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Blades Pitch Angle Control and Crowbar Protection of a Wind Turbine using Adaptive Neuro-Fuzzy Inference System at Severe Faulty Conditions

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ABSTRACT

Due to their superior efficiency, stability, and ability to produce maximum power at various typical operating situations, wind turbines driving doubly fed induction generator systems are widely utilized in the extraction of wind energy. These systems have stability issues, particularly at severe faulty conditions. This paper focuses on the fault ride-through of a doubly fed induction generator (DFIG) driven by a wind turbine using Adaptive Neuro-Fuzzy Inference System (ANFIS). The measured voltages and currents at the generator's terminals are used by the proposed ANFIS technique to identify the faulty conditions. ANFIS technology activates the wind turbine's pitch angle controller in times of failure to avoid the system's rotating components from over speeding and to make sure that the generator does not deviate from stability by modifying the wind turbine's aerodynamic torque. Additionally, the ANFIS controller turns on the crowbar resistance to protect the system's electrical components, particularly the power electronics converters and DC bus voltage. This paper compares the behavior of the DFIG under faulty conditions with and without the application of the suggested ANFIS approach. Using the Matlab^{TM}/Simulink environment, the system is modeled and simulated. The results are then recorded and analyzed.

Keywords: Wind energy, DFIG, fault, ANFIS, Crowbar protection, pitch angle control

Nomenclature

ANN	Artificial Neural Network	N	Gear ratio
FIS	Fuzzy Inference System	Ki	Integral controller gain
FRT	Fault Ride Through	L_m	Mutual inductance
MPPT	Maximum Power Point Tracking	P	Number of pole pairs
PSO	Particle Swarm Optimization	λ_{opt}	Optimal tip speed ratio
T_t	Aerodynamic torque	P_t	Output mechanical power of wind turbine
ρ	Air density	β	Pitch angle
R	Blade radius	C_P	Power coefficient
i_{dr}, i_{qr}	d-axis and q-axis rotor currents	K_p	Proportional controller gain
ψ_{dr}, ψ_{qr}	d-axis and q-axis rotor fluxes	$\omega_{g\text{-}Ref}$	Reference generator mechanical angular speed
v_{dr}, v_{qr}	d-axis and q-axis rotor voltages	P_S, Q_S	Stator active and reactive powers
i_{ds}, i_{qs}	d-axis and q-axis stator currents	R_s, R_r	Stator and rotor resistances
ψ_{ds}, ψ_{qs}	d-axis and q-axis stator fluxes	L_S	Stator inductance
v_{ds}, v_{qs}	d-axis and q-axis stator voltages	λ	Tip speed ratio
T_{em}	Electromagnetic torque	C_t	Torque coefficient
ω_r	Frequency of rotor voltages and currents	ω_R	Turbine mechanical angular speed
ω_s	Frequency of stator voltages and currents	V_W	Wind speed

1 INTRODUCTION

Wind energy is one of the oldest sources of energy used by humans and today it has become the most growing, widespread, and efficient source of renewable energy. Wind energy is inexhaustible and does not pollute the environment, and its frequent use limits the use of fossil fuels, which are a source of greenhouse gases that cause global warming [1- 3].

Fixed and variable speed generators are the two types of wind turbine generators [4, 5]. Variable-speed wind turbines can generate 8% to 15% more electricity than fixed-speed turbines [6, 7]. There are many variable speed wind turbine topologies, each of which differs from the other depending on the generator used and the method of connecting the power electronic converters [8, 9]. Due to its high efficiency, flexible power management, and small converter capacity, the doubly-fed induction generator is the most extensively utilized generator in variable speed wind turbines [10, 11]. The stator of the DFIG is directly connected to the grid, while the rotor is connected to the grid via a low rating back-to-back converter together with DC bus voltage connected between them [12, 13]. The amount of energy taken from the wind is dependent on the type of control utilized in the wind energy conversion system, as well as the speed of the falling wind. The vector control strategy is one of the best control strategies that can be used [14]. The vector control approach is used in this study to decouple the control of the generator's active and reactive power [15]. The rotor and grid side converters are controlled by proportional plus integral (PI) controllers. The Particle Swarm Optimization (PSO) technique is used to optimize the parameters of the controllers. The optimal torque control strategy is also used to track the maximum power [16].

Power electronic converters and capacitors are found in DFIG, and these components are extremely susceptible to network faults and voltage dips. A high fault current travels through the stator windings, rotor windings, and power electronic converters when a fault develops and creates voltage dips. Mechanically, the generator speed is accelerated when a grid fault occurs. Acceleration occurs as a result of mechanical power from the turbine and lack or absence of electrical power drawn from the generator [17, 18].

In the past, disconnecting the DFIG when a fault occurred was the common decision to protect its components from dangerous effects and damage. Wind turbines must be connected to the grid during Fault Ride Through (FRT) in order to support grid voltage and frequency, according to the new grid code requirements [19]. As a result, wind turbine control and protection is a hot topic of study around the world.

The crowbar resistance is employed in this study to prevent excessive currents from going through the stator, rotor, and power electronic converters, as well as to defend against DC-link capacitor voltage increases [20]. When a fault occurs, the converters are disconnected and bypassed to protect them, and instead of the power electronic converters and DC-link capacitor, a crowbar resistor is connected to the slip rings of the rotor windings [21]. The pitch angle control is also used to protect the generator speed from acceleration by reducing the wind turbine's mechanical power in the event of a grid fault [22-24]. All previous controls are activated and deactivated using the Neuro-Fuzzy Inference System (ANFIS).

ANFIS integrates both an artificial neural network (ANN) and a fuzzy logic inference system, so it can be used to get the advantages of both in one approach. An ANN is a group of artificial neurons that simulates the human brain system. Each node (neuron) performs a specific function on incoming signals, and the form of node functions can vary from one node to the next.

The essential nucleus of ANFIS is the fuzzy inference system (FIS), which is described by a collection of fuzzy rules (IF-THEN) that are adapted by the neural network's learning algorithm. ANFIS has been utilized to regulate nonlinear systems in a number of publications [25-28]. In this paper, ANFIS is used as a tool to detect grid faults and take the necessary action to protect the generator components from potential dangers and damage.

The paper structure is organized as: Section 2 shows the mathematical representation of wind turbines and DFIG. Section 3 explains how to use ANFIS technique with the proposed system as well as explaining the configuration of ANFIS technology in detail. Section 4 illustrates the pitch angle control theory and how it is applied to the proposed control system. Section 5 presents the simulation results and discusses the significance of the proposed system in protecting DFIG in a faulty condition, and finally a conclusion is in section 6.

2 SYSTEM MODELLING

The DFIG model from the MATLABTM/Simulink SimPowerSystem toolbox is used in this study.

2.1 DFIG WIND TURBINE MODELING

The following formula is used to compute the mechanical power extracted by a wind turbine from the wind. [29-31]

$$P_t = \frac{1}{2}\rho\pi R^2 {V_W}^3 C_P(\beta, \lambda_i) \tag{1}$$

$$\lambda = \frac{R\omega_R}{V_W} \tag{2}$$

$$C_P = K_1\left(\frac{K_2}{\lambda_i} - K_3\beta - K_4\beta^{K_5} - K_6\right)e^{\frac{K_7}{\lambda_i}} \tag{3}$$

The relationship between the power coefficient and the tip speed ratio is shown in Figure 1, and it is obvious that the power coefficient reaches its maximum value of 0.44 when λ_{Opt} =7.2.

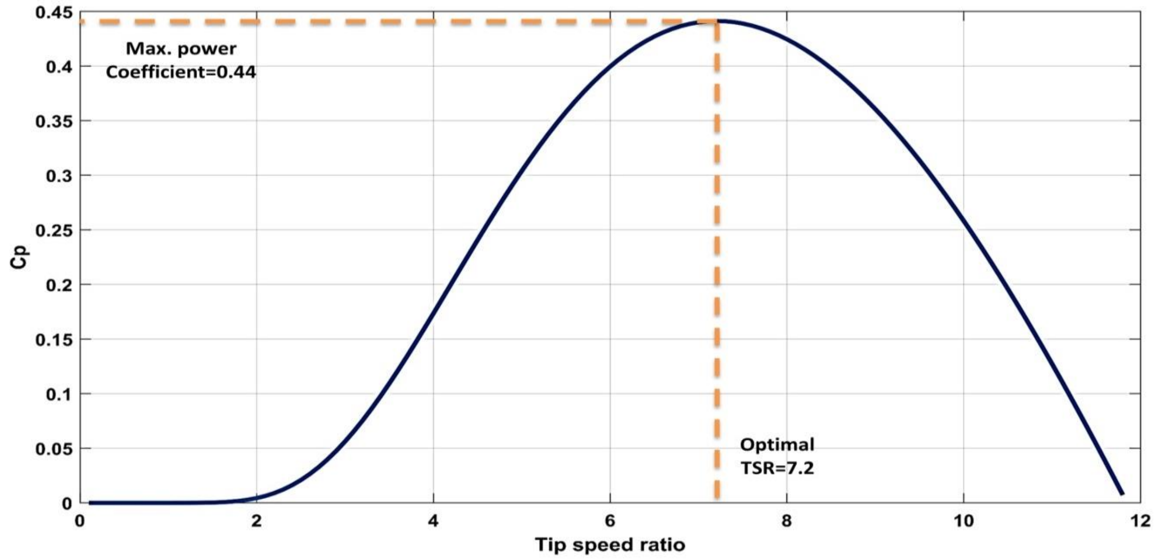

Figure 1 A modern three-blade wind turbine's performance curve.

The following formula is used to compute the aerodynamic torque.

$$T_t = \frac{P_t}{\omega_R} \tag{4}$$

Using eq. (1) and eq. (2), the aerodynamic torque can be expressed as

$$T_t = \frac{\rho \pi R^2 {V_W}^3 C_P}{2\omega_R} = \frac{\rho \pi R^3 {V_W}^2 C_P}{2\lambda} \tag{5}$$

$$C_t = \frac{C_P}{\lambda} \tag{6}$$

As a result, the torque equation is as follows:

$$T_t = \frac{\rho \pi R^3 {V_W}^2}{2} C_t \tag{7}$$

The DFIG receives this torque as input.

2.2 DOUBLY FED INDUCTION GENERATOR MODEL

Because it is difficult to undertake dynamic control of an AC machine with a three-phase rotating phasor, transformation (Park transformation) of three phases (ABC) into two phases (d-q) has been implemented by providing a reference frame that rotates at the same speed as the stator flux. The d-q voltage equations are expressed as follows [32]:

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \tag{8}$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \tag{9}$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \tag{10}$$

$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} \quad (11)$$

In the d-q frame, the torque expression is as follows:

$$T_{em} = \frac{3}{2} P \frac{L_m}{L_S} (\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \quad (12)$$

In the d-q frame, the stator active and reactive power expressions are as follows:

$$P_S = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (13)$$

$$Q_S = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (14)$$

3 MODELING OF THE PROPOSED SYSTEM USING ANFIS TECHNIQUE

The proposed study system, as shown in Figure 2, consists of a 2 MW wind turbine connected to a 22 kV distribution system, with generated power transported to a 220 kV grid through a 30 km transmission line. The stator windings of the generator are directly connected to the grid, while the rotor windings are supplied with variable voltage and frequency via power electronic converters. The parameters of transmission line are Resistance (R) = 0.0486 ohm/km and Inductance (H) =0.0038 henry/km. ANFIS technology detects grid faults and takes necessary actions to keep the generator from disconnecting and protect it during faults. When the fault occurs, ANFIS opens circuit breaker 2 and closes circuit breaker 1, thus the converters are disconnected and the crowbar resistance is connected to the slip rings of the rotor windings. When the fault is cleared, ANFIS opens circuit breaker 1 and closes circuit breaker 2, thus the converters are connected to the slip rings of the generator rotor windings and the crowbar resistance disconnected. The pitch angle controller is activated and deactivated also using ANFIS. As shown in Figure 3, the ANFIS consists of 5 layers and has two inputs and one output. The first layer is the input layer and it has two input variables, the first is voltage V_{abc} and the second is current I_{abc}. This layer's neurons merely transmit the crisp signal on to the next layer. The fuzzification layer is the second layer, and the neurons in this layer fuzzify the signals received from the first layer and act as membership functions (MFs) to represent the fuzzy sets of incoming input variables. The rule layer, which receives input from the fuzzification neurons and calculates the firing strength of the rule they represent, is the third layer. In this layer, each neuron corresponds to a single Sugeno type fuzzy rule. The defuzzification layer is the fourth layer, and the neurons in this layer turn the preceding layer's fuzzy output into a crisp value that is utilized as a control signal. The output layer is the fifth layer, which is represented by a single neuron, gathers the outputs of all defuzzification neurons and delivers ANFIS' overall output.

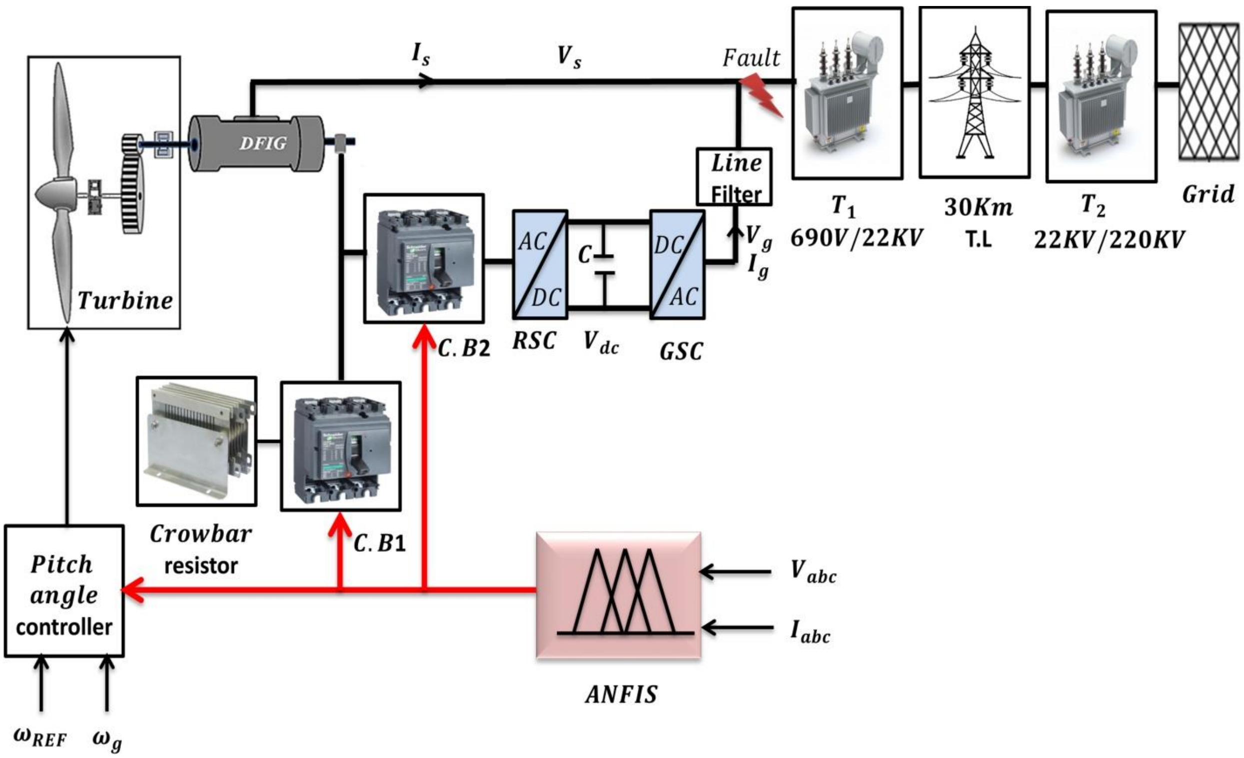

Figure 2 Block schematic of the proposed ANFIS technology for the DFIG wind turbine

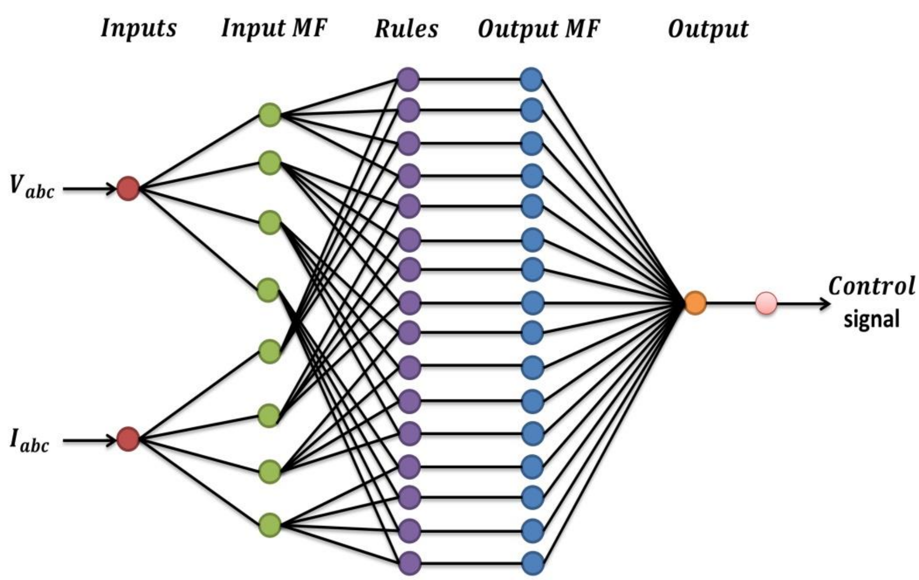

Figure 3 Structure of proposed ANFIS technique

The parameters for ANFIS are as follows: For each input, there are two inputs and four MFs; the type of input MF is Gaussian; the output MF is constant; the error tolerance is set to zero; the number of epochs is 400; grid partition and the optimization method is a hybrid algorithm, as shown in Figure 4.

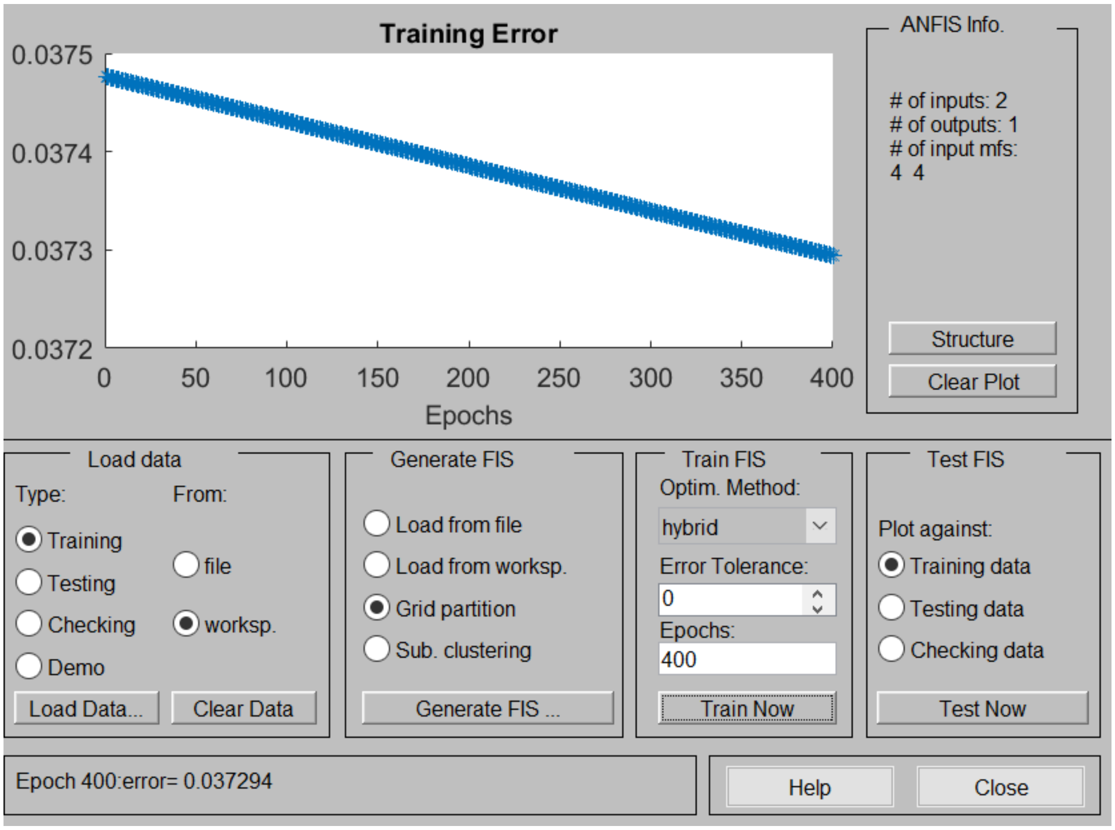

Figure 4 Neuro-Fuzzy Designer in MATLAB program

The training data are the voltage and current values on the DFIG terminals in the normal state and the abnormal state. The data includes different fault types of faults locations. Table 1 shows a sample of training data in the normal case and the fault case when a three-phase fault occurs. Training and testing are performed using MATLAB Simulink toolbox. The root mean square value of the measured three-phase voltages (V_a, V_b and V_c) and three-phase currents (I_a, I_b and I_c) on the DFIG terminals are the inputs to ANFIS, as shown in the equations below:

$$V_{abc} = \frac{1}{3}(V_a + V_b + V_c) \tag{15}$$

$$I_{abc} = \frac{1}{3}(I_a + I_b + I_c) \tag{16}$$

The output is the control signals to the three - phase circuit breakers and pitch angle controller.

Table 1 Sample training data

	V_{abc}	I_{abc}	**ANFIS output**
Normal Case	397.95 V	1337.2 A	0
Fault Case	1.0567 V	1661.7 A	1

4 DESIGN OF A TRANSIENT FAULT CONTROLLER FOR STABILIZATION OF POWER SYSTEMS

When a short-circuit fault occurs, the system oscillates in a sub-synchronous manner, which must be damped before the system becomes unstable. Traditionally, such oscillations have been dampened by synchronous generators and power system stabilizers in traditional power plants. Wind turbines must have highly effective techniques of managing their electrical output power if they are to take up such dampening jobs. Pitch angle can be used to adjust the amount of aerodynamic power generated by a turbine rotor. The speed of the generator increases when the fault occurs, and therefore the aerodynamic torque must be reduced. As the pitch angle increases, the angle of attack of the wind decreases. The effect of raising the pitch angle on the power coefficient is seen in Figure 5.

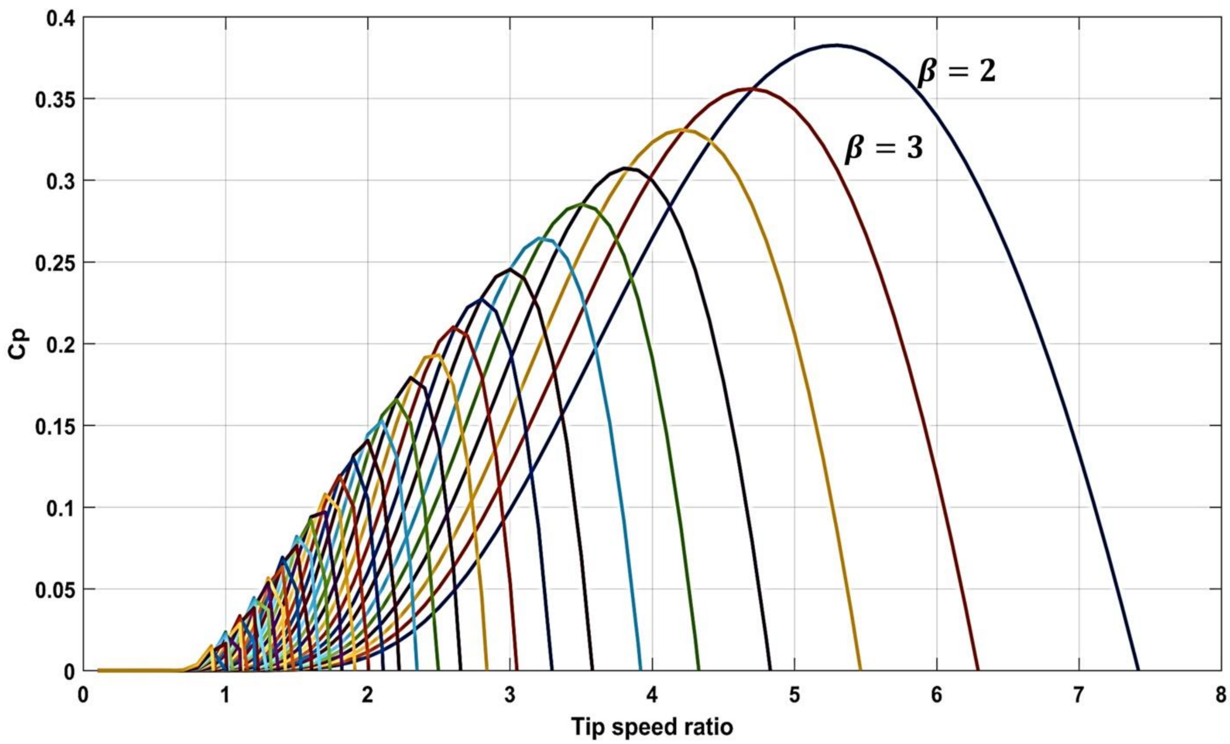

Figure 5 Characteristics of power coefficients at varied pitch angles (pitch=2°, 3°, 4°… 39°)

Figure 6 shows a model of a wind turbine using MATLAB software. The pitch angle (β) is the angle that must be controlled when a fault occurs, and after the fault is cleared it returns to the value 0 to take full advantage of the wind energy falling on the blade, Where:

$$f_1(u) = \frac{1}{\frac{1}{\lambda - 0.02\beta} + \frac{0.003}{\beta^3 + 1}} \tag{17}$$

The equations of f_2 (u) and f_3 (u) are mentioned in Section 2.1.

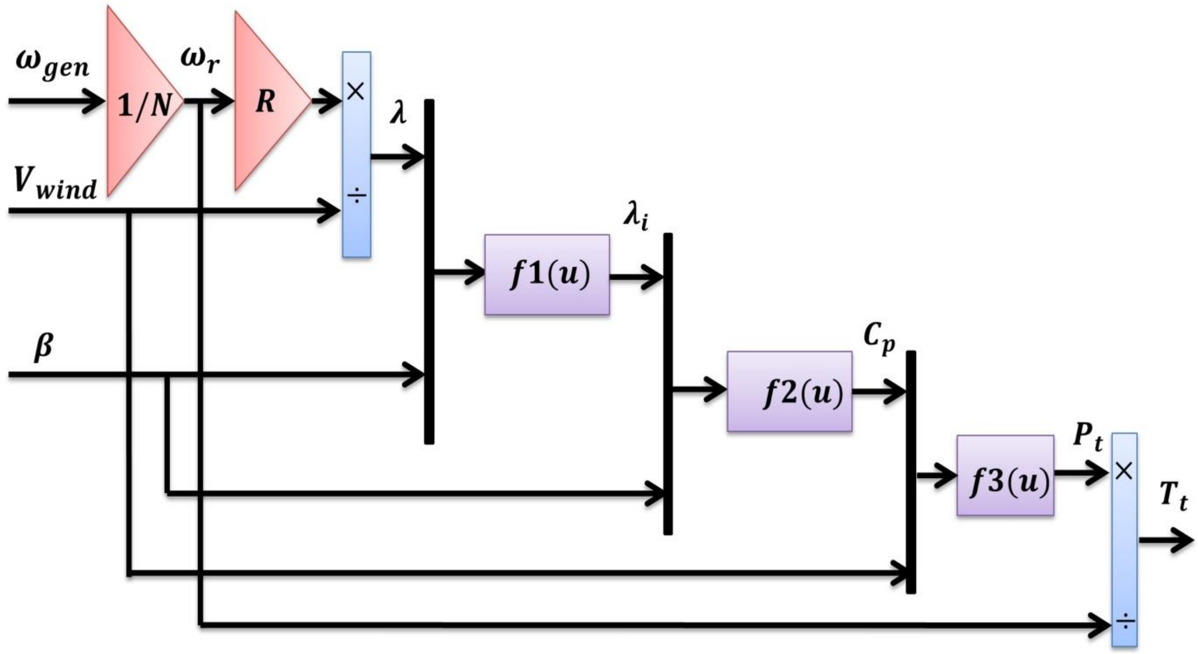

Figure 6 explain the role of pitch angle in a wind turbine model

The idea of the control work is based on comparing the reference speed of the generator (ω_{Ref}) that is calculated using the maximum power point tracking strategy (MPPT) as in Eq. 18 with its current speed

$$\omega_{g-Ref} = \frac{\lambda_{opt} V_w}{R} * N \tag{18}$$

The error signal goes to the PI controller. The controller gains (K_p and K_i) are selected using particle swarm optimization method (PSO). All of the above are activated or deactivated using ANFIS as in Figure 7.

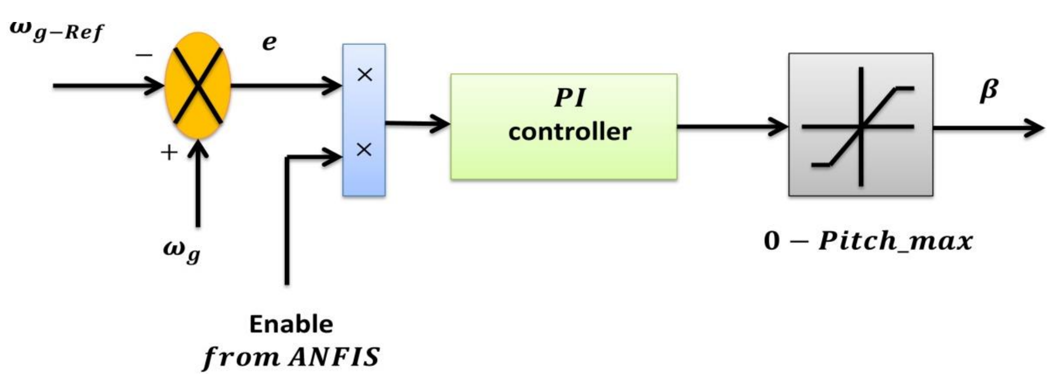

Figure 7 PI pitch controller

5 RESULTS AND DISCUSSION

The wind speed is 10 m/s, so the optimal speed of the generator is 171.42 rad/sec, and the value of the maximum generated power is 1.49 MW. A simulated fault is a three-phase to ground fault at the terminals of wind turbine generator, which is the worst type of fault that can occur. The fault occurred at the instant 8 s and lasted 300 ms until it is cleared by the protection devices. Figure 8 shows the control signal coming out from ANFIS to circuit breaker No. 1 & pitch angle controller. Figure 9 shows the control signal coming out from ANFIS to circuit breaker No.2. From Figure 8 and Figure 9, it is clear that ANFIS efficiently detected the fault and correctly output control signals before, during and after the fault.

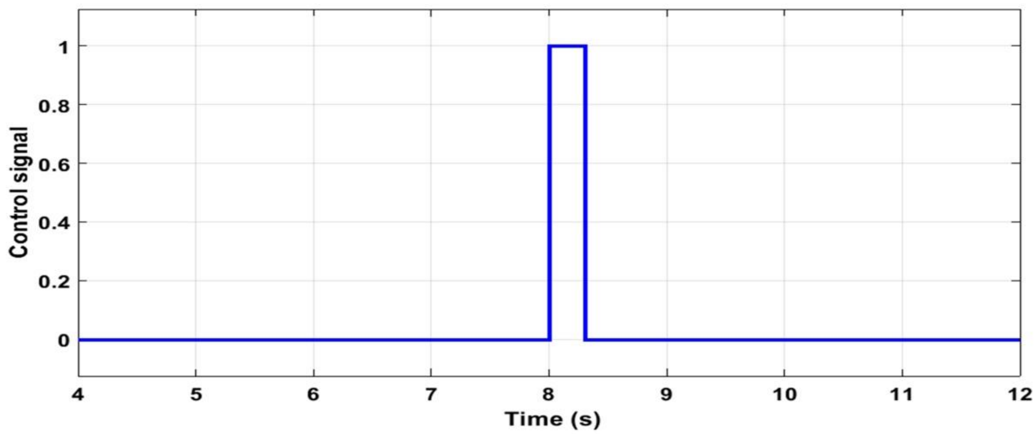

Figure 8 ANFIS technique output for C.B 1& pitch angle controller

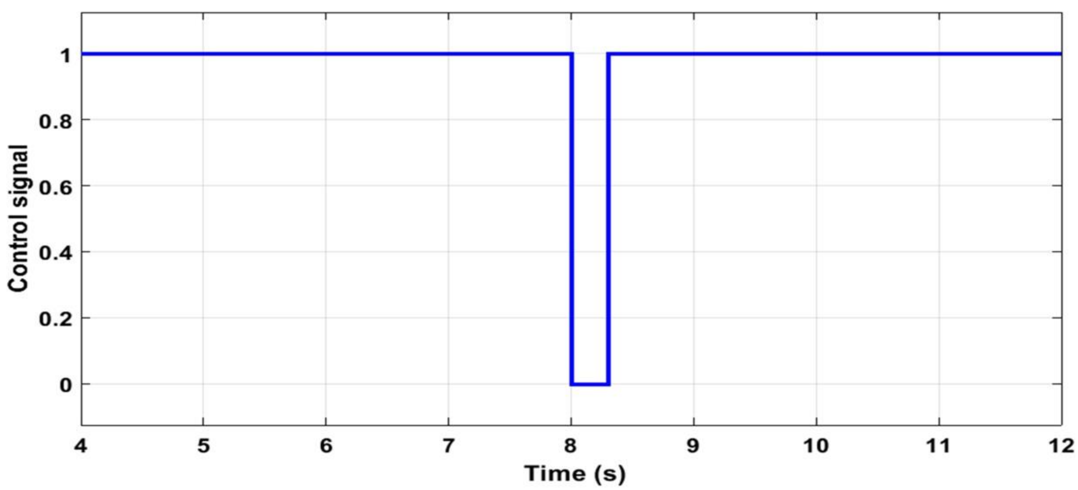

Figure 9 ANFIS technique output for C.B 2

Figure 10 shows the variations in rotor speed during fault when the pitch angle control technology is used and not used. If ANFIS technology is not used when the fault occurs, the generator speed increases from 171.42 rad/s to 196.4 rad/s, which may cause the generator to come out of stability. With ANFIS, the pitch angle control is activated when the fault occurs, so aerodynamic torque is reduced and the generator speed is almost constant in the event of the fault. Rotor speed is more stable with suggested ANFIS technique and pitch angle control.

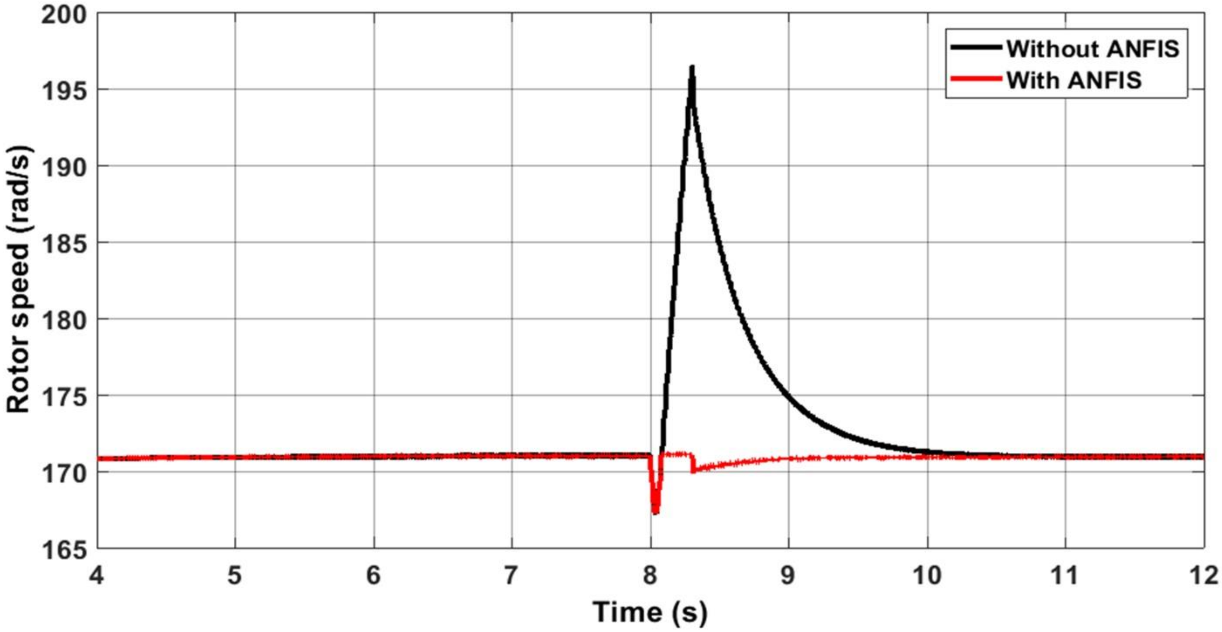

Figure 10 the rotor speed responses during a grid fault

Figure 11 shows the change in frequency when the fault occurs with and without the proposed ANFIS control method. The frequency when using ANFIS is less fluctuating and returns to its original value faster than without using ANFIS

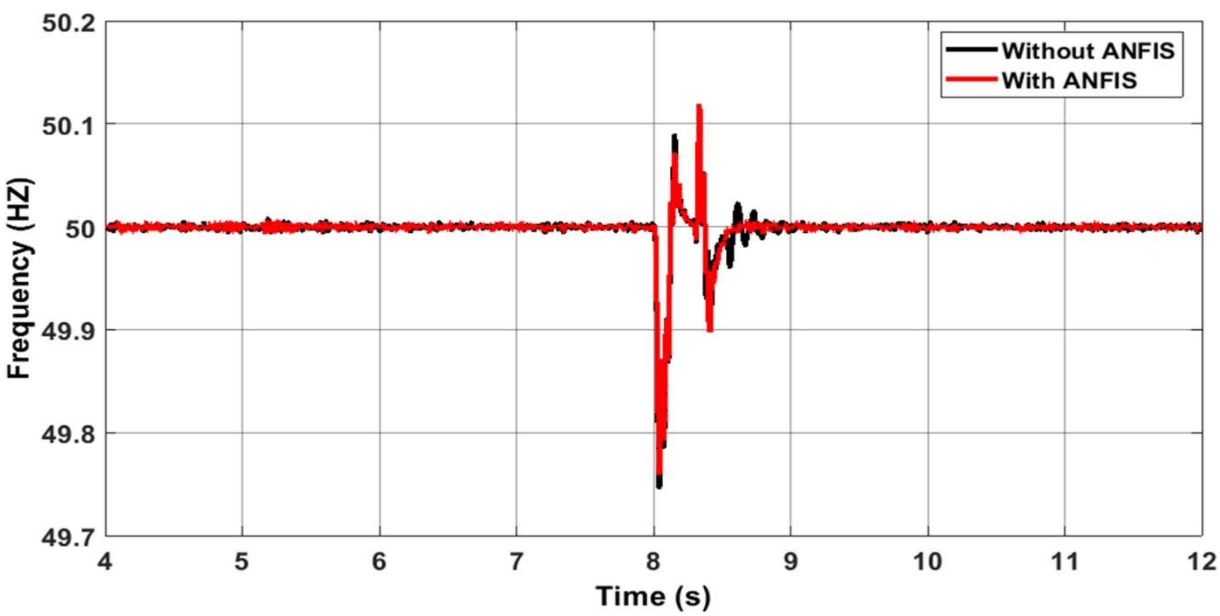

Figure 11 the frequency response during a grid fault

As in Figure 12, the DC bus voltage has reached about 2150 V without using ANFIS when the fault occurs, and this value may damage the components of power electronic converters. When using ANFIS, the DC bus voltage value reached about 1300V. Thus, the proposed ANFIS technology fulfills its function of protecting the DFIG elements in the event of a grid fault.

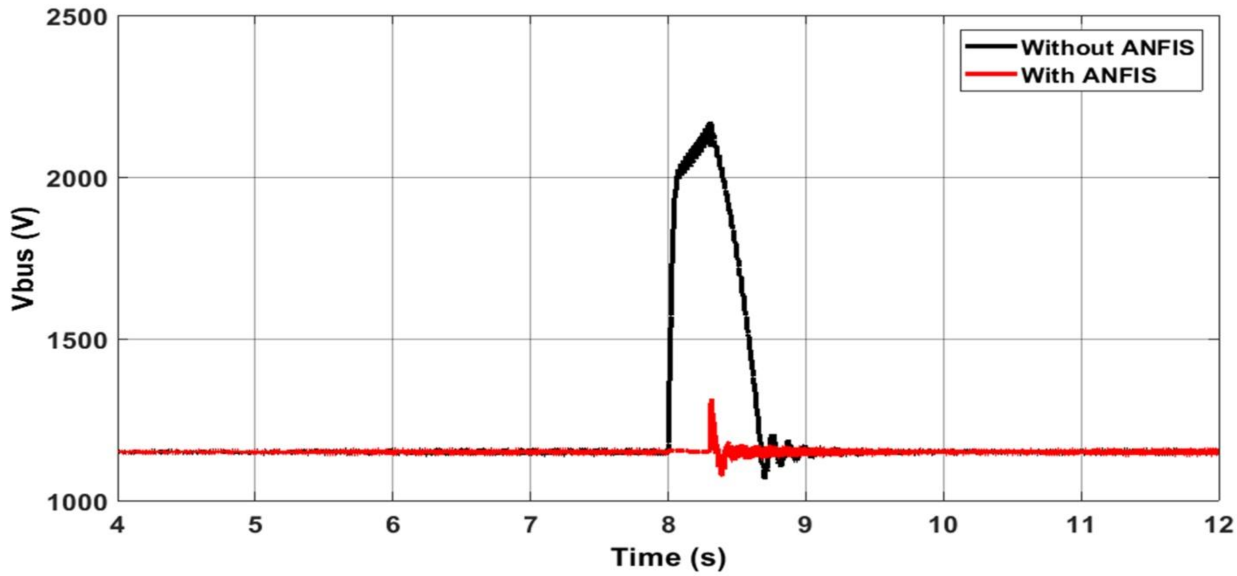

Figure 12 the DC-link voltage response during a grid fault

As in Figure 13, the grid active power in the event of a fault using ANFIS has a lower overshoot value, as well as a lower settling time than when not using ANFIS.

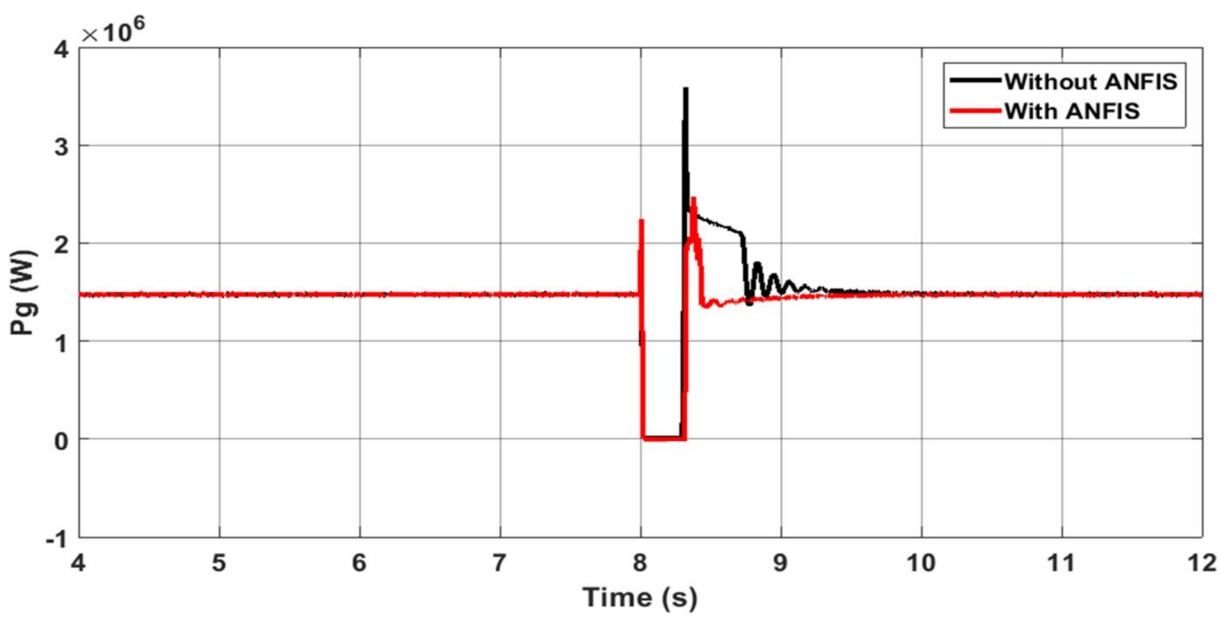

Figure 13 The Grid active power responses during a grid fault.

6 CONCLUSION

During a fault, this paper provides an ANFIS control approach for a DFIG wind turbine that is connected to the electrical grid. The proposed ANFIS control technology identifies the fault by measuring three-phase voltages and currents at the DFIG wind turbine's terminals, then activates the crowbar protection system and pitch angle controller during the fault period and deactivates them after the fault has been cleared. The behavior of a DFIG wind turbine during a grid fault is compared with and without the proposed ANFIS. Variations in rotor speed, grid active power, DC-link voltage, and frequency are also evaluated during fault occurrence and after fault clearance. When compared to the scenario without the ANFIS, the simulation findings show that the analyzed grid-connected wind turbines are more stable, have less fluctuation during grid faults, and can return to a stable condition in a short period when fitted with the suggested ANFIS technique. The proposed ANFIS control system has proven its effectiveness in protecting the DFIG in the event of a grid fault..

APPENDIX

Wind turbine parameters	
Blade radius (R)	42m
Nominal wind speed	12.5 m/s
Gear ratio (N) = 100	100
DFIG parameters	
Rated Stator power (Ps)	2MW
Frequency (F)	50 HZ
Synchronous speed	1500 rpm
Pole pairs (p)	2
Rated stator Voltage	690V
Stator resistance (Rs)	2.6mΩ
Rotor resistance (Rr)	2.9mΩ
Stator / Rotor inductance	2.587mH

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