

Design and Implementation of ANFIS Based Controller on Variable Speed Isolated Wind-Diesel Hybrid System for Better Performance

Aiman Khan*, Vivek Pahwa

Department of Electrical and Electronics Engineering, UIET, Panjab University, Chandigarh, India

*Corresponding author: aimankhan549@gmail.com

Abstract In this paper, a transient study on Isolated Wind-Diesel Hybrid System (IWDHS) of 200 kW has been carried out in MATLAB/SIMULINK environment. The detailed model of synchronous generator coupled to diesel engine, self-excited induction generator and load is studied and considered for analyzing the dynamic behavior of IWDHS. It has been taken into consideration that most of the time; the energy is to be provided by wind turbine in comparison to diesel generator. Instead of a fixed wind speed, the IWDHS is being supplied by variable wind speeds, that are more than its nominal value (10 m/s). This function is accomplished by using a conventional PI controller which regulates the pitch angle of the wind turbine blades during incoming varying gusts of wind. Further the system performance is improved by implementing an ANFIS controller. A controller design process is identified; it consists of generating input-output data pairs to identify the control variables range and initial fuzzy memberships, and then to tune or adapt them using an ANFIS network structure. The control objective was to extract maximum power at varying wind speeds and to limit the power as well as improve settling time at rated value at high wind speeds. The simulations have shown how advantageous an ANFIS based controller is over a conventional PI controller.

Keywords: IWDHS, ANFIS controller, self-excited induction generator, Diesel unit

Cite This Article: Aiman Khan, and Vivek Pahwa, "Design and Implementation of ANFIS Based Controller on Variable Speed Isolated Wind-Diesel Hybrid System for Better Performance." *American Journal of Electrical and Electronic Engineering*, vol. 5, no. 5 (2017): 172-178. doi: 10.12691/ajeec-5-5-2.

1. Introduction

The issues related to depletion of conventional sources of energy has led to the selection of non-conventional sources like wind, solar, biomass etc. where most of the developing nations and grid isolated areas rely heavily on them because of their abundance [1,2]. In recent years, there has been a growing interest in wind energy power systems because of the environmental benefits and the economic benefits of fuel savings. Wind energy is a clean, renewable energy source and offers many advantages like being an inexhaustible and cost efficient source of energy. Also, the continuity of supply is maintained in grid-isolated areas as the diesel units are connected in parallel with wind generation [3,4,5].

When a wind turbine remains connected to the grid during fault conditions, it may get damaged due to stress on rotor shaft caused by the electromagnetic torque oscillating at double the grid frequency [6,7].

Self-Excited Induction Generator (SEIG), being less expensive, robust, requiring low maintenance and better transient performance than its counterparts, makes it the most suited generator for wind turbine energy generation in remote grid isolated areas. A three phase induction machine is driven by a wind turbine which is operated in

self-excitation mode by connecting a capacitor bank parallel to its stator terminal [8,9,10]. A power system network comprising of two types of power generation: wind turbine generation and diesel generation is analyzed in [11]. The quality of power, the interaction of diesel generation, the wind turbine facing wind at a constant speed, and the local load were also examined. A diesel generator comprising of synchronous generator and diesel engine, keeping the balance of power supply on check whenever there is a load and wind speed change thereby leading to change in wind turbine generation are investigated in [12,13,14].

At high wind speeds, an unnecessary active power might be generated by wind turbine which may lead to consumption of more reactive power by the SEIG. In addition, an over speed of wind can cause more mechanical force to be applied on wind turbine which can cause damage to its parts. Therefore, the necessity of existence of an automatic controller arises.

This controller plays an important role during over rated wind speed by varying rotary position of the whole blades to regulate attack angle of wind to blades. Consequently, the overall aerodynamic force on turbine which is contingent to pitch angle can be controlled and hence speed of turbine can adjust.

Many different methods and control algorithms have been proposed in the recent years [15,16,17]. One of the

most common control procedures is to make use of a conventional PI control of output active and reactive power to expand dynamic behavior of wind turbine. But due to ambiguity about the exact model and behavior of some parameters such as wind, wind turbine, etc. and also parameter values differences during operation because of temperature, events or unpredictable wind speed, tuning of PI parameters is one of the main problems in this control method.

In this paper, the performance of IWDHS is analyzed using ANFIS control to generate a more consistent controller outputs and to considerably improve the response time of blades in the occurrence of change in wind speed. Also, tuning of parameters can be done more readily without the requirement of an exhaustive mathematical model of the system and just using the knowledge of the total operation.

2. Mathematical Modelling

E. Mujaldi *et al.* in [11] gave a comprehensive analysis of wind-diesel hybrid systems in grid isolated areas comprising of a fixed-speed wind turbine. [14] provided a method for pitch angle control during variable wind speed using a conventional PI controller on the same system. The IWDHS model presented in this paper is an extension of these two.

The modified single line diagram of IWDHS including an ANFIS based controller is shown in Figure 1. It comprises of a 480 V, 275 kVA SEIG driven by a prime mover i.e. wind turbine. A 75kVAR capacitor bank connected in parallel with the SEIG stator terminals which provide excitation. A 400 kW diesel generator [11] is required to preserve the balance of power supply. This hybrid power system is feeding a load of 150 hp and a local load of 200kW.

The IWDHS is composed of the following components:

1. Wind Turbine;
2. SEIG;
3. Diesel Generator;
4. Heavy Load;
5. ANFIS controller (Section III).

2.1. Wind Turbine

The mechanical output power is given as [18,19]

$$P_m = P_i(\alpha, \gamma) \frac{A \rho}{2} v_{wind}^3 \tag{1}$$

Where

- Mechanical output power = P_m (in Watts)
- Performance coefficient = P_i
- Air density = ρ (in kg per m3)
- Pitch angle of blades = γ (in degrees)
- Area swept by blades = A (in m2)
- Wind Speed = v_{wind} (in m per s)
- Tip speed ratio = α

The performance coefficient of wind turbine is:

$$P_i(\alpha, \gamma) = P_1 \left[\left(\frac{P_2}{\lambda} \right) - P_3 \gamma - P_4 \right] e^{-\frac{P_5}{\lambda}} + P_6 \alpha \tag{2}$$

Where

$$1/\lambda = (\alpha + 0.08\gamma)^{-1} - 0.035(1 + \gamma^3)^{-1}$$

And $P_1=0.50, P_2=116, P_3=0.40, P_4=5, P_5=21, P_6=0.0068$.

2.2. SEIG

The SEIG is driven by wind turbine while the shunt capacitor provides the necessary reactive power required for starting. The mathematical modelling of three-phase SEIG has not been discussed in detail as several papers have already been published [20,21,22,23].

2.3. Diesel Generator

The Diesel Generator comprises of a prime mover i.e. diesel engine and a synchronous generator. The diesel engine, consisting of a governor, maintains a constant rotor speed and hence a constant frequency, by delivering power at rated value.

On the other hand, the synchronous generator along with the exciter provides an output voltage control that is affected by the field winding time constant, the DC power supplied to field windings and its response [24].

Since the wind speed and load by no means remains constant, as a result, frequency and its voltage will not remain constant under transient conditions. Consequently the diesel generator will follow change in wind speeds and loads. [25]

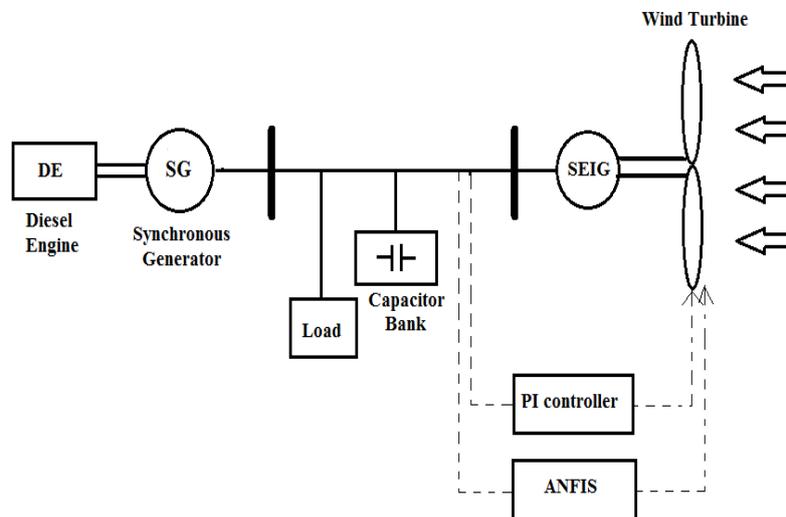


Figure 1. Modified single line diagram of IWDHS with conventional PI and ANFIS based controller

3. ANFIS Design

An Adaptive Neuro Fuzzy Inference System (ANFIS) based controller has been designed and the system is examined in terms of the power generation and consumption.

An architecture and learning algorithms was proposed by Jang in 1993 which is combination of fuzzy logic with neural networks for drawing inference [26]. The adaptive-network-based fuzzy inference system performs mapping of input data using input membership functions (MFs) with its associated parameters, and then through output MFs to generate outputs. Human expert knowledge about the target system to be modelled is used to calculate initial

membership function and rules for the fuzzy inference system. The fuzzy if-then rules and membership functions to illustrate the input-output behavior of a complex system is then refined by ANFIS [27]. Multi-layer adaptive network-based fuzzy inference architecture involves a total of five layers to implement different node functions in order to learn and tune parameters in a FIS using a hybrid learning mode. The hybrid learning algorithm allows identification of parameters of a Sugeno-type fuzzy inference system. The training of FIS membership function parameters to follow a given training data set are done by applying a combination of the least-squares method and the back-propagation gradient descent method.

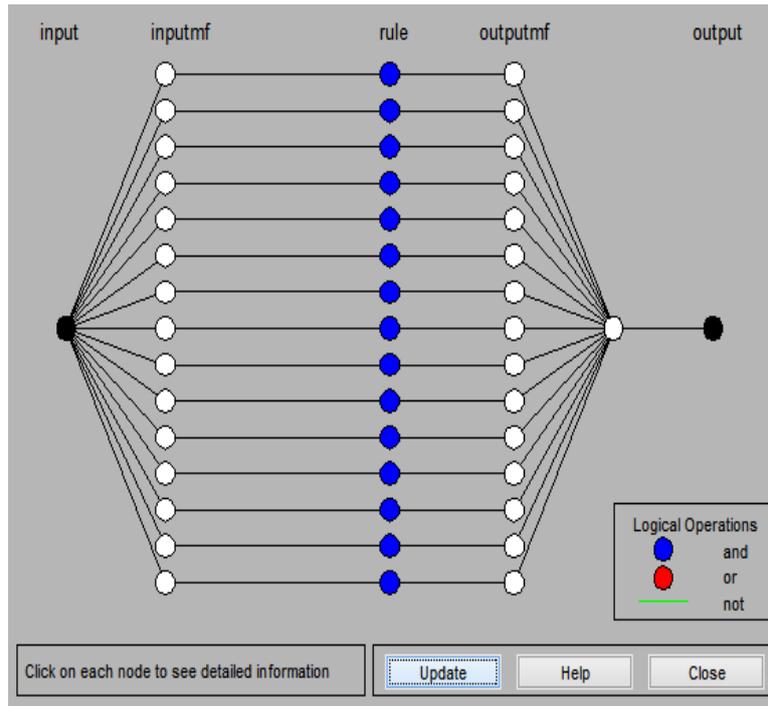


Figure 2. ANFIS model structure of the trained data

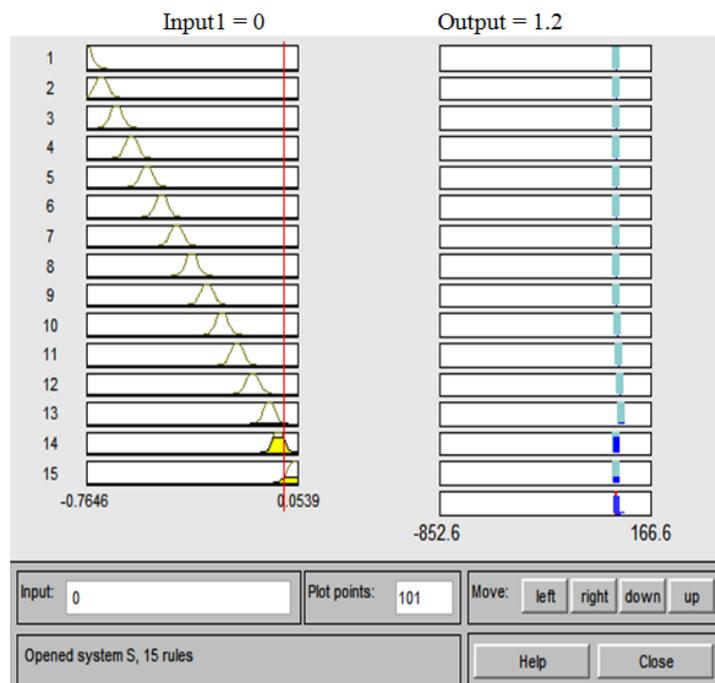


Figure 3. Rule Viewer displaying membership function rules for the trained data

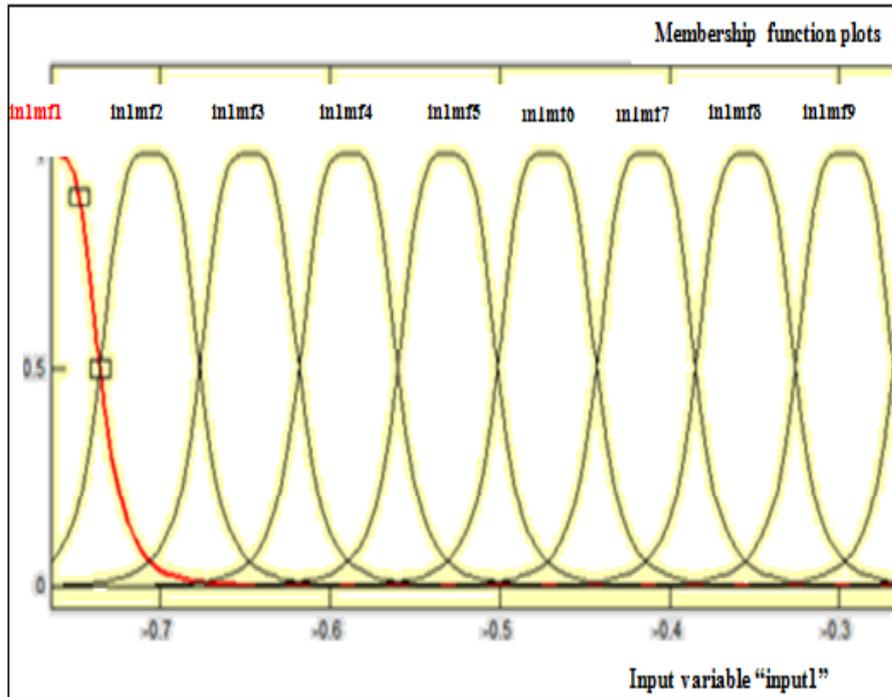


Figure 4. Membership Function Plots displaying the Generalized Bell Curves

One can create, train, and test Sugeno-type fuzzy systems using the ANFIS Editor GUI in MATLAB environment.

To start the GUI, type the following command at the MATLAB prompt:
`anfisedit`

The ANFIS Editor GUI window includes four distinct areas to support a typical workflow. The GUI accomplishes the subsequent tasks:

- i. Loading, Plotting, and Clearing the Data
- ii. Generating or Loading the Initial FIS Structure
- iii. Training the FIS
- iv. Validating the Trained FIS

Firstly, data from IWDHS with conventional PI controller ($K_p = 5$ and $K_i = 25$) is taken and loaded into the ANFIS editor toolbox. From there, an FIS structure is developed by choosing a suitable input and output membership function. This is followed by training the FIS repeatedly until desired results are obtained. The trained data taken from conventional PI controller is then loaded in ANFIS editor toolbox and another simulation is run. The corresponding membership functions, network structure, its plot and rules are given in Figure 2.

Figure 2 shows the network structure of ANFIS model developed for this system. This network structure is composed of a set of units arranged into five interconnected network layers. Layer 1 consists of input variable (P_{mech}), Layer 2 checks the weight of each membership function, Layer 3 performs the precondition matching of the fuzzy rules, Layer 4 provides the output resulting from the inference of rules and Layer 5 sums up all the incoming from Layer 4 and transfers the fuzzy results into a crisp. Further, the fuzzy rules associated with the generated membership functions are as follows:

- 1. If (input1 is in 1mf1) then (output is out1mf1) (1)
- 2. If (input1 is in 1mf2) then (output is out1mf2) (1)

- 3. If (input1 is in 1mf3) then (output is out1mf3) (1)
- 4. If (input1 is in 1mf4) then (output is out1mf4) (1)
- 5. If (input1 is in 1mf5) then (output is out1mf5) (1)
- 6. If (input1 is in 1mf6) then (output is out1mf6) (1)
- 7. If (input1 is in 1mf7) then (output is out1mf7) (1)
- 8. If (input1 is in 1mf8) then (output is out1mf8) (1)
- 9. If (input1 is in 1mf9) then (output is out1mf9) (1)
- 10. If (input1 is in 1mf10) then (output is out1mf10) (1)
- 11. If (input1 is in 1mf11) then (output is out1mf11) (1)
- 12. If (input1 is in 1mf12) then (output is out1mf12) (1)
- 13. If (input1 is in 1mf13) then (output is out1mf13) (1)
- 14. If (input1 is in 1mf14) then (output is out1mf14) (1)
- 15. If (input1 is in 1mf15) then (output is out1mf15) (1)

Figure 3 and Figure 4 lets us display and edit all of the membership function associated with the fuzzy inference system. Each column shows the set of membership function for a particular input. Each membership function in the set is associated with a particular rule and maps input variable values to rule input values. The numbers of rows are the total number of rules that we have. The plots in the output column show how the rules are applied to output variable.

The output of the proportional integral (PI) controller is taken as the input training data set for the ANFIS. Table 1 displays the specifications that are required for the design of the ANFIS based controller.

Table 1. Design specifications for ANFIS based controller

Number of input(s)	1
Number of output(s)	1
Number of Membership Functions	15
Type of Membership Function	Gbellmf
Number of Epoch	10
Error	0.014

4. Result and Discussion

The IWDHS comprising of a conventional PI and ANFIS based controller is analyzed through modelling and simulation in MATLAB/Simulink environment and following results were obtained.

The speed of wind is 10m/s upto $t=5s$ after which it is increased to 11m/s causing the pitch angle controller to adjust to new parameters.

The wind speed is never constant and keeps on changing owing to atmospheric pressure. When there is no change in the wind speed i.e. 10m/s, the pitch angles of the blades of the wind turbine remain zero. Whenever the wind speed is more than 10m/s, the wind turbine will generate more power in comparison to its nominal power. Therefore, to limit the power generation to its nominal value, the pitch angle is controlled by a conventional PI controller [14] and in this paper, using an ANFIS based controller, which takes input power from the SEIG driving wind turbine, processes the error and changes the pitch angle in order to limit output power to its rated value as shown in Figure 5 and Figure 6.

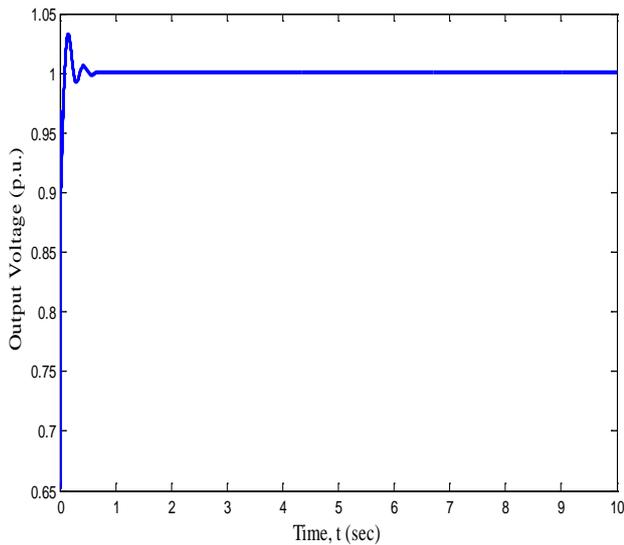


Figure 5. Output Voltage of Wind Turbine in p.u

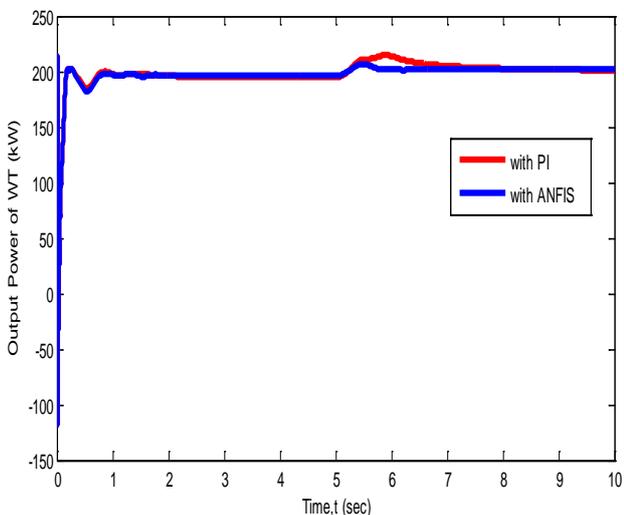


Figure 6. Comparison of Output Power (kW) of Wind Turbine

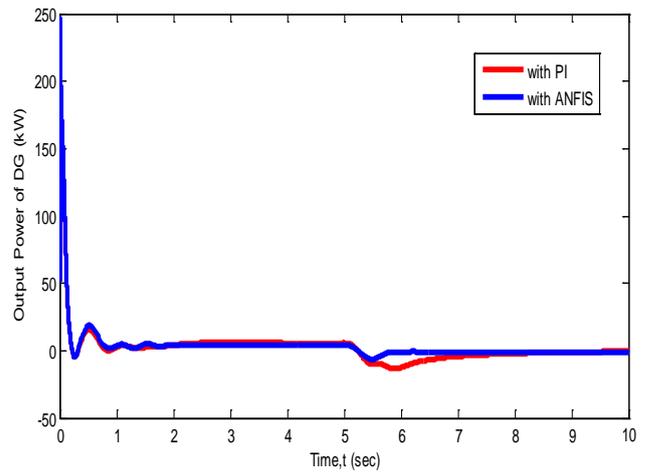


Figure 7. Comparison of Output Power of Diesel Generator (kW)

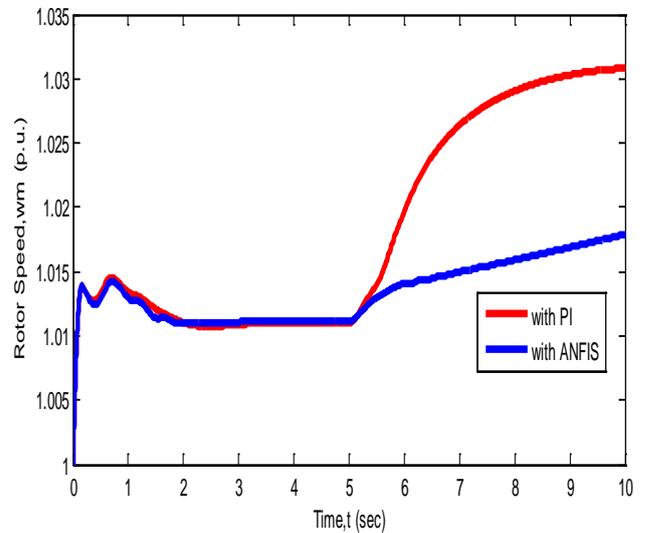


Figure 8. Comparison of Rotor Speed of SEIG in p.u.

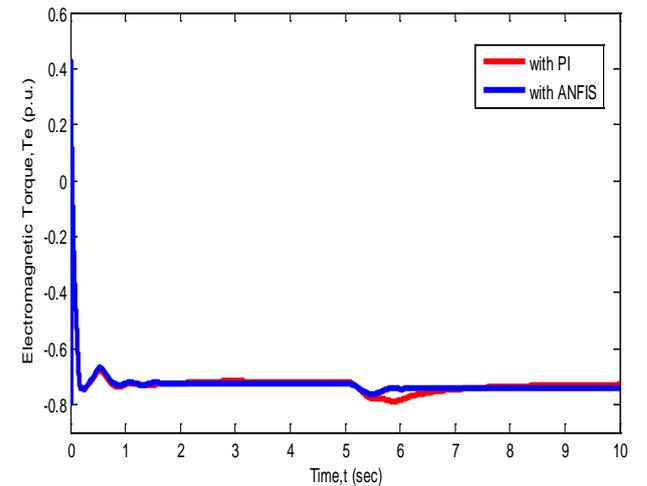


Figure 9. Comparison of Electromagnetic Torque of SEIG

Originally, the synchronous generator is supplying a constant 200-kW load when the wind turbine is turned on. While the speed is below synchronous speed, the wind turbine is in motoring mode. Consequently, the power (as well as the reactive power) absorbed by the wind turbine need be supplied by the diesel generator. As the speed of wind turbine is equal to synchronous speed, it begins to

produce power and contributes to power generation (delivering the 200-kW load). The diesel power generation drops as power is now supplied by the wind turbine as shown in Figure 7. The ANFIS controller also causes the settling time for power output to be reduced considerably as compared to a conventional PI controller.

Figure 8 and Figure 9 demonstrate how the rotor speed and torque of SEIG is affected by using ANFIS based controller. It can be seen that the generator remains protected from gust as the pitch angle control assists the

alteration of generated power reducing the pressure on the SEIG and therefore extending its life and efficiency. Without control, mechanical power can exceed nominal power in a wind turbine, owing to wind speeds increase above the nominal wind speeds (10m/s) for the turbine. Subsequently, adopted wind turbine can operate as a variable speed wind turbine which is able to regulate its output during its operation based on wind speed fluctuation. Alternatively, the results have been shown in Table 2.

Table 2. Comparison between various parameters of IWDHS

	Settling time for output power of WT, t (sec)	Peak Overshoot (kW)	Rotor Speed of SEIG, ω_m (p.u.)	Electromagnetic Torque, T_e (p.u.)
With conventional PI controller	1.82	215	1.0308	-0.79
With ANFIS based controller	0.41	207	1.0179	-0.74

5. Conclusion

In this paper, a Fuzzy controller, based on ANFIS architecture was presented. The controller was trained at the instant of wind speed change on the IWDHS equipped with an ANFIS based controller. The new controller gave an enhanced performance compared to that of the conventional PI controller and was able to acclimatize to various turbulences caused by increasing wind speed.

It is further resolved that by implementing this new controller, the peak overshoot of the output power of wind turbine and its settling time is reduced to a considerable extent. It is also determined from the simulation results, that the rotor speed and electromagnetic torque of SEIG has been improved which suggest that during every transient change, the conventional PI controller will make the Induction Machine to produce increased torque and settle in more time.

Thus, ANFIS based controller is able to provide more control and stability in reduced time. In other words, the dynamic performance of Isolated Wind-Diesel Hybrid System (IWDHS) has been improved, when it is subjected to variable wind speeds.

Acknowledgements

The authors acknowledge the strong support of Design Innovation Centre (DIC) sponsored by MHRD under sub-theme "Energy Harvesting and Management Technology" for providing the necessary financial aid and laboratory facilities for the completion of this research.

References

- [1] Mitra P, Zhang L, Harnefors L, "Offshore wind integration to a weak grid by VSC-HVDC links using power-synchronization control: A case study." IEEE Transaction on Power Delivery. 2014 Feb; 29(1): 453-61.
- [2] Wang Z, Yuwen B, Lang Y, Cheng M, "Improvement of operating performance for the wind farm with a novel CSC-type wind turbine-SMES hybrid system." IEEE Transaction on Power Delivery. 2013 Apr; 28(2):693-703.
- [3] Muljadi E, Flowers L, Green J, Bergey M, "Electrical design of wind-electric water pumping." ASMEJ Solar Energy Engineering. 1996; 118(4): 246-52.
- [4] Roy S, "Reduction of voltage dynamics in isolated wind-diesel units susceptible to gusting." IEEE Transaction on Sustainable Energy. 2010 Jul; 1(2): 84-91.
- [5] Pena R, Cardenas R, Proboste J, Clare J, Asher G, "Wind-diesel generation using doubly fed induction machines." IEEE Transaction Energy Conversion. 2008 Mar; 23(1): 202-14.
- [6] Rahimi M, Parniania M, "Grid-fault ride-through analysis and control of wind turbines with doubly fed induction generators." Electrical Power System Research. 2010 Feb; 80(2)z: 184-95.
- [7] Nian H, Song Y, Zhou P, He Y, "Improved direct power control of a wind turbine driven doubly fed induction generator during transient grid voltage unbalance." IEEE Transaction Energy Conversion. 2011 Sep; 26(3): 976-86.
- [8] Bansal RC, Bhatti TS, Kothari DP, "A bibliography survey on induction generators for application of nonconventional energy systems." IEEE Transaction Energy Conversion. 2003 Sep; 18(3): 433-9.
- [9] Suarez E, Botolotto G. "Voltage-frequency control of a self-excited induction generator". IEEE Transaction on Energy Conversions. 1999 Sep; 14(3): 394-401.
- [10] Chan TF. "Steady-state analysis of self-excited induction generators." IEEE Transaction on Energy Conversion. 1994; 9(2): 288-96.
- [11] Muljadi E, McKenna HE, "Power quality issues in a Hybrid Power System." IEEE Transaction on Industrial Application. 2002 May/June; 38(3): 803-9.
- [12] Nacfaire HN, "Wind-diesel and wind autonomous energy systems." New York: Wiley; 1984.
- [13] Saha TK, Kastha D, "Design optimization and dynamic performance analysis of a standalone hybrid wind diesel electrical power generation system." IEEE Transaction on Energy Conversion. 2010 Dec; 25(4):1209-17.
- [14] Kaur N, Pahwa V, "Enhanced Performance of Isolated Wind-Diesel (IWD) Hybrid System feeding Heavy Load under various Operating Conditions." Indian Journal of Science and Technology, [S.I.], Oct. 2016.
- [15] T. S. Bhatti, A. A. F. Al-Ademi, and N. K. Bansal, "Dynamics and control of isolated wind-Diesel power systems," International Journal of Energy Research. 1995, vol. 19, pp.729-740.
- [16] I. Kamwa, "Dynamic modeling and robust regulation of a no-storage wind-Diesel hybrid power system," Electric Power System Research. 1990, vol. 18, no. 3, pp. 219-233.
- [17] R. Chedid, Member IEEE F. Mrad, Member IEEE M. Basma, "Intelligent Control of a Class of Wind Energy Conversion Systems", IEEE Transactions on Energy Conversion, Vol. 14, No. 4, December 1999.
- [18] Heier S, "Grid integration of wind energy conversion systems." John Wiley and Sons Ltd; 1998.
- [19] Van TL, Nguyen TH, Lee DC, "Advanced pitch angle control based on fuzzy logic for variable-speed wind turbine systems." IEEE Transaction on Energy Conversion. 2015 Jun; 30(2): 578-87.
- [20] Bose BK, "Power electronics and AC drives." Pearson Prentice Hall; 2007.
- [21] Krishnan R, "Electric motor drives. Modeling, analysis and control." Pearson Prentice Hall; 2007.

- [22] Singh B, Singh M, Tondon AK, "Transient performance of series-compensated three-phase self-excited induction generator feeding dynamic loads. *IEEE Transaction on Industrial Application.*" 2010 Jul-Aug; 46(4):12-72.
- [23] Pahwa V, Sandhu KS, "Transient analysis of three-phase self-excited induction generator using new approach." *International Journal of Engineering and Science.* 2012 Dec; 2(6):1-11.
- [24] Abbey C, Li W, Joos G, "An online control algorithm for application of a hybrid ESS to a wind-diesel system." *IEEE Transaction on Industrial Electronics.* 2010 Dec; 57(12): 3896-904.
- [25] Krause PC, Wasynczuk O, Sudhoff S, "Analysis of electric machinery." *IEEE Press; Piscataway, NJ.* 1995. p. 1-632.
- [26] J. R. Jang, "ANFIS: Adaptive Network-Based Fuzzy Inference System," *IEEE Transactions on Systems, Man, and Cybernetics.* 1993, vol. 23, no. 3.
- [27] X. Lou and K. A. Loparo, "Bearing fault diagnosis based on wavelet transform and fuzzy inference," *Mechanical Systems and Signal Processing, Elsevier.* 2004, vol. 18.