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Modelling and Simulation of ANFIS Controlled Doubly FED Induction Generator Based Wind Energy System for Performance Enhancement

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Abstract: In this paper doubly fed induction generator (DFIG) based wind energy conversion system (WECS) integration with the grid is presented. DFIG facilitates a wide range of speed variations with constant frequency, due to its controllable excitation given to rotor through a back to back connection. DFIG has a better output profile compared to other generators due to its controllable input given to rotor separately. DFIG control has two controllers one is stator/grid side control (GSC) and another is the rotor side controller (RSC). The stator side control has been designed based on stator flux control orientation and the controller of rotor side is designed depends on grid voltage oriented control to keep a stable voltage at DC-link. The adaptive Neuro fuzzy inference system is used instead of conventional PI and fuzzy controllers. ANFIS can reduce deviations present in system response for a change in input wind speed, short grid faults and system parameter variation. Implemented ANFIS control has involved in grid side control and rotor side control, than these combinations gives better performance.

Keywords: Adaptive Neuro fuzzy inference system, Wind energy conversion system, Rotor side control, Grid side control and Doubly fed induction generator.

1. INTRODUCTION

From past few decades, utilization of electrical energy is increasing day by day due to world technology growth. This growing utilization of fossil fuel consumption leads to shortage in future generations. To overcome this situation much more research was held in the area of renewable power generation optimization methods and loss reduction methods. Among all renewable power sources, wind energy generation plays a leading role due to availability of high wind pressure, pollution free, clean and economically cheaper. Due to this, Research on wind turbines increased rapidly [1, 6]. Basically wind turbines are of two types one is fixed speed and the other one is a variable speed wind turbine. Among this variable speed wind turbine (VSWT) can facilitate a wide range of power generation. The doubly fed induction generator (DFIG) based wind farms have high efficiency and it is having a high fault ride through capability. The back-to-back conversion set was included in the design of DFIG based WECS in between the rotor of DFIG and grid. Due to variable speed wind turbine utilization, frequency is the effecting factor. This can be overcome by controlling the excitation of rotor by controlling back to back set firing pulses [6, 7]. This can give a constant frequency of the variable speed machine. The vector control technique is used in DFIG, it can facilitate a variety of operations among real and reactive power, WECS is shown in fig1. Variable wind turbines are using two controlling methods to extract maximum power from available wind speeds; one is tip speed ratio control (TSR) and pitch angle control. Pitch angle control can adjust the blade to change the angle of attack to extract maximum energy. With combination of these reactive power controls are used to monitor power generation. The conventional PI and fuzzy controllers are used to perform error controlling action. PI can take some delay time to reach steady state after that fuzzy is introduced it can

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perform better than PI due to its rule base operation. To increase DFIG performance one new control technique is proposed which is better than fuzzy i.e., an Adaptive Neuro fuzzy system (ANFIS). It is a rule based training system, it uses a sugeno type of rule base system. ANFIS with sugeno combination can give better performance than conventional methods .The ANFIS system has been utilized to execute the proposed model .To start with, it utilizes the training data information to build the fuzzy system in which membership functions are adjusted [2],[3]. The system will take grid parameters as a reference for integration of DFIG with grid. Grid voltage is taken as reference during synchronization, from this phase angle and frequency is measured. The controller can take DFIG voltage, phase angle and frequency, then the reference and measured parameters are compared. The error between these two are given to ANFIS, it will reduce error near to zero. By these the pulse generation to control DFIG inverter output is same as grid. In a grid failure, system goes to islanded mode of operation, In this case the loads are operated up to 60% without using battery storage system. In islanding mode load parameters are taken as a reference parameter. From island to grid mode above procedure follows.

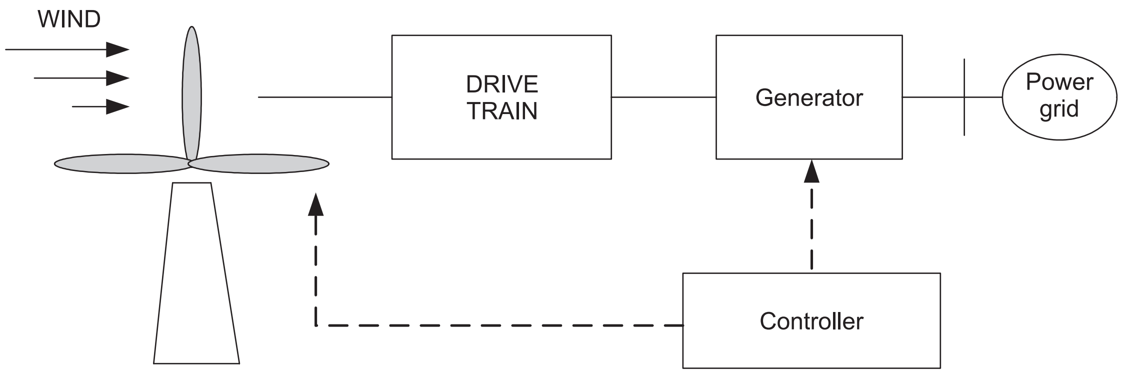

Figure 1: Wind power generation

2. WIND TURBINE

The captured mechanical power (in W) by a VSWT can be written by

$$P = \frac{1}{2}\rho A V_W^3 \tag{1}$$

Where ρ is the air density (kg/m^2), A is the blade impact area (m^2), V_W is the wind speed (m/s), and C_P is the power coefficient of the VSWT. The power coefficient of the VSWT C_P is given by

$$C_P = 0.5[0.5(116/\lambda_i) - 0.4\beta - 5]\, e^{-21/\lambda_i} + 0.0068\lambda \tag{2}$$

λ Tip Speed ratio (Keep the TSR constant at all times of the optimal level) [11], β Pitch angle of the blade

$$\lambda = \frac{\omega R}{V_W} \tag{3}$$

Where ω Rotor angular speed in rad/sec, R Rotor blade radius in meter

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.088\beta} + \frac{0.035}{\beta^3 + 1} \tag{4}$$

Pitch Angle controller will start when the wind speed reaches its rated or above rated value. Up to cut in to rated speed pitch angle will maintain zero for Optimum power extraction from the wind [9]. The cut-in, rated, and cut-out wind speeds of the studied VSWT are 4, 14, and 24 m/s, respectively. When $V_W < 14$ m/s, $\beta = 0$. When $V_W > 14$ m/s, the pitch-angle control system get activated to increase β. The two-inertia reduced-order equivalent mass-spring damper model of the VSWT coupled to the rotor shaft of the wind

DFIG through an equivalent gearbox is used. The per-unit (pu) equations of motion are explained in [6], [19], and [21].

3. MATHEMATICAL MODEL OF DFIG

Mathematical model implementation of DFIG in the synchronous reference frame is

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{d}{dt}\Phi_{ds} - \omega_s \Phi_{qs}, \\ V_{qs} = R_s i_{qs} + \frac{d}{dt}\Phi_{qs} - \omega_s \Phi_{ds}, \\ V_{dr} = R_r i_{dr} + \frac{d}{dt}\Phi_{dr} - p\omega_m \Phi_{qr}, \\ V_{qr} = R_r i_{qr} + \frac{d}{dt}\Phi_{qr} - p\omega_m \Phi_{dr}, \end{cases} \tag{5}$$

Where i_{ds}, i_{qs} are direct and quadrature axis stator current. R_s, R_r are stator and rotor resistance. ω_s, ω_r are synchronous and DFIG speed.

Stator fluxes estimation,

$$\begin{cases} \varnothing_{ds} = L_s i_{ds} + M i_{dr}, \\ \varnothing_{qs} = L_s i_{qs} + M i_{qr}, \\ \varnothing_{dr} = L_r i_{dr} + M i_{ds}, \\ \varnothing_{qr} = L_r i_{qr} + M i_{qs}, \end{cases} \tag{6}$$

Where $\varnothing_{ds}$, $\varnothing_{qs}$ are d-q stator fluxes include self and mutual flux linkages. $\varnothing_{dr}$, $\varnothing_{qr}$ are d-q rotor fluxes. L_s, L_r and M are stator, rotor and mutual inductances respectively.

Stator power representation,

$$\begin{cases} P_s = V_{ds} i_{ds} - V_{qs} i_{qs}, \\ Q_s = V_{qs} i_{ds} - V_{ds} i_{qs}, \end{cases} \tag{7}$$

Where P_s, Q_s are stator active and reactive power. V_{ds}, V_{qs} are stator voltages in d-q reference frame.

Rotor power generation,

$$\begin{cases} P_r = V_{dr} i_{dr} - V_{qr} i_{qr}, \\ Q_r = V_{qr} i_{dr} - V_{dr} i_{qr}, \end{cases} \tag{9}$$

Where P_r, Q_r are rotor active and reactive power. V_{dr}, V_{qr} are d-q rotor voltages.

Electromagnetic torque is

$$T_{em} = p(\varnothing_{ds} i_{qs} + \varnothing_{qs} i_{ds}) \tag{9}$$

Where p is Number of pole pairs

4. VECTOR CONTROL DESIGN FOR BACK-TO-BACK CONVERTERS

A DFIG is a doubly actuated machine or doubly exited machine. Stator of the DFIG is directly connected to the grid means without using any power converters and rotor is connected to the grid with rectifier, inverter back to back set with a DC link capacitor for stabilization.The back to back converters of DFIG are evaluated only for 30% of rated power of a generator. Rotor side converter and grid side converter can control the system frequency and power generation by facilitating appropriate controllers. The major advantage of DFIG is it can regulate both active and reactive power.

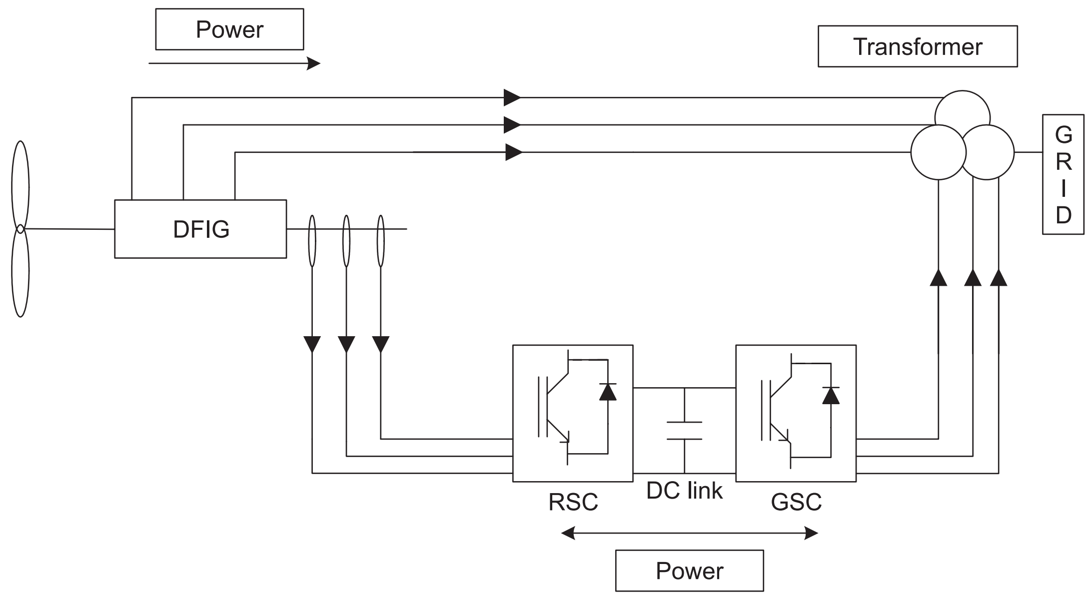

Figure 2: DFIG based wind turbine system configuration

Reactive and active power can be controlled individually. DFIG control can be divided into RSC control and GSC control. The reactive power control can be achieved by controlling the RSC, and GSC can limit the DC link voltage for a constant value to maintain the required power factor. The rotor side control can be designed on field oriented control basis. The performance of controllers are good for the synchronous reference frame. This controller monitors and control the system dq component of current where d-axis current correlates to active power and q-axis current corresponds to reactive power. The grid side controller can manage the voltage of DC link capacitor nearer to its reference. dq axis component of flux calculation is

$$\varnothing_{qs} = \varnothing_s \text{ and } \varnothing_{qs} = 0 \tag{10}$$

$$\varnothing_s = L_s i_{qs} + M i_{qr} = 0 \quad \Rightarrow \quad i_{qs} = -\frac{M}{L_s} i_{qs} \tag{11}$$

$$i_{ds} = \frac{V_s}{\omega_s L_s} - \frac{M}{L_s} i_{dr} \tag{12}$$

$$P_s = -\frac{V_s M}{L_s} i_{qr} \tag{13}$$

$$Q_s = \frac{V_s \varnothing_s}{L_s} - \frac{V_s M}{L_s} i_{dr} \tag{14}$$

5. ANFIS CONTROLLER DESIGN

Adaptive Neuro-fuzzy technique (or Adaptive Neuro-fuzzy inference controlling system, ANFIS) has been suitably involved in the designing of the fuzzy inference system (FIS). In this context, the designing has been accomplished with the sugeno type technique that lines out the input characteristics to input membership functions. Fuzzy inference is applicable to only modeling system whose structure is designed by the users is as shown in Figure 3. In some sort of designing conditions, it may not be easy to analyze the data of the membership functions, it should be more correlated with the membership functions directly. A network-type design same as a neural network system has been adopted to strengthen and improvise the input/output map in such a way that it will evaluate the input units through the regular membership functions of input/output parameters that are linked with the membership functions which can be altered through the learning procedure. In the process of calculation, the variable parameter changes are supplemented with a gradient vector, which has been used as reference to the FIS to measure the input/output data in correspondence with the pre-determined parameters. The controller takes measured values as inputs to do a particular task. To maintain DFIG synchronism with grid, the voltage, phase angle and frequency are same for these two. This can be achieved by comparing measured values with reference value. The measured DFIG voltages and currents are compared with reference values, then the error between these two and change in error taken as an input to ANFIS controller. ANFIS can reduce error in two stages, one is rule base action. In this case the ANFIS can check error value range.

Based on this, output can generate with a range closer to reference, and then this output is given to trained system. Further the error is reduced based on this trained parameters, it will make the system outputs closer to reference values [4], [5] and are indexed in Tables 2 and 3. The vector control performance of proposed ANFIS controller is contrasted with a vector control utilizing fuzzy logic controllers. The wind speed is set at 6 m/s in accordance with a angular speed of 78 rad/s (Figure 5(d)).

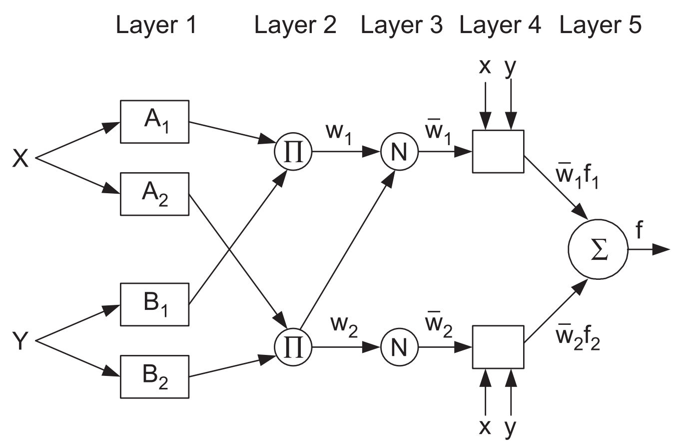

Figure 3: The architecture of the ANFIS

Layer 1 (L1): Each node produces the membership grades of a linguistic label. An example of a membership function is the generalised bell function:

$$\mu(x) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}}$$

where $\{a, b, c\}$ are the parameters. By changing the values of the parameters, the shape of the bell-shaped function varies. Parameters in that layer are called premise parameters.

Layer 2 (L2): Each node calculates the firing strength of each rule using the min or prod operator. In general, any other fuzzy AND operation can be used.

Layer 3 (L3): The nodes calculate the ratios of the rule's firing strength to the sum of all the rules firing strength. The result is a normalised firing strength.

Layer 4 (L4): The nodes compute a parameter function on the layer 3 output. Parameters in this layer are called consequent parameters

Layer 5 (L5): Normally a single node that aggregates the overall output as the summation of all incoming signals

6. THE ANFIS LEARNING ALGORITHM

When the premise parameters are fixed, the overall output is a linear combination of the consequent parameters. In symbols, the output f can be written as

$$f = (\bar{w}_1 x)c_{11} + (\bar{w}_1 y)c_{12} + \bar{w}_1 c_{10} + (\bar{w}_2 x)c_{21} + (\bar{w}_2 y)c_{22} + \bar{w}_2 c_{20}$$

which is linear in the consequent parameters c_{ij} ($i = 1, 2, j = 0,1,2$). A hybrid algorithm adjusts the consequent parameters c_{ij} in a forward pass and the premise parameters $\{a_i, b_i, c_i\}$ in a backward pass. In the forward pass the network inputs propagate forward until layer 4, where the consequent parameters are identified by the least-squares method. In the backward pass, the error signals propagate backwards and the premise parameters are updated by gradient descent.

Because the update rules for the premise and consequent parameters are decoupled in the hybrid learning rule, a computational speed up may be possible by utilizing variants of the gradient method or other optimisation techniques on the premise parameters.

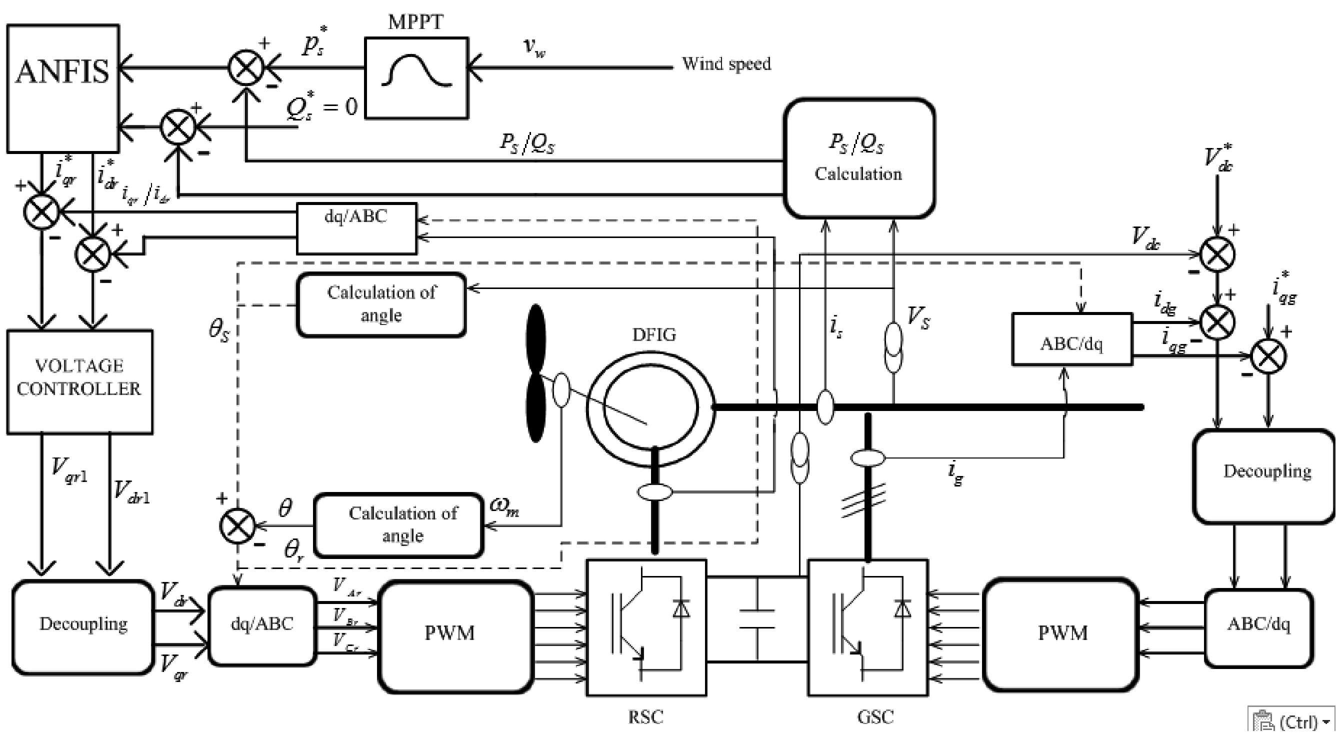

Figure 4: Proposed control design for DFIG integrated system

7. SYSTEM RESULTS AND DISCUSSION

Proposed system consists of ANFIS to limit error in minimum range based on rules written and its membership functions. The proposed method is as shown in Figure 4. The simulation has been done on a DFIG system integrating the proposed FLCs for the vector control as shown in Figure 4. The parameters of induction machine are influenced from Refs. [17] and are indexed in Tables 2 and 3. The vector control performance of proposed ANFIS controller is contrasted with a vector control utilizing fuzzy logic controllers. The wind speed is set at 6 m/s in accordance with a angular speed of 78 rad/s (Figure 5(d)).

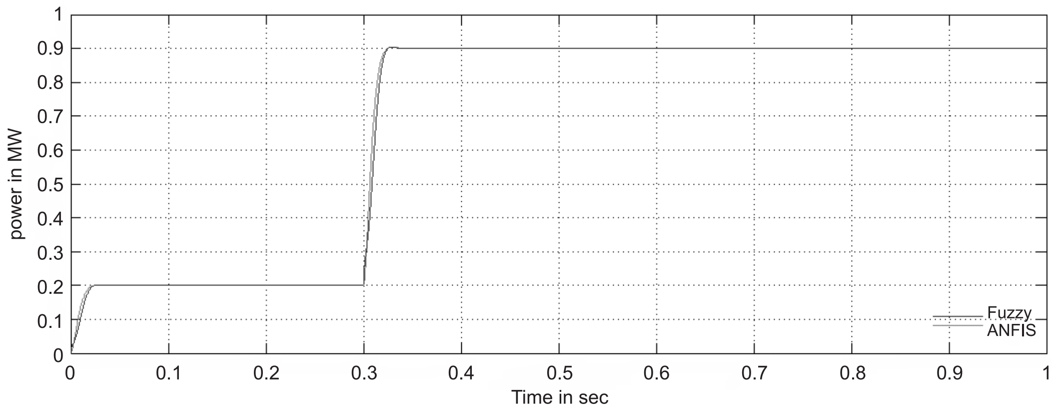

Figure 5(a)

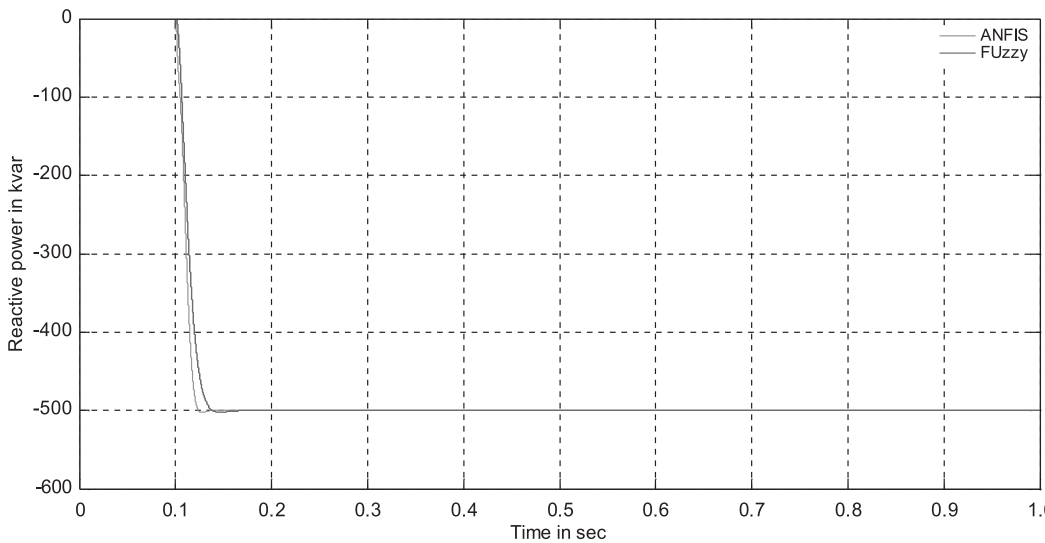

Figure 5(b)

P_s-ref is equivalent to 0.2 MW and Q_s-ref is selected to be –0.5 KVAR at $t = 0.1$ s. The wind speed at $t = 0.3$s is altered to get 10 m/s, so the generator reference speed is varied to 130.5 rad/s also to track the maximum power point curve the P_s-ref became 0.95 MW at the same time keeping Q_s-ref constant at –0.5 KVAR. It could be seen from Figure 5 (a) and (b).

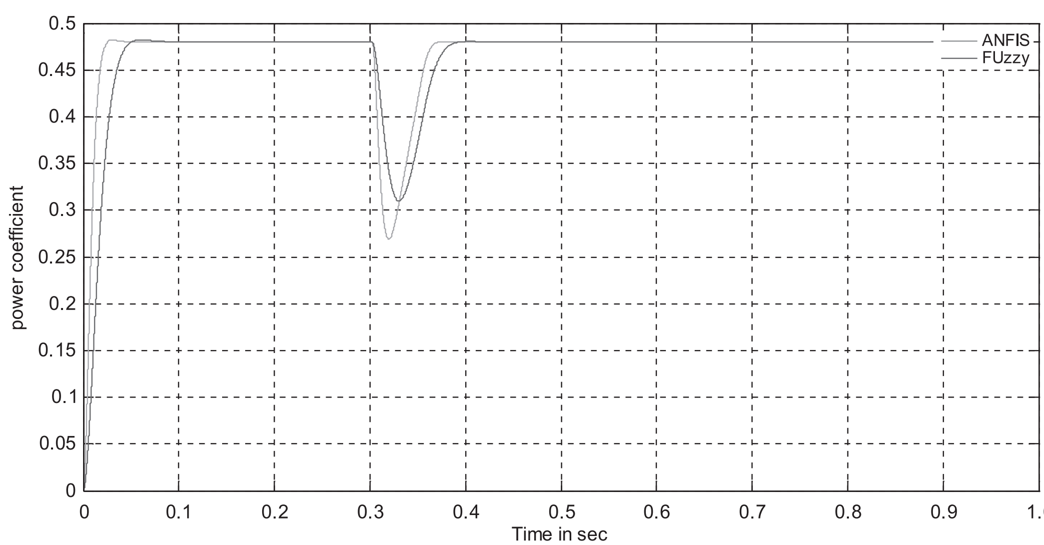

Figure 5(c)

The ANFIS controller is robust, but the two Fuzzy controller and the ANFIS controller attain the same coefficient of efficiency value relatively 0.48. It is noticed from the Figure 5(c) that by employing the proposed FLCs, a faster dynamic approach can be achieved. Further, there is no overshoot, and settling time is less, in contrast to the Fuzzy controller.

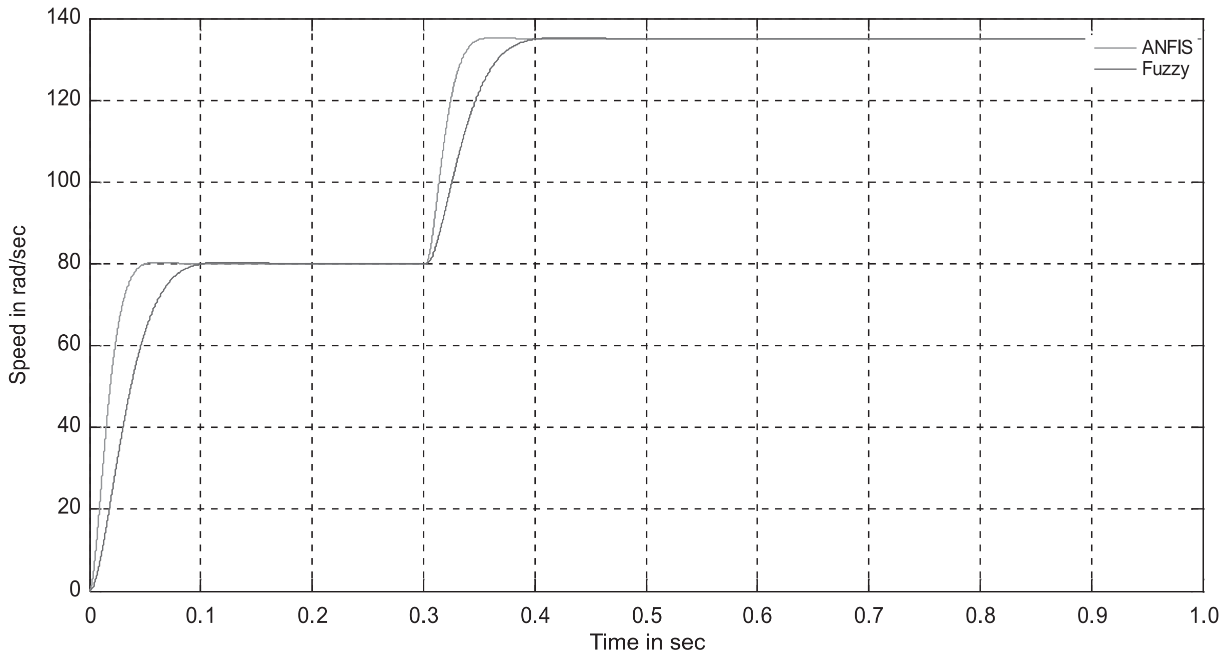

Figure 5(d)

The wind speed is set at 6 m/s accordingly to a set rotational speed of 78 rad/s. The deviation of rotational speed in the MPPT operating mode is as shown in Figure 5 (d). In the closed loop speed control of the MPPT system the ANFIS controller is rapid than the Fuzzy controller, but both of the controllers will achieve actually zero steady state error.

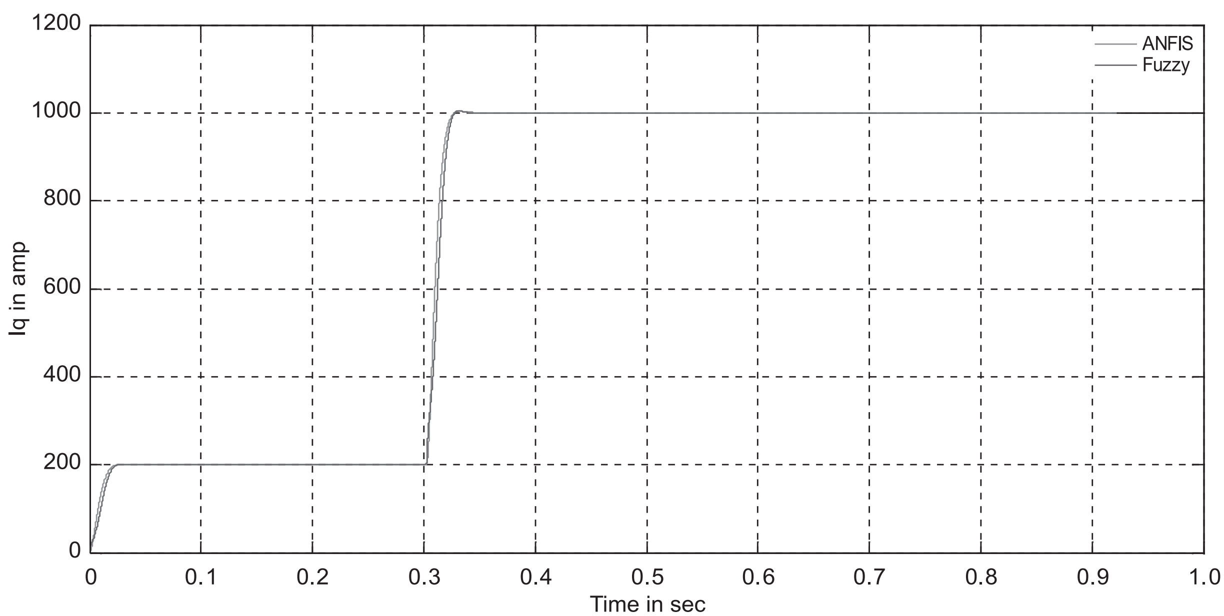

Figure 5(e)

The rotor *d* and *q*-axis current components i_{dr} and i_{qr} respectively, are shown in the Figures 5(e) and 5(f) It can be found that an increase in the *q*-axis component of the rotor current i_{qr} is required for the raise of active power generated, and the same thing is going on within the reactive power and the rotor current d-axis component i_{dr}.

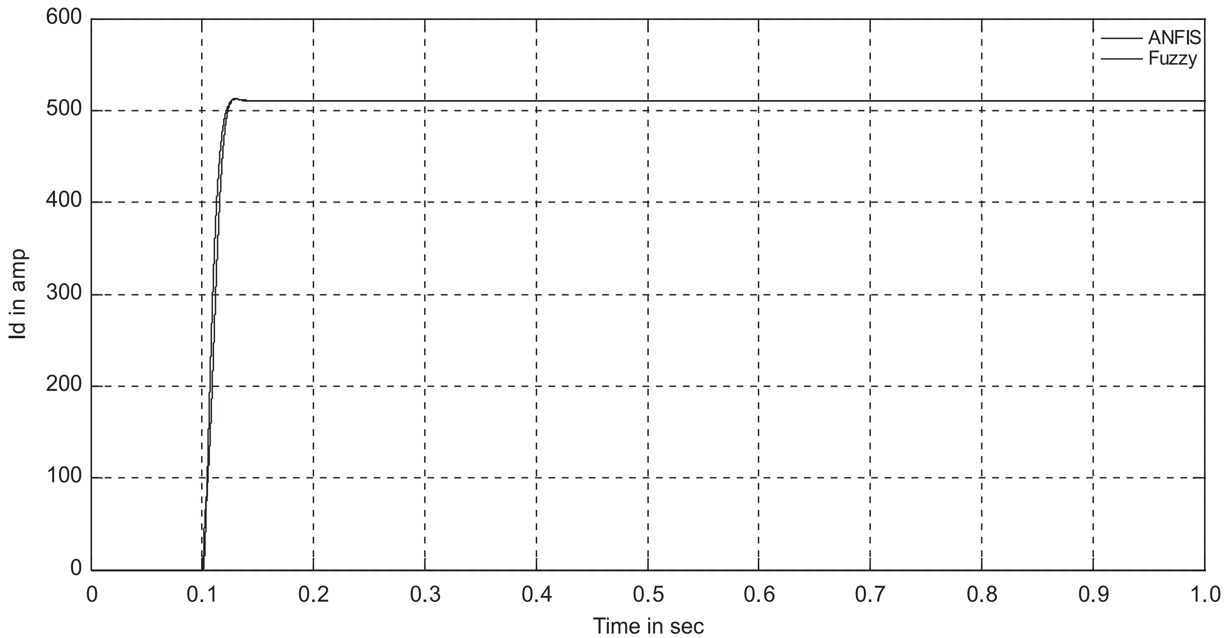

Figure 5(f)

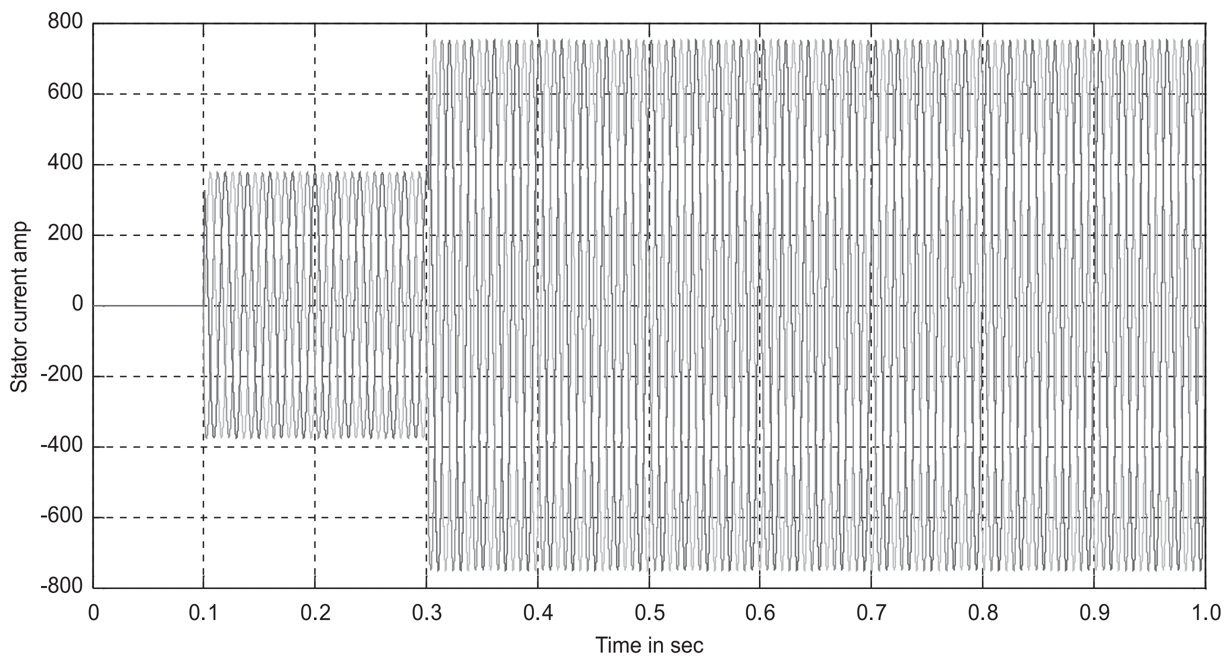

Figure 5(g)

The 3-phase currents of the stator and the rotor respectively, are shown in Figure 5 (g) and (h). It is realized from Figure 5 (g) and (h) that they proportionally varied across the stator reactive and active power changes. In addition, when the rotor speed reaches to the synchronous speed the frequency of the rotor current reduces, but its magnitude gives the power transferred with the DC-link in the rotor.

Figure 5 Grid integrated DFIG response with proposed ANFIS and Fuzzy controller (a) Active Power in MW (b) Reactive power in KVAR (c) coefficient of power (d) DFIG speed (e) Quadrature axis and (f) Direct axis current of DFIG (g) DFIG Stator current and (h) Rotor current.

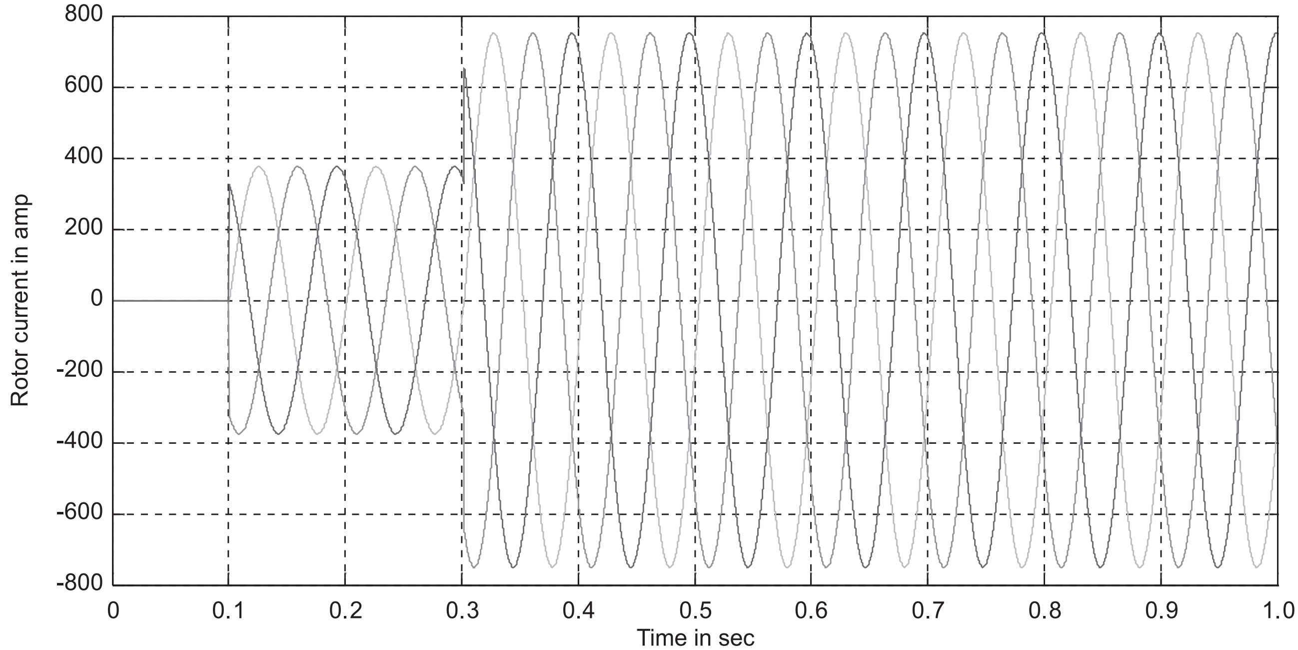

Figure 5(h)

Proposed system has a variable speed wind turbine. The wind speed was changed from 8 m/s to 13.5 m/s at 0.3 Sec, due to these changes, wind turbine prime mover torque was changed then DFIG output power changes. By analyzing power, reactive power, coefficient of power and Speed variations proposed ANFIS controller forces the system into steady state as earlier than fuzzy

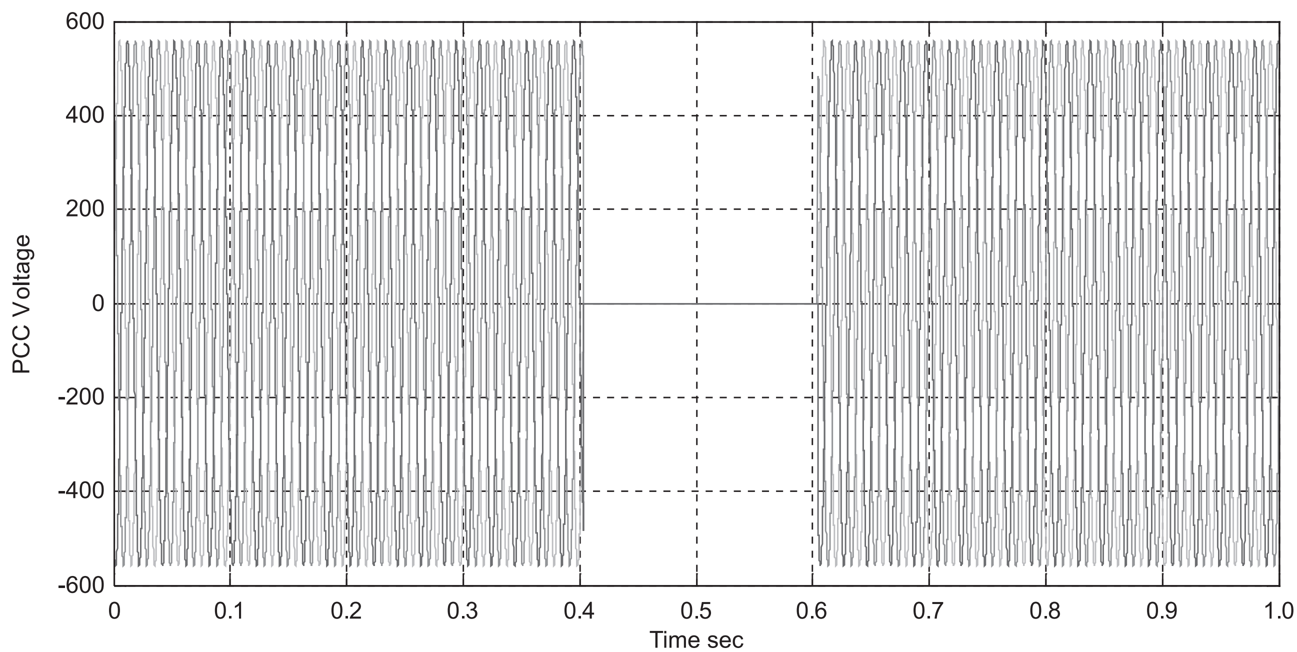

Figure 6: Voltage at PCC

The fault is applied at PCC from 0.4 to 0.6 secs, there is a drop in voltage drastically as shown in Figure 6. The swell is occurring in the current which is shown in Figure 7 from 0.4-0.6 secs.

At this condition the DFIG isolates from grid to fed supply to load for maintaining reliability. Figure 8 shows current supplied by DFIG to load up to their capability. Here DFIG is sufficient to meet the load is shown in Figure 8.

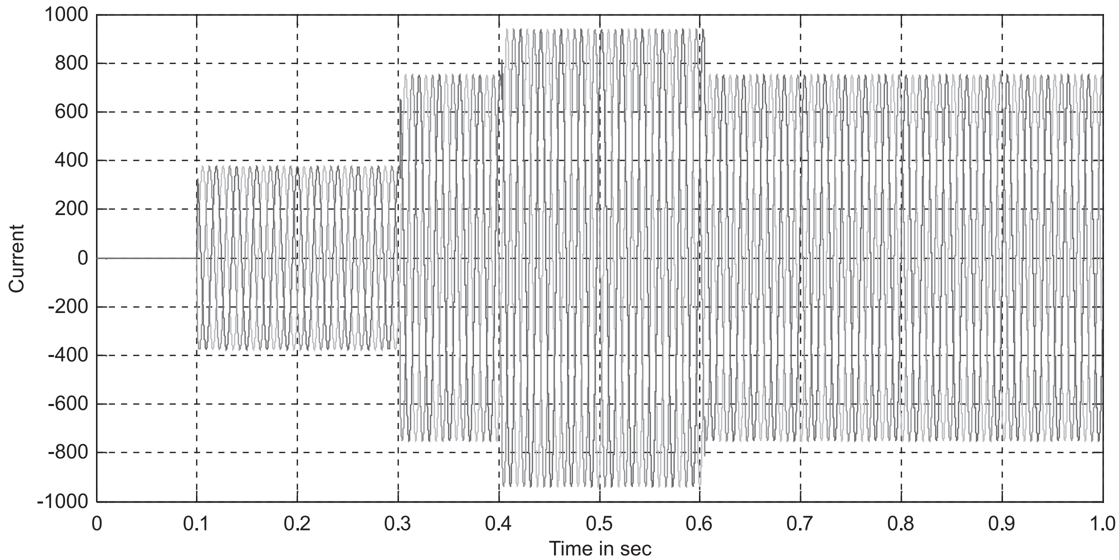

Figure 7: Current at PCC under fault condition

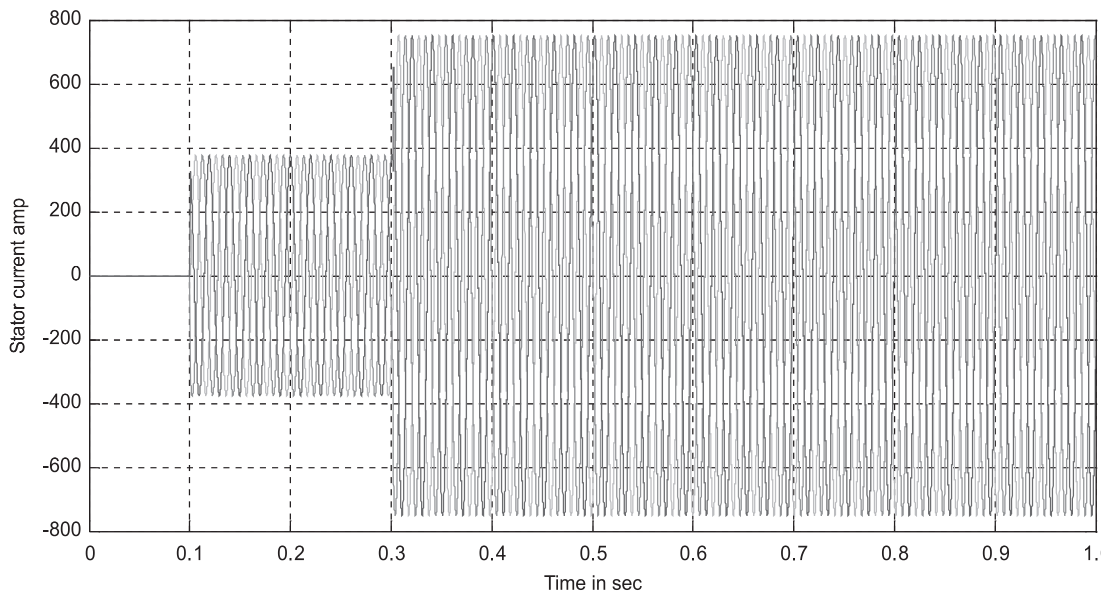

Figure 8: DFIG Current in islanded mode

Table 1
Parameters of DFIG

Parameter	*Value*
V_s (line to line)	575
P_s in MW	1.5
V_{dc} in volts	1200
No. of poles	4
F_s in Hz	50
R_s in ohm	0.012
R_r in ohm	0.021
L_s in H	0.0137
Mutual inductance/ H	0.0135
DC link capacitor/F	0.04
L_r in H	0.0136

Table 2
Specifications of wind turbine

Specification	*Value*
Wind speed (m/s)	12
No. of blades	3
Radius of the blade	35.25
Gain of gearbox	91
Moment of inertia	1000
Viscosity factor	0.0024

8. CONCLUSION

Grid integrated DFIG based WECS has ANFIS controller to control reactive and active power by controlling rotor side controller and a DC-link capacitor voltage will maintain by controlling stator side controller. The ANFIS controller was introduced instead of fuzzy logic controller. The proposed technique withholds all the advantages of artificial neural networks and fuzzy logic controllers such as flexibility, robustness and rapidity [2], [3].

The system performance at the wind speed and parameter variation are analyzed with fuzzy and ANFIS controller. By comparing system response, ANFIS can reduce system oscillations effectiveness and reduces the time taken to reach a steady state value is less compared to fuzzy logic controller.

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