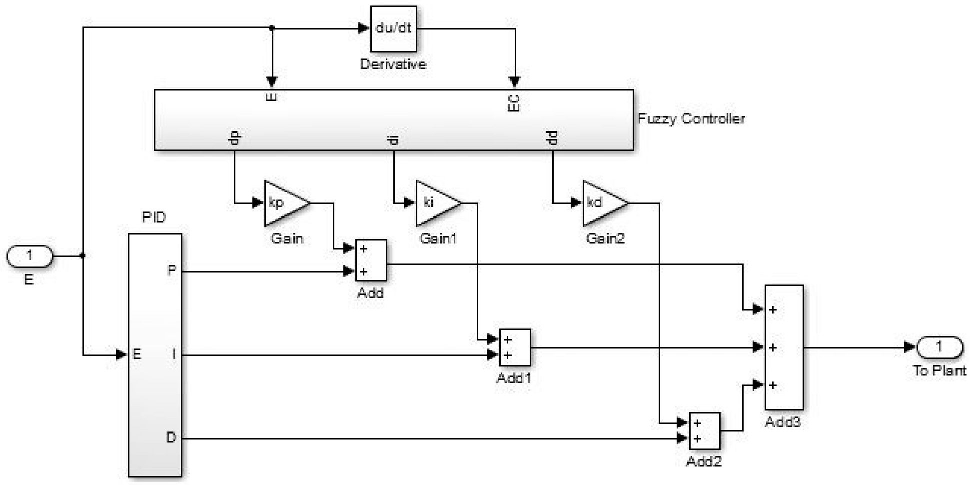


Fig. 8: *Fuzzy tuned PID controller.*

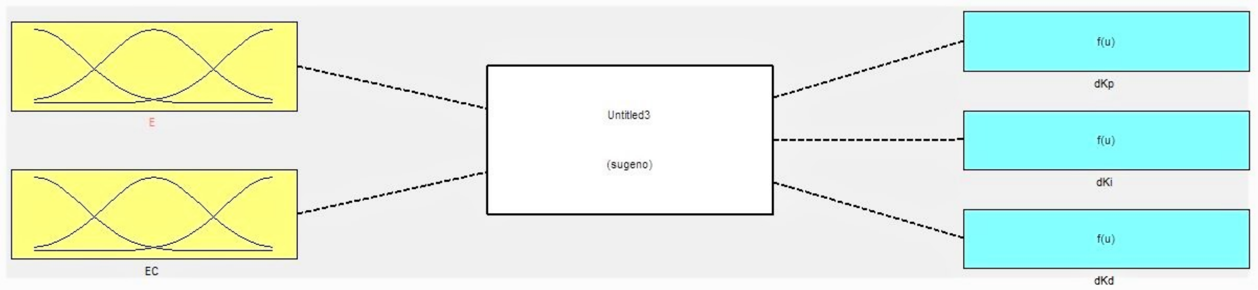


Fig. 9: *Layout of the ANFIS model.*

are selected as the two inputs for the FLC and three outputs, i.e., changes in PID gain parameters are obtained from the FLC. Fig. 8 shows the operation of the FLC [16].

The aerodynamically developed torque of a WT with a variable pitch and speed is affected by a change in the blade pitch angle. To maintain the output power from the DFIG generator at rated power levels, the C_p is updated as per the PID gains, adjusted using fuzzy tuner. The electromechanical torque (T_m) is selected as the output parameter of the WT to drive the doubly-fed induction generator [11].

3.4 Design of ANFIS

The ANFIS structure for the proposed fuzzy tuned PID controller is developed as shown in Fig. 9. The ANFIS model generates a fuzzy inference structure which is used as the FIS for the FLC. To train the ANFIS model, seven linguistic variables for membership functions in the discourse of [−1 to 1] are selected, namely N3, N2, N1, ZE, P1, P2, and P3 for inputs E and EC while three membership functions are selected for outputs (i.e., Δk_p, Δk_i, and Δk_d), namely T, M, and B). The linguistic variables are Gaussian membership functions devised in a total of 49 fuzzy rules [12]. The fuzzy rule base contains a first-order set of IF-THEN Sugeno-type rules where each output is the average weighted sum of all inputs plus a bias.

$$\begin{aligned} &\text{IF 'E' is } A_i, \text{ and 'EC' is } B_i, \\ &\text{THEN } \mu_e = g_i\text{E} + h_i\text{EC} + b_i \end{aligned} \tag{7}$$

Tables 1–3 present the fuzzy rule, while Fig. 10 shows the rule surface for all three outputs [17].

3.5 Training and Testing of ANFIS

Firstly, the inputs to the FLC, namely E and EC along with the corresponding changes in gain parameters i.e., Δk_p, Δk_i, and Δk_d, are observed using a conventional F-PID controller only. The results obtained are used as the training data for the ANFIS and FIS, regenerated from the ANFIS for use as new fuzzy inferences for the F-PID controller [18]. The system is tested for another set of inputs and the results validated. Fig. 11 shows the proposed ANFIS with the following parameters:

name:	ANFIS1
type:	sugeno
andMethod:	prod
orMethod:	probor
defuzzMethod:	wtaver

***Table 1**: Fuzzy rules for Δk_p.*

E \ EC	N3	N2	N1	ZE	P1	P2	P3
N3	T	T	T	T	T	M	M
N2	T	T	T	T	T	M	B
N1	T	T	T	T	M	B	B
ZE	T	T	T	M	B	B	B
P1	T	T	M	B	B	B	B
P2	T	M	B	B	B	B	B
P3	M	M	B	B	B	B	B

***Table 2**: Fuzzy rules for Δk_i.*

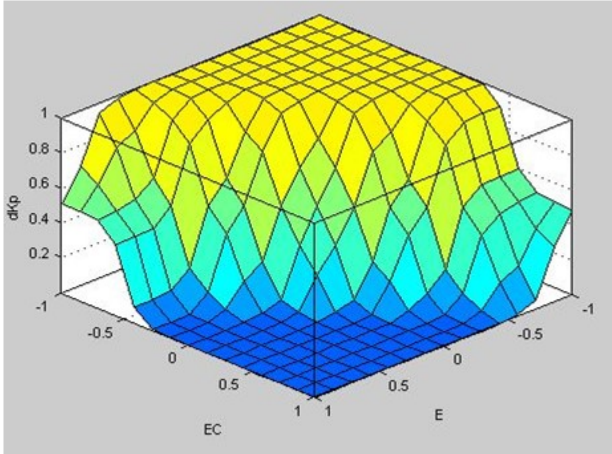
E \ EC	N3	N2	N1	ZE	P1	P2	P3
N3	B	B	B	B	B	M	M
N2	B	B	B	B	B	M	M
N1	B	B	B	B	M	T	T
ZE	B	B	B	M	T	T	T
P1	B	B	M	T	T	T	T
P2	M	M	T	T	T	T	T
P3	M	M	T	T	T	T	T

***Table 3**: Fuzzy rules for Δk_d.*

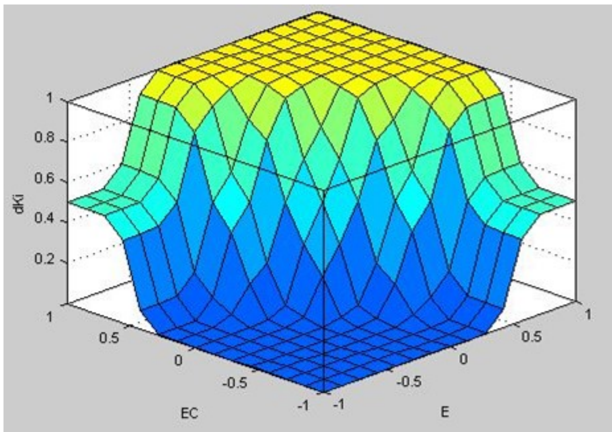
E \ EC	N3	N2	N1	ZE	P1	P2	P3
N3	T	B	B	B	B	B	T
N2	T	B	B	B	B	B	M
N1	M	B	B	B	B	B	M
ZE	M	B	B	B	B	B	M
P1	M	M	M	M	M	M	M
P2	T	B	T	T	T	T	T
P3	T	T	T	T	T	T	T

***Table 4**: Wind turbine and generator parameters.*

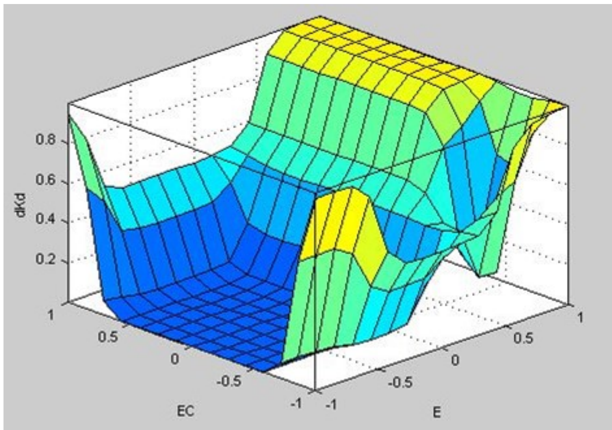
Rated Wind Speed	9 m/s
Rated Output Power	1.5 MW
Gear Box Ratio	6
Frequency	60 Hz
Voltage	575 V



(a) dKp



(b) dKi



(c) dKd

***Fig. 10**: Rule surface for FLC outputs (a) dKp, (b) dKi, and (c) dKd.*

4. SIMULATION AND RESULTS

The simulation of the model is developed in the MATLAB/Simulink environment. Fig. 12 shows the conventional PID controller, while a fuzzy tuned PID controller is shown in Fig. 8.

Test simulation is performed on an asynchronous generator with the turbine and generator parameters as presented in Table 4, while the Simulink model is shown in Fig. 13.

Fig. 14 shows the wind speed profile while Figs. 15(a) and (b) present a comparison between the performance of conventional PID and the neuro-fuzzy tuned PID controller in terms of generator rotor speed and corresponding pitch angle. However, Fig. 16 presents a comparison of the power generated by the two controllers. A comparative study between the PID controller and neuro-fuzzy tuned PID controller when subjected to a unit step test input is presented in Table 5.

***Table 5**: Comparison between unit step response specifications.*

	Rise Time; tr (s)	Overshoot; Mp (%)	Peak Time; tp (s)	Settling Time; ts (s)	Error (%)
Untuned PID	2.15	45.20	4.32	21.3	2.328
NF-tuned PID	2.82	6.80	4.92	7.86	1.368

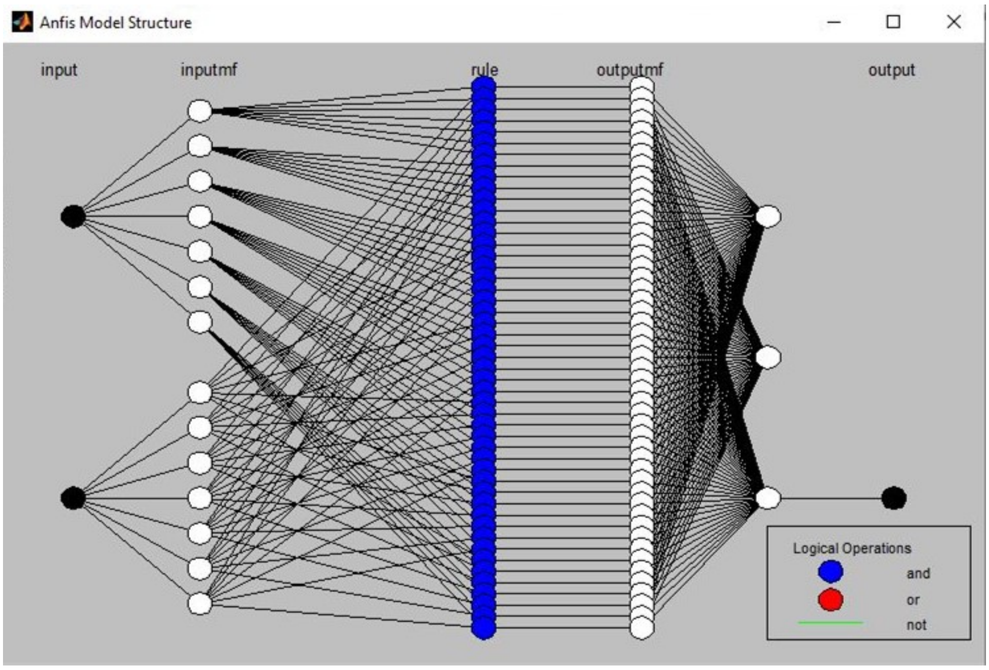


***Fig. 11**: Architecture of the ANFIS controller.*

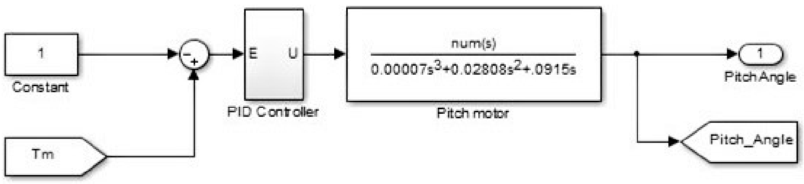


***Fig. 12**: Conventional PID controller.*

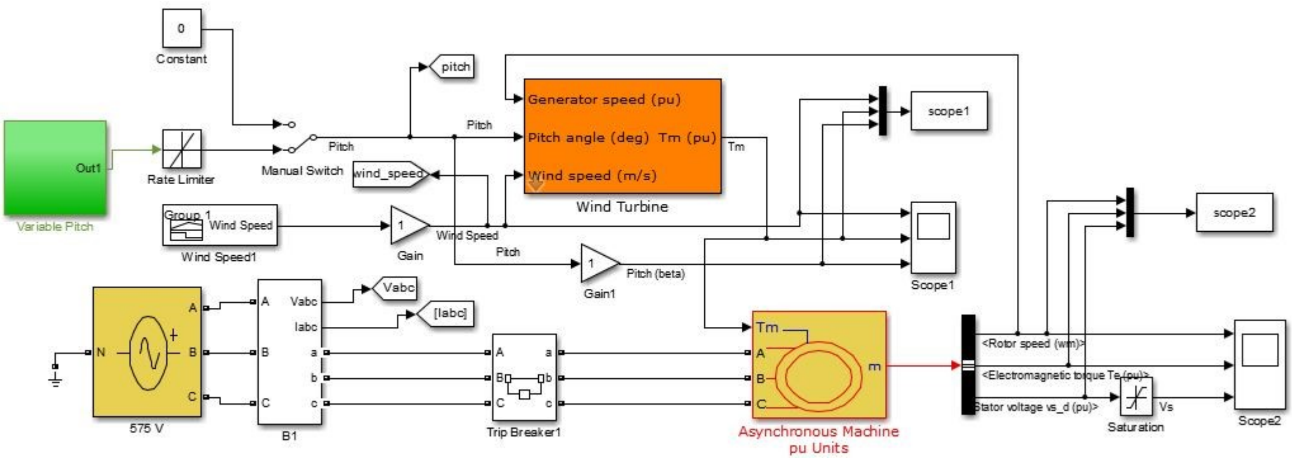


***Fig. 13**: A neuro-fuzzy tuned PID pitch controller for a WECS.*

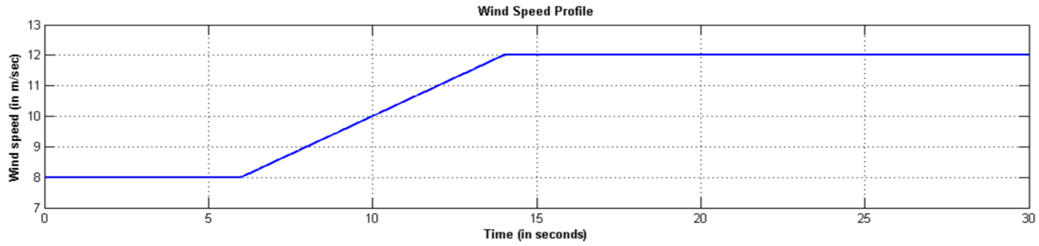
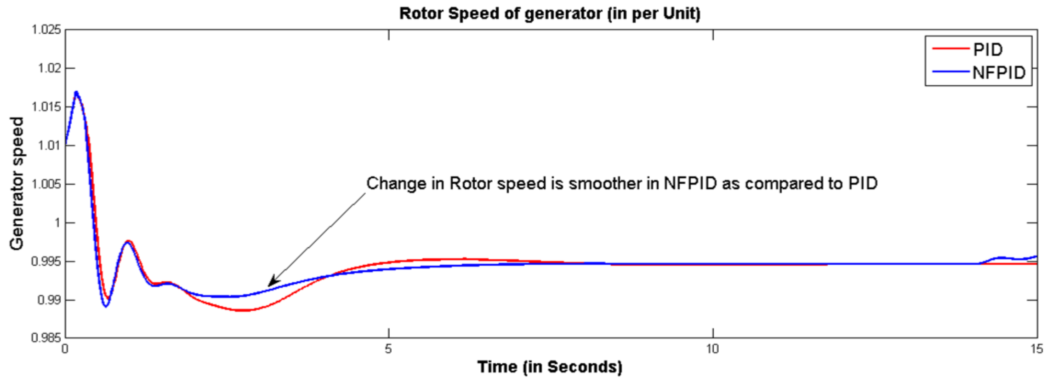
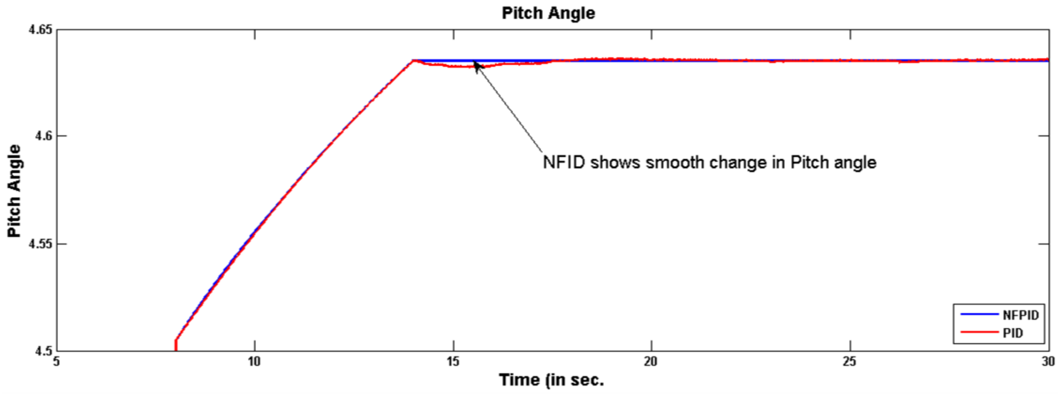


Fig. 14*: Wind speed profile.*



(a) Generator rotor speed



(b) Pitch angle

Fig. 15*: Performance comparison between conventional PID and neuro-fuzzy tuned PID: (a) generator rotor speed and (b) pitch angle.*

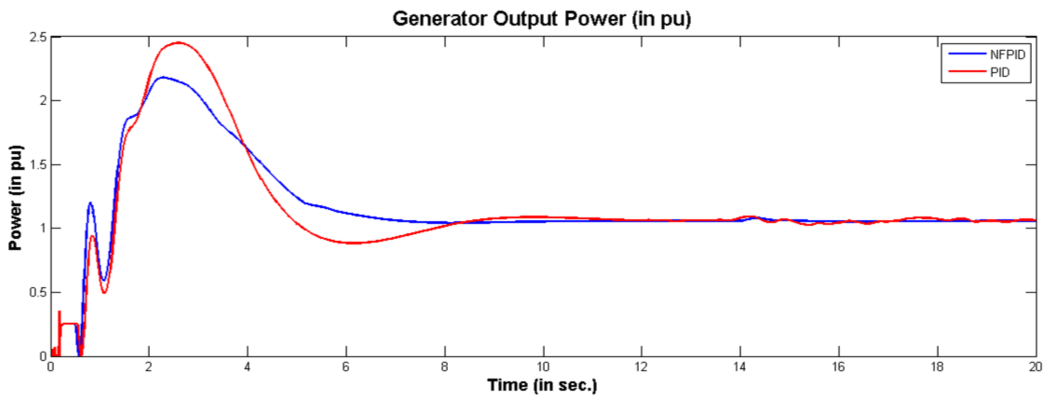


Fig. 16*: Generator output power comparison between conventional PID and neuro-fuzzy tuned PID.*

5. CONCLUSION

In this study, a neuro-fuzzy tuned PID (NF-PID) controller is developed for pitch control applications in VSWT to smoothen the output power in the above-rated wind speed region. As the wind speed varies, the pitch control action quickly responds and maintains the output power at the rated levels. The simulation results also validate that the output power swing is within safe limits when controlled by the NF-PID pitch controller and substantiate that the performance of an NF-PID controller is better than a conventional PID controller.

REFERENCES

[1] I. Yadav, S. K. Maurya, and G. K. Gupta, "A literature review on industrially accepted MPPT techniques for solar PV system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 2, pp. 2117–2127, Apr. 2020.

[2] "Worldwide wind capacity reaches 744 gigawatts – an unprecedented 93 gigawatts added in 2020," Mar. 2021, World Wind Energy Association. http://wwindea.org/worldwide-wind-capacity-reaches-744-gigawatts (accessed Nov. 5, 2021).

[3] "Wind power capacity worldwide reaches 597 GW, 50,1 GW added in 2018," Jun. 2019, World Wind Energy Association. https://wwindea.org/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/ (accessed Nov. 5, 2021).

[4] "Wind power in india." Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Wind_power_in_India (accessed Jan. 2, 2020).

[5] "World wind energy report 2011," World Wind Energy Association, Bonn, Germany, Tech. Rep., May 2012. [Online]. Available: http://www.wwindea.org/webimages/WorldWindEnergyReport2011.pdf

[6] "Indian Wind Energy – A Brief Outlook," Global Wind Energy Council, Brussels, Belgium, Summary Report, 2016. [Online]. Available: https://www.gwec.net/wp-content/uploads/vip/GWEC_IWEO_2016_LR.pdf

[7] P. W. Carlin, A. S. Laxson, and E. B. Muljadi, "The history and state of the art of variable-speed wind turbine technology," National Renewable Energy Laboratory, Colorado, USA, Tech. Rep. NREL/TP-500-28607, Feb. 2001.

[8] E. A. Bossanyi, "Individual blade pitch control for load reduction," *Wind Energy*, vol. 6, no. 2, pp. 119–128, 2003.

[9] X. Gang, "Research on application of fuzzy PID in collective pitch control system," in *2011 International Conference on Control, Automation and Systems Engineering (CASE)*, 2011.

[10] S. Behera and S. Sahoo, "Design of a pitch controller for a wind turbine using hybrid mean-variance mapping optimization," *ECTI Transactions on Electrical Engineering, Electronics, and Communications*, vol. 19, no. 3, pp. 298–311, Oct. 2021.

[11] V. Akhmatov, "Variable-speed wind turbines with doubly-fed induction generators," *Wind Engineering*, vol. 26, no. 2, pp. 85–108, Mar. 2002.

[12] S. Sahoo, B. Subudhi, and G. Panda, "Pitch angle control for variable speed wind turbine using fuzzy logic," in *2016 International Conference on Information Technology (ICIT)*, 2016, pp. 28–32.

[13] D. K. Sahoo, R. K. Sahu, and S. Panda, "Fractional order fuzzy PID controller for automatic generation control of power systems," *ECTI Transactions on Electrical Engineering, Electronics, and Communications*, vol. 19, no. 1, pp. 71–82, Feb. 2021.

[14] K. A. Naik and C. P. Gupta, "Fuzzy logic based pitch angle controller/or SCIG based wind energy system," in *2017 Recent Developments in Control, Automation & Power Engineering (RDCAPE)*, 2017, pp. 60–65.

[15] M. M. M. Ali, A.-R. Youssef, G. Abdel-Gaber, and A. S. Ali, "Adaptive fuzzy-PID based pitch angle control of wind turbine," in *2018 Twentieth International Middle East Power Systems Conference (MEPCON)*, 2018, pp. 1110–1114.

[16] J. Huang, H. Jia, and G. Cheng, "Fuzzy-PI and fuzzy feedforward compound control of variable pitch system," in *2017 36th Chinese Control Conference (CCC)*, 2017, pp. 4251–4254.

[17] M. H. Mughal and L. Guojie, "Review of pitch control for variable speed wind turbine," in *2015 IEEE 12th Intl Conf on Ubiquitous Intelligence and Computing and 2015 IEEE 12th Intl Conf on Autonomic and Trusted Computing and 2015 IEEE 15th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom)*, 2015, pp. 738–744.

[18] D. Yadav and A. Verma, "Behaviour analysis of PMSM drive using ANFIS based PID speed controller," in *2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, 2018.

Sachin Goyal received his B. Tech. from the UP Technical University, India, in 2008, and his M.E. from the Punjab Engineering College Chandigarh, India, in 2013. He is currently working as an Assistant Professor and also pursuing his Ph.D. in the Department of Electrical Engineering, GLA University, Mathura, India. His research interest includes control, renewable energy, wind energy conversion system, pitch control system, soft computing, and integration of Solar Wind systems.

Vinay Kumar Deolia is working as a professor and is Head of the Department of Electronics and Communication Engineering, Institute of Engineering and Technology, GLA University, Mathura, India. He completed his Ph.D. in Back-stepping control from NIT, Allahabad, India. His areas of interest include non-linear control systems, IDMA, power electronics converter control, and other recent trends in technology. He has more than 20 years of experience in teaching and research.

Sanjay Agrawal received his B.Tech. from MMM Gorakhpur, India, his M.Tech. from UP technical University Lucknow, India, and his Ph.D. from IIT, Delhi, India. He was a Post-Doctoral Fellow SMERC, University of California, Los Angeles, CA, USA. Currently, he is working as a Professor at the Institute of Engineering and Technology, Indira Gandhi National Open University (IGNOU), India. His research interests are Solar photovoltaic systems, hybrid PV/T, CO2, Exergy analysis, and Carbon trading. He has published more than 75 research papers and attended many workshops in the area of renewable energy. He has worked on two sponsored projects, and has been invited as a guest for expert talk in various prestigious institutes. He has guided 10 post-graduate thesis and 4 Ph.D. theses, currently 6 more Ph.D. thesis are in progress. He is a professional member of Institution of Engineers and Institute of Electrical and Electronics Engineers.