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# Development and Simulation of Adaptive Neuro Fuzzy Controller Based Pitch Angle Controlled DFIG System For Wind Turbine

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***Abstract*****—** Wind energy is clean and renewable, which will never be dried up. The development of wind power has drawn the attention of the world and the proportion of wind power in the grid is getting higher and higher. Nowadays, the mainstream model of the wind power generator (WTG) is doubly-fed wind power generator (DFIG). With more and more wind power generators connected to the grid, the safe and steady operation of the power system will be deeply influenced.

Wind turbines can operate with either fixed speed or variable speed. For fixed speed wind turbines, the generator (induction generator) is directly connected to grid. Since the speed is about fixed to the grid, and mainly certainly not controllable, the turbulence of the wind will result in power variations, and thus affect the power quality of the grid. Modern high power wind turbines are capable of adjustable speed operation and use either singly-fed induction generator (SFIG) or doubly-fed induction generator (DFIG) systems. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, presently DFIG based wind turbines are quite popular as it can extract maximum power. Though the DFIG based wind turbines can able to provides maximum extent of power but greatly suffers from the power oscillation, to overcome this problem this paper proposes a novel adaptive neuro fuzzy controller (ANFIS) for efficient pitch angle control of DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations. For the comparative analysis, a comparison is also presented between the conventional PI controller and proposed ANFIS based controller. The obtained result indicates that, the proposed method is highly efficient to sustain the power oscillations as compare to state of art techniques. In addition to this it is also found that, the proposed ANFIS based pitch angle controller takes 80% less settling time as compare to conventional PI controller.

***Keywords-*** *Non conventional energy generation, wind power generator, DFIG, power quality enhancement, Power oscillation damping, pitch angle control, PI controller, ANFIS Controller.*

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## I. Introduction

A wind energy conversion system mainly consists of the wind turbine, the generator and the power electronic converters. Figure 1.1 shows the basic mechanical electrical functional chain in wind power generation. The control characteristics of the electric generator and remaining control-related properties of wind-turbines, particularly blade pitch control or stall behavior, must be considered collectively.

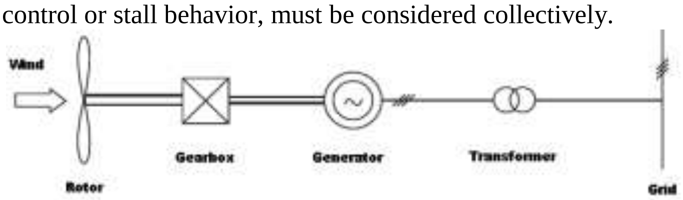


Figure 1.1 Mechanical-electrical functional chain in wind power generation.

Due to environmental, technical and financial issues, there is unprecedented interest in effective integration of wind based energy sources [1]–[3]. The intermittent nature of wind could be accounted as its most challenging characteristic. To extract the maximum available power from wind with fluctuating speed, variable-speed turbine is required [1]. To cope with this requirement, a doubly-fed induction generator (DFIG) is commonly used in type-3 wind turbines as it can be controlled to maximize the extracted energy using partial-scale converters with lower ratings as compared to the full-scale back-to-back converter topology used with synchronous generators. Recently, and especially after introducing the concept of micro grid to enhance supply reliability and increasing utilization of inertia-less types of generation in power grids, it becomes essential for wind turbines to participate in frequency regulation. Even in the grid-connected mode, many grid codes have changed to allow or even force wind power generation to participate in primary frequency regulation [4]. Significant part of research efforts is devoted to the use of wind turbine rotating mass [5]–[7], whereas several proposals are made to provide this energy by deviating from maximum power extraction point [8], [9]. Interestingly, the use of frequency deviation, i.e., frequency droop method, instead of frequency derivative, conventional inertia emulation, or at least a combination of both [4], [9]–[12] is proposed. It is reported that this method has more advantages [4], [5]; however, detailed analysis was not provided to prove these arguments. It may be worthy to mention that in all of these works, a secondary, usually dispatchable, source of energy was employed to restore the frequency to its nominal value. While almost all of the proposed methods for long-term participation of wind in frequency/power regulation agreed on deloading and using droop control method, the adopted approaches are different.

Many of these methods use wind speed for deloading; however, its accurate measurement does not seem easy [14]. On the other hand, the pitch-angle is used to deviate from optimum power extraction in [10] and [15], whereas the DFIG torque control and over-speeding [8], [14] are used. In [16], it is reported that pitch-angle control is fast enough for deloading; however, comparative results among other techniques reveal its slower behavior. It is also suggested that similar to the conventional wind control, pitch-angel could be utilized for high wind speed, whereas torque could be used for under-rated speeds [4], [14]. Despite its advantages, this approach needs wind speed measurement for switching between both control methods. Using both methods simultaneously based on a fuzzy control is proposed in [9]; however, similar to all discussed references, detailed stability analysis is not presented. In addition, none of mentioned papers, except a recently published article [17], allude to the stand-alone operation of DFIG-wind generators in the absence of any dispatchable sources. However, the work in [17] does not also include any stability analysis. Further, it only considers constant wind speed with always excessive generation and instead of modifying the widely-accepted conventional control method, it proposes a completely new and relatively complicated method.

Though the DFIG based wind turbines with PI pitch angle controller can able to provides maximum extent of power but greatly suffers from the power oscillation, to overcome this problem this paper proposes a novel adaptive neuro fuzzy controller (ANFIS) for efficient pitch angle control of DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations.

## II. DOUBLY-FED INDUCTION GENERATOR (DFIG) SYSTEM

### *A. General*

Today, doubly-fed induction generators (DFIG) are more increasingly used for the large wind power generation. Since their power electronic equipment only has to handle a fraction (20–30%) of the total system power. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the full system power as for a direct driven induction generator, apart from overall cost effectiveness. The semiconductor AC/DC and then DC/AC conversion is used to control the bidirectional power delivered from/to the rotor circuit to/from the grid.

### *B.* BASIC OPERATING PRINCIPLE OF DFIG

The doubly-fed induction generator (DFIG) is a ‘special’ variable speed induction machine and is widely used as modern large wind turbine generators. It is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through an AC/DC/AC pulse width modulated (PWM) converter. The AC/DC/AC converter normally consists of a rotor-side converter and a grid-side converter. By means of the bi-directional converter in the rotor circuit, the DFIG is able to work as a generator in both sub-synchronous (positive slip s > 0) and over-synchronous (negative slip s < 0) operating area. Depending on the operating condition of the drive, the power is fed in or out of the rotor. If ($\boldsymbol{P}_{rotor} < 0$): it is flowing from the grid via the converter to the rotor in sub-synchronous mode or vice versa ($\boldsymbol{P}_{rotor} > 0$) in over-synchronous mode. In both cases (sub-synchronous and over-synchronous) the stator is feeding energy to the grid ($\boldsymbol{P}_{stator} > 0$) [27].

For variable speed systems with limited variable-speed range, e.g. ±30% of synchronous speed, the DFIG is reported to be an interesting solution. A detailed representation of DFIG with its back to back converters is depicted in Figure 2.1. The back-to-back converter consists of two converters, i.e., rotor-side converter (RSC) and grid-side converter (GSC), connected “back-to-back.” Between the two converters a DC-link capacitor is placed. With the rotor-side converter it is possible to control the torque or the speed of the DFIG. Doubly fed induction machines can be operated as a generator as well as a motor in both sub-synchronous and super synchronous speeds using the rotor side converter control. Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation.

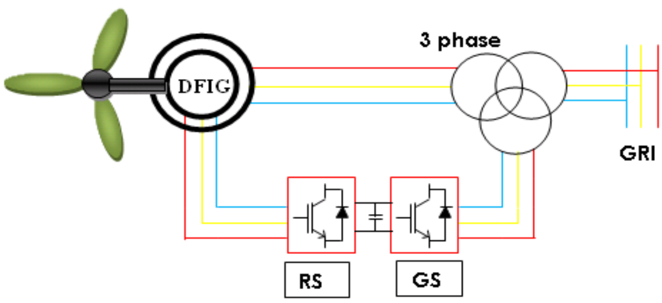


Figure 2.1 Schematic of conventional DFIG wind system

The speed–torque characteristics of the DFIG system can be seen in Figure 2.2. As also seen in the figure, the DFIG can operate both in motor and generator operation with a rotor-speed range of $\pm \Delta\omega_r^{max}$ around the synchronous speed, $\omega_s$.

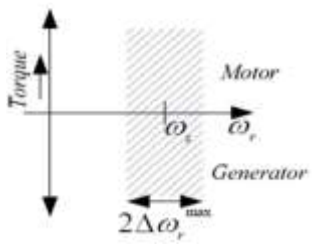


Figure 2.2 Speed-torque characteristics of DFIG system

### C. THE DFIG WIND TURBINE

The DFIG is constructed from a wound rotor asynchronous machine. Variable speed operation is obtained by injecting a

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variable voltage into the rotor at slip frequency. The injected rotor voltage is obtained using two AC/DC insulated gate bipolar transistors (IGBT) based voltage source converters (VSC), linked by a DC bus. The converter ratings determine the variable speed range. The gearbox ratio is set so that the nominal speed of the IG corresponds to the middle value of the rotor-speed range of the wind turbine. This is done in order to minimize the size of the inverter in the rotor circuit which will vary with the rotor speed range. With this inverter it is possible to control the speed (or the torque) and also the reactive power on the stator side of the induction generator (IG). The speed range, i.e., the slip, is approximately determined by the ratio between the stator to rotor voltage. The stator to rotor turns ratio can be designed so that maximum voltage of the inverter corresponds to the desired maximum rotor voltage to get the desired slip [28], [29].

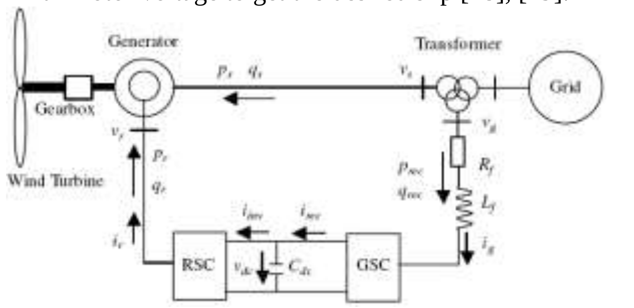

Figure 2.3 The DFIG wind turbine system.

D. SPEED CONTROL FOR OPTIMUM POWER

Wind turbines operate by exciting energy from the wind. The available energy in a wind stream is given by $P_{air} = \frac{1}{2}\rho A_r \omega^2$, where $\rho$ is the air density, $\omega$ is the wind speed and $A_r$ is the area swept by the wind turbine blades. However, the energy which can be extracted by the wind turbine is less than the energy in the wind. Therefore the power extracted by the aerodynamic rotor ($P_m$) is expressed with respect to the power available in the wind ($P_{air}$) as follows:

$$P_m = C_p - P_{air} \quad (2.1)$$

$C_p$ is called the power coefficient and depends on the tip-speed ratio (λ) which is the ratio between the velocity of the rotor tip and wind speed defined by:

$$\lambda = \frac{\Omega_r r_r}{\omega} \quad (2.2)$$

where $\Omega_r$ is the aerodynamic rotor speed and $r_r$ is the radius of the rotor. To extract the maximum power from the wind, the rotor speed should vary with the wind speed, maintaining the optimum tip speed ratio ($\lambda_{opt}$). In practical DFIG wind turbine the rotor torque is used as a set point reference. A typical set-point torque-speed characteristics applied for controlling DFIG wind turbines is shown in Figure 4.9. The cut-in and the rated speed limits are mainly due to converter ratings although the upper rotational speed may also be limited by an aerodynamic noise constraint. For low-medium wind speeds (A-B) the speed control defined by the set point torque is applied by controlling the injected rotor voltage. When the rotor reaches pint B, blade pitch regulation dominates the control and limits the aerodynamic power. For very high wind speeds the pitch-control will operate until the wind speed shutdown limit is reached.

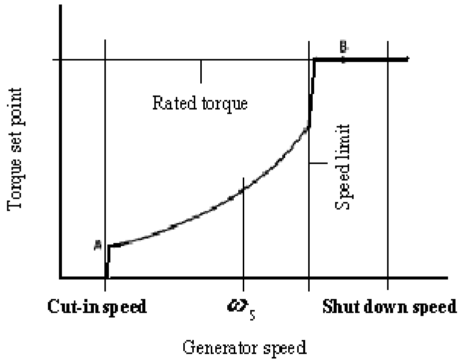


Figure 2.4 Torque-speed characteristic for turbine control strategy

E. CONTROL OF DFIG WIND TURBINE

A simplified diagram of the control scheme used for the DFIG wind turbine is shown in Figure 4.10. In the configuration shown, the rotor side converter (C1) is used for both speed control and for power factor and/or voltage control. Converter C2 acts to transmit real power only. The generator control is based on a d-q coordinate system, where the q component of the stator voltage is selected as the real part of the bus bar voltage and d component as the imaginary part.

The new co-ordinate system decouples the speed control action from the power factor and/or voltage control. This allows the two rotor injection voltages – $V_{qr}$ and $V_{dr}$ to be regulated separately for speed control and/or voltage control, respectively. The DFIG wind turbine voltage control strategy is typically defined to provide power factor control of the induction generator, using converter C1. Terminal voltage control can also be provided through the rotor side converter and this scheme is illustrated in Figure 2.5. However, reactive power injection can be obtained from either the rotor side converter (C1) or the network side converter (C2). Using the rotor side converter (C1) is likely to be preferred to the network side converter for DFIG voltage control schemes. This is largely due to the reduction in the converter-rating requirement as reactive power injection through the rotor circuit is effectively amplified by a factor of 1/slip [28].

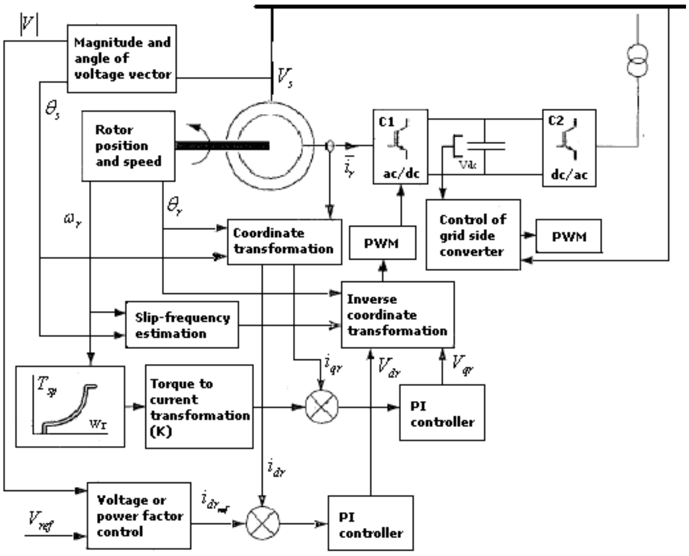


Figure 2.5 Simplified schematic of a DFIG wind turbine typical control system

## III. PROPOSED ANFIS BASED PITCH ANGLE CONTROLLED DFIG SYSTEM FOR WIND TURBINE

### A. DESCRIPTION OF THE PROPOSED SYSTEM

This paper proposes a novel adaptive neuro fuzzy controller (ANFIS) for efficient pitch angle control of DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations.

A 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder is developed. The proposed system having Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. In this proposed work the initial wind speed is maintained constant at 8 m/s and then increases to 15 m/s at time (in sec). The control system uses a torque controller in order to maintain the speed at 1.2 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar. The sample time used to discretize the model is 50 microseconds. For a wind speed of 15 m/s, the turbine output power is 10 MW approximately, the pitch angle is 8.7 deg and the generator speed is 1.2 pu. Figure (3.1) shows the simulation model developed for the proposed work in MATLAB Simulink 2012b version.

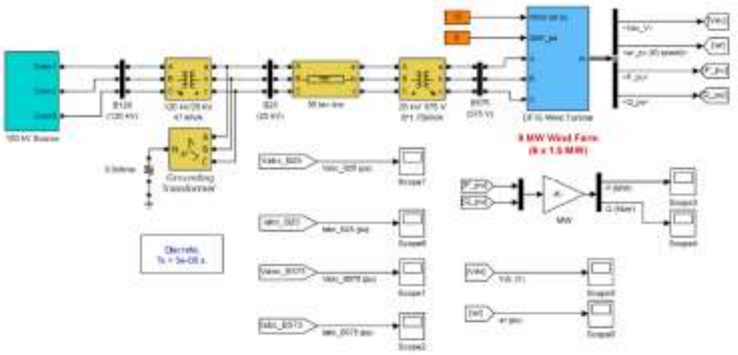

Figure (3.1) Developed Simulation Model of the proposed work.

Figure 3.2, shows the proposed pitch angle control structure of an ANFIS controller based DFIG wind turbine system, in which an ANFIS controller is used for pitch angle control and a PI controller for its compensation.

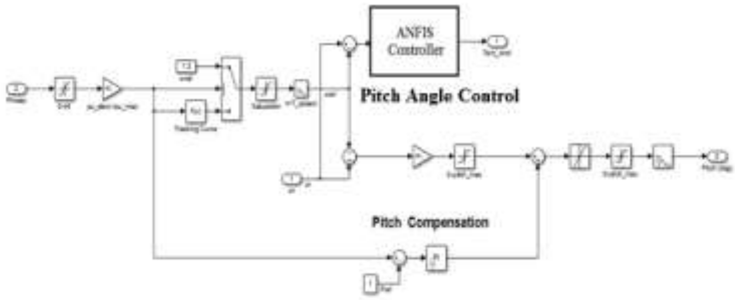


Figure (3.2), Pitch angle control structure of proposed DFIG wind turbine system.

### B. DEVELOPMENT OF ANFIS BASED PITCH ANGLE CONTROLLER

For the development of proposed ANFIS based pitch angle controller following steps have been employed:

**Step-1.** Obtain the input and outputs of conventional PI controller.

**Step-2.** Make a correction on output of conventional PI controller, which will provide our desired controlled pitch angle.

**Step-3.** Train the ANFIS for obtained new input and output data.

**Step-4.** Test the developed and trained ANFIS.

After following above steps an ANFIS based pitch angle controller has been successfully developed, whose parameters are given as:

| | |
|---|---|
| name: | 'vst' |
| type: | 'sugeno' |
| andMethod: | 'prod' |
| orMethod: | 'probor' |
| defuzzMethod: | 'wtaver' |
| input: | [1x1 struct] |
| output: | [1x1 struct] |
| rule: | [1x3 struct] |

Figure (3.3) shows the ANFIS editor after loading input and target data for proposed ANFIS controller.

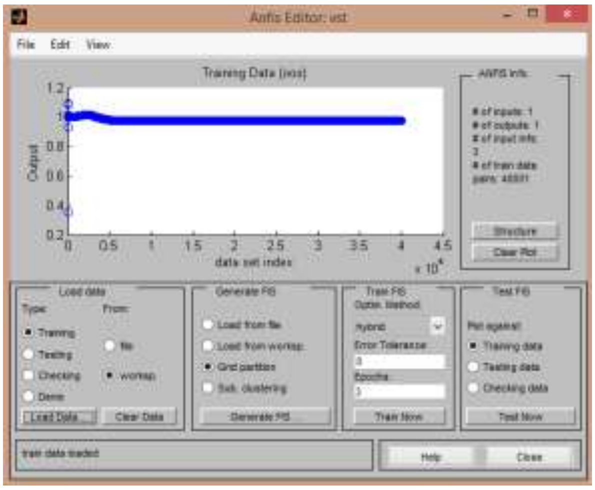


Figure (3.3) loading input and target data for proposed ANFIS controller.

Figure (3.4) shows the training process of proposed ANFIS controller, the training error achieved is 0.0066096.

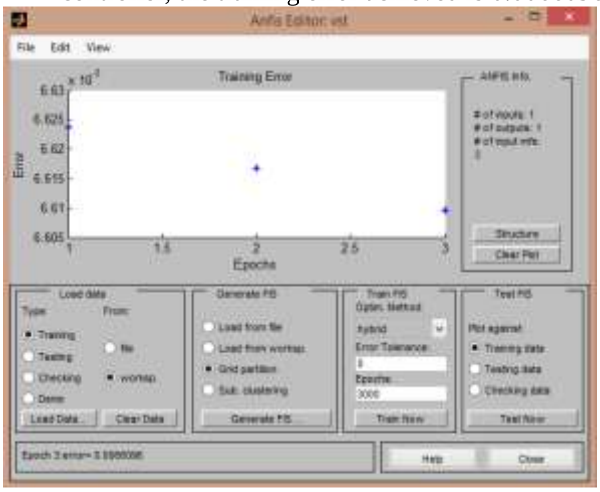


Figure (3.4) Training process for proposed ANFIS controller.

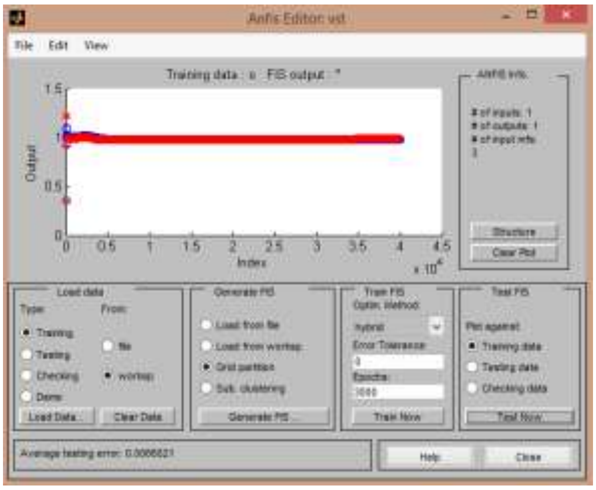


Figure (3.5) Testing process for proposed ANFIS controller.

Figure (3.5) shows the testing error of developed ANFIS controller is 0.0066021, which is very small. After the successful development of ANFIS controller figure (3.6) shows its input variable membership function plot. Its structure and layout are shown in figure(3.7) and figure (3.8).

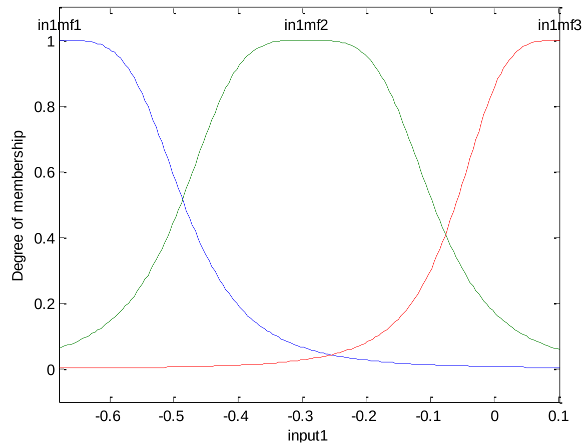


Figure (3.6) Input Member ship function of developed ANFIS (vst.fis).

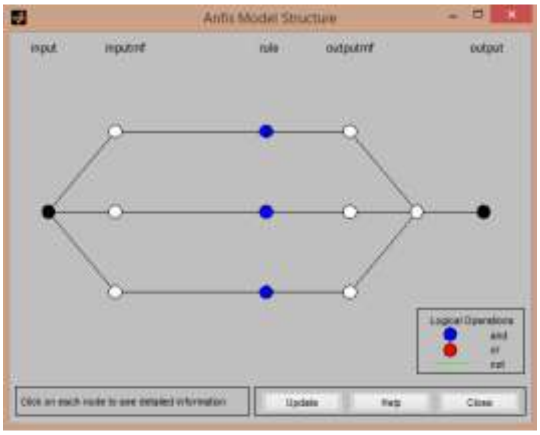


Figure (3.7) Structure of developed ANFIS (vst.fis).

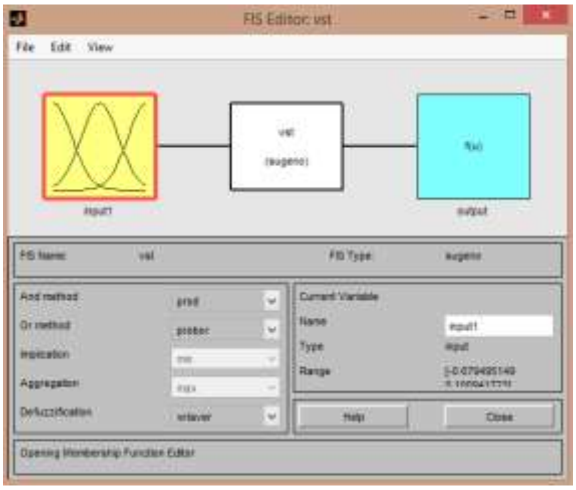


Figure (3.8) layout of developed ANFIS (vst.fis).

The rule base generated is given as:
1. If (input1 is in1mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf3) then (output is out1mf3) (1)

## IV. RESULT AND DISCUSSION

### A. Turbine Response to a Change in Wind Speed

Let's observe the turbine response to a change in wind speed. Initially, wind speed is set at 10 m/s, then at t = .5 seconds,

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wind speed is increases to 15 m/s. At t = .5 seconds, the generated active power starts increasing (together with the wind speed) to reach its rated value of 10 MW in approximate .15 seconds. Over that time frame the turbine speed increases from 0.8 - 1.21 pu. primarily, the pitch angle of the turbine blades is zero degree and changes rapidly to incorporate with wind speed change to limit the mechanical power. examine also the voltage and generated reactive power. The reactive power is controlled to maintain a 1 pu voltage. At small power, wind turbine absorbs 0.68 Mvar (generated Q = -0.68MVar) to control voltage at 1150 volt. The resultant responses are shown from figure (4.1) to figure (4.6).

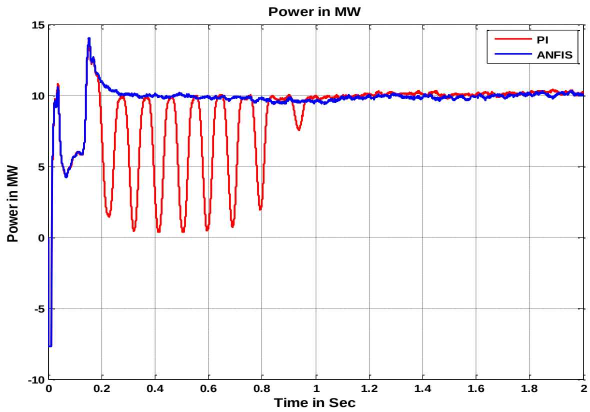


Figure (4.1) Plot of output power from DFIG Wind Turbine.

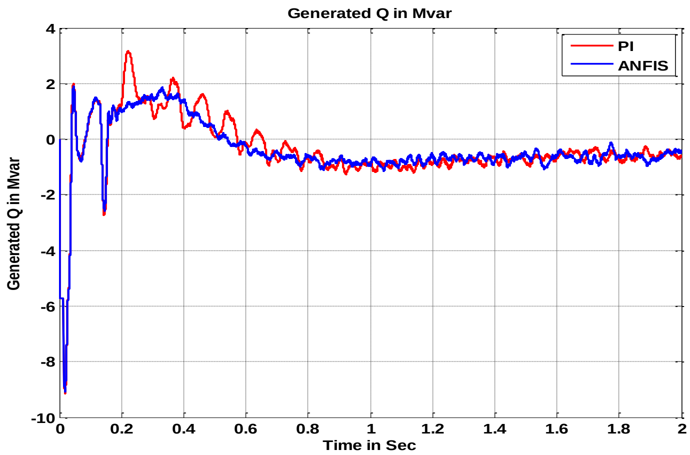


Figure (4.2) Plot of Reactive power from DFIG Wind Turbine.

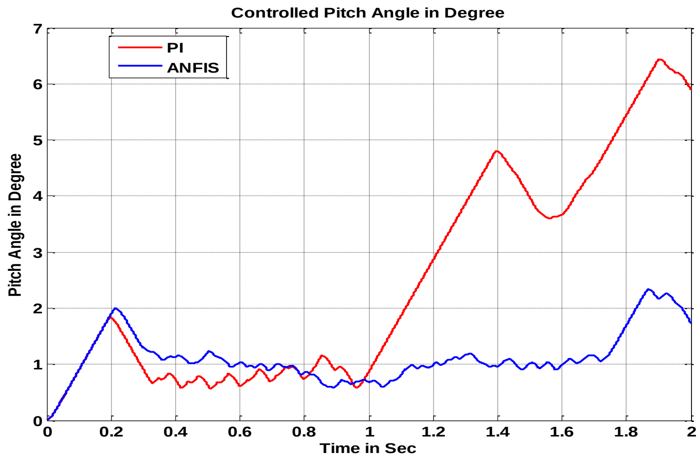


Figure (4.3) Plot of Controlled Pitch Angle.

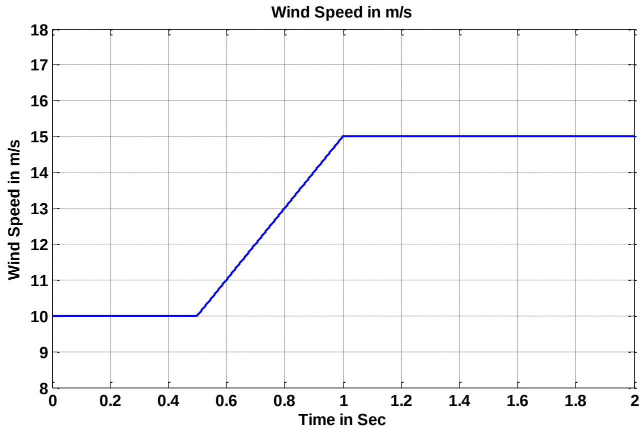


Figure (4.4) Plot of change in Wind speed.

Table-5 Diagnostic Result for Motor with one Broken Bar.

## V. CONCLUSTIONS

Complete description of the DFIG system equipped with the PI controller and proposed ANFIS based controller for pitch angle control has been successfully described and implemented in this paper. In the result section it has been shown that, the developed system can able to provide efficiently damp the power oscillation during change in wind speed and hence provides constant power output at the transient state and keeps it constant during the steady state. While comparative plots of results shows that the conventional PI controller can provide controlled constant power after constant wind speed, and cannot able to maintain constant power during variable wind speed.

In addition to this it is also evident from the resultant plots, that conventional PI controller takes higher timing slot to maintain the constant power, while proposed ANFIS based controller takes 80 percent less time to sustain the power oscillation. Therefore this work has put forwarded a novel power oscillation damping straightgy using adaptive neuro fuzzy controller based pitch angle control during variable speed of wind.

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