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Fault Diagnosis in Wind Power System Based on Intelligent Techniques

Abstract-*Wind energy is one of the most important sources as well as being environmentally friendly and sustainable. In this paper, different types of faults of Doubly-Fed Induction Generator (DFIG) have been studied based on Artificial Neural Network (ANN), Particle Swarm Optimization (PSO) and Field Programmable Gate Array. To simulate the wind generators model MATLAB/Simulink program has been used. Artificial Neural Network (ANN) is trained for detection the faults and (PSO) technique is used to get the best weights. After the training process, the network was transformed into a Simulink program and then converted into the Very High Speed Description Language (VHDL) for downloading on the (FPGA) card, which in turn is used to detect and diagnosis the presence of faults where it can be re-programmed with high response and accuracy.*

Keywords- *Doubly-Fed Induction Generator (DFIG), Artificial Neural Network (ANN), Particle Swarm Optimization (PSO), Field Programmable Gate Array (FPGA).*

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1. Introduction

Renewable energy has been developed rapidly because of increasing the environmental interests during last years. The main facilities and advantages of electricity generated from sources of renewable energy are; the availability and sustainability, absence of harmful emissions and infinite availability to prime mover that is converted electricity. Wind energy is considered as a main source of generating electricity from renewable energy, and many wind turbines have a capacity of 4MW or more. The Induction Generator (IG) represents an important component in such power system, where its efficiency, stability and any fault can effect on the generated power of the wind turbine. The fault diagnosis can be considered as a technology based on equipment status information to detect the source of the fault and determine the suitable decision-making. Many new methods, tools and techniques are available that can be used to monitor the condition of electrical machines in order to extend the duration of their operational life. Some of these techniques include using sensors, which can measure speed, output torque, vibration, flux densities, temperature …etc. These sensors can be coupled and combined together with architectures and algorithms based on Artificial Intelligence (AI) such as; Artificial Neural Networks (ANNs) and swarm optimization methods which can allow more efficient, reliable and better monitoring of the machine and equipment conditions. The traditional fault diagnosis methods such as; devices based on observation, equivalent relations and parameters estimation require complex analytical models, while the intelligent methods need not such analytical models. The most common methods and techniques of Induction Machine (IM) condition monitoring utilize the steady state components of the stator quantities. These components are; voltage, current and power which can be used to detect; the turn fault, broken rotor bar, bearing failure, and air gap eccentricities [1, 2, 3, 4]. Therefore, in this paper section 2 describes a fault diagnosis in a wind power system. The mathematical model of DFIG in wind energy system is presented in section 3. Section 4 discusses description of the proposed intelligent model and algorithm, section 5 introduces a wind power model description, section 6 presents the simulation results of DFIG of the proposed model**,** section 7 introduces the experimental results of fault detection and diagnosis**,** while the main conclusions are given in section8.

2. Fault Diagnosis in Wind Energy System

Minimization of the operational and maintenance costs of wind power plants are very necessary and important tasks. The most reliable and efficient methods of minimization these costs would be to continuously monitor the condition of these systems especially the induction generator used in such systems which represents the main component in wind power system. This allows for

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early detection of the degeneration of the generator's health, maximizing the productivity, facilitating a proactive response and minimizing downtime. Wind generators are also inaccessible since they are installed on high towers, which are about 50m or more in height. There are also plans to increase the number of offshore sites increasing the need for a remote methods, means and techniques of monitoring the generator, which eliminates some of the difficulties faced due to accessibility problems. Therefore, monitoring of a wind power system from faults is very important as a protection process, which increases the system reliability, reduces preventive maintenance increasing its operational life [4, 5, 6].

3. Mathematical Modeling of DFIG

The mathematical analysis is implemented for 3-phase electrical generators by using Park transformation. The abc frame (dynamic equations) can be transformed into rotating dq frame [7, 8, 9, 10]. The main equations of stator and rotor voltages can be written as follows:

$$V_{ds} = r_s\, i_{ds} + \omega_s \Psi_{qs}$$
$$V_{qs} = r_s\, i_{qs} + \omega_s \Psi_{ds}$$
$$V_{dr} = r_r\, i_{dr} - S\omega_s \Psi_{qr} + \frac{d\Psi_{qr}}{dt}$$
$$V_{qr} = r_r\, i_{qr} - S\omega_s \Psi_{dr} + \frac{d\Psi_{dr}}{dt} \quad (1)$$

the flux linkage equations are:

$$\Psi_{ds} = l_s\, i_{ds} + l_m i_{dr}$$
$$\Psi_{qs} = l_s + i_{qs} + l i_{qr}$$
$$\Psi_{dr} = l_r\, i_{dr} + l_m i_{ds}$$
$$\Psi_{qr} = l_r\, i_{qr} + l_m i_{qs} \quad (2)$$

The active and reactive powers at stator and rotor side:

$$P_s = V_{ds} i_{ds} + V_{qs} i_{qs}$$
$$Q_s = V_{qs} i_{ds} - V_{ds} i_{qs}$$
$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr}$$
$$Q_r = V_{qr} i_{dr} - V_{dr} i_{qr} \quad (3)$$

The total power output is:

$$P_{total} = P_s + P_r = V_{ds} i_{ds} + V_{qs} i_{qs} + V_{dr} i_{dr} + V_{qr} i_{qr}$$
$$Q_{total} = Q_s + Q_r = V_{qs} i_{ds} - V_{ds} i_{qs} + V_{qr} i_{dr} - V_{dr} i_{qr} \quad (4)$$

The mechanical and electromagnetic torques is:

$$T_e = \frac{3}{2}\frac{p}{2}(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds})$$
$$T_m = T_e + \frac{J}{p}\frac{d\omega_r}{dt} \quad (5)$$

where r_r, r_s, l_r, l_s are rotor, stator winding resistances and inductances, l_m is the mutual inductance. $V_{ds}, V_{qs}, V_{dr}, V_{qr}$ are direct and quadrate of stator and rotor voltages. $i_{dr}, i_{qr}, i_{ds}, i_{qs}$ are direct and quadrate of rotor and stator currents, ω_s is stator current angular velocity, S is the slip, and ω_r is the angular velocity of rotor current.

4. Description of the Proposed Model

The proposed model in this work focused on fault detection and diagnosis of Doubly Fed Induction Generator (DFIG) in wind power system using Artificial Neural Networks (ANNs) and Particle Swarm Optimization (PSO). The software of the proposed model and the recorded data which are obtained from previous literatures and works and implemented and processed using MATLAB in order to obtain the required data of the normal and faulty cases of the generator. The Artificial Neural Network (ANN) is widely used in field of fault diagnosis. Therefore, the hybrid Neural Network-Particle Swarm Optimization (PSO) implemented on FPGA platform is proposed to improve the convergence rate and real time processing. The software translates the model into equivalent Field Programmable Gate Array (FPGA) card type Xilinix for processing by the board. The proposed optimum training process based on ANN-PSO of fault diagnosis can be summarized as follows:

1-Initialization particle of ANN.
2-Calculate fitness value (MSE).
3-If the fitness or objective value is better than the best fitness value (pbest), then set current value as a new (pbest).
4-Select the best value of particle of all particles as a (gbest).
5-Determine the velocity for each particle.
6-Update particle position (ANN weight).
7-If the condition is not reached,repeat steps (2-6).
8-Translate the outputs and downloading the program and the recorded data on FPGA board.

Figure 1 shows the flowchart of the proposed model based on ANN trained by PSO using FPGA for fault diagnosis using FPGA.

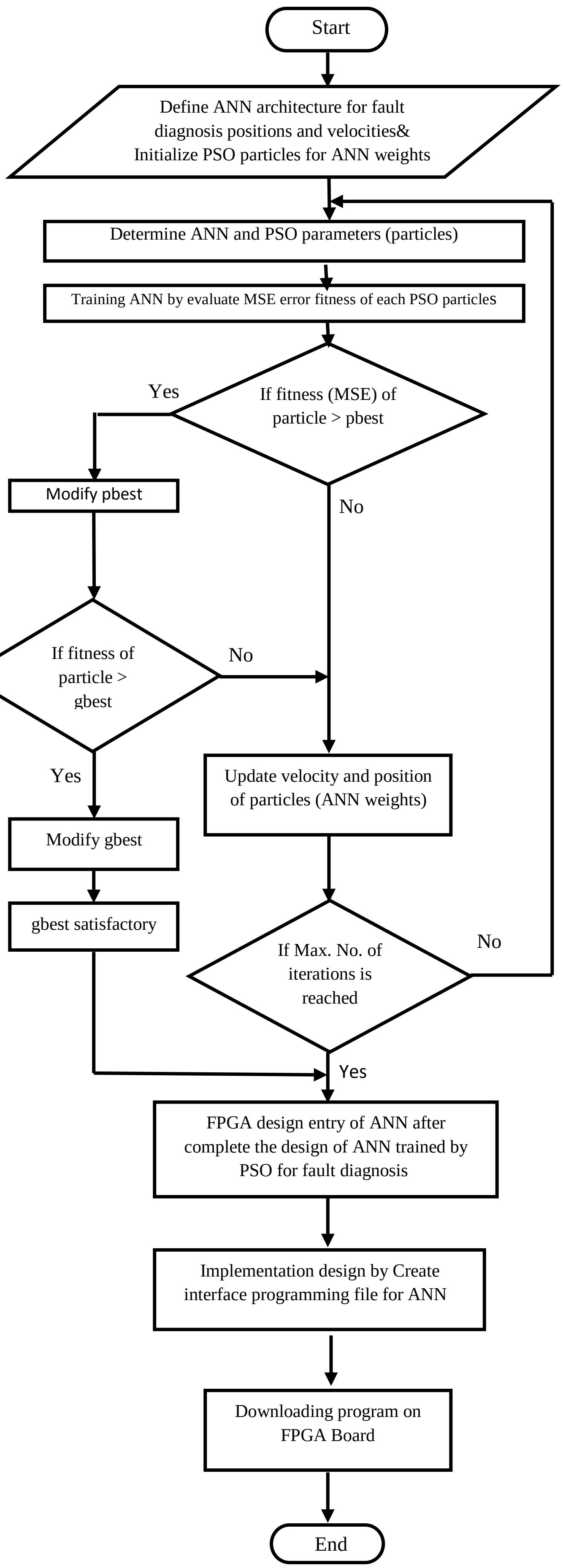

Figure 1: Flowchart of ANN - PSO using FPGA for fault diagnosis of DFIG

The ANN architecture is trained using feed-forward pack-propagation algorithm. The artificial neural network consists of one input layer consisting of five inputs neuron which represent active power (P_{active}), v_{ds}, v_{qs}, i_{ds} and i_{qs} which are generated from wind turbine system according to operational and environmental conditions, two hidden layers consisting of ten neurons in each hidden layer based on trial and error method, and one output layer consisting of five neurons which represent the output data of the proposed faults. The number of inputs and outputs depend on the problem specified to be solved and trained. Figure 2 shows the ANN architecture of the proposed network. The ANN training process of the proposed fault diagnosis is performed by evaluating the Mean Square Error (MSE) fitness of each particle to obtain the best solution and outputs based on the minimum of MSE, which can be reached, and then downloading the results on FPGA.

5. Description of Wind Power Model

The wind power model under study consisting of six generators with 1.5 MW for each generator is connected to a grid with voltage and frequency compactable with that adopted in Iraqi National Grid stander as depicted in Figure 3. An Induction Generator type Double- Fed squirrel cage (DFIG) is adopted to be used in this system and an AC/DC/AC IGBT-based on PWM converter. The generator stator is connected with 50Hz Grid frequency, while the side of rotor is connected through a convertor.

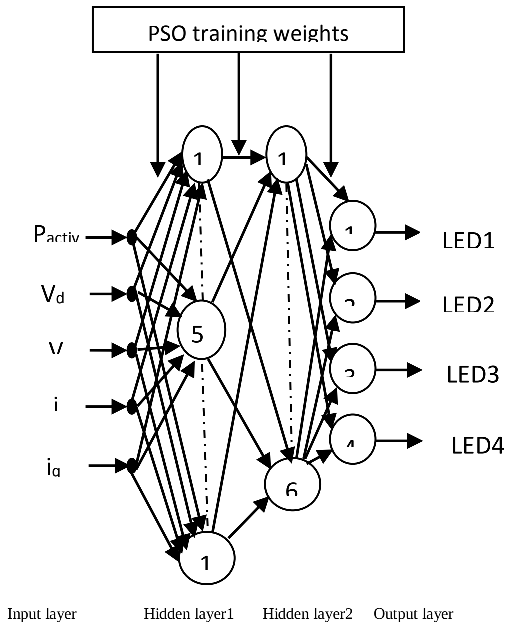

Figure 2: ANN-PSO architecture of the proposed network based on fault diagnosis

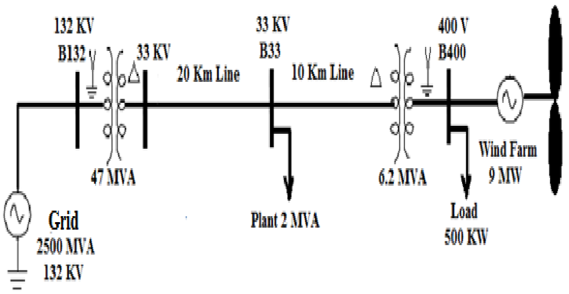

Figure 3: Single line diagram of wind power system connected to grid

6. Simulation Results of DFIG of the Proposed Model

The normal responses of turbine (voltage and current) are shown in the following cases and the responses after applying various types of faults on bus 400V.

Case 1: Response of turbine at normal state

When the system operates at normal state with balance load, the active power at bus 400V is 9MW and the voltage and current responses are shown in Figures 4 and 5 respectively.

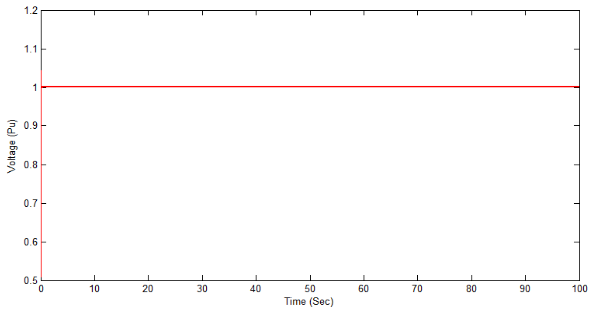

Figure 4: Response of 3-phase voltage at normal or healthy state

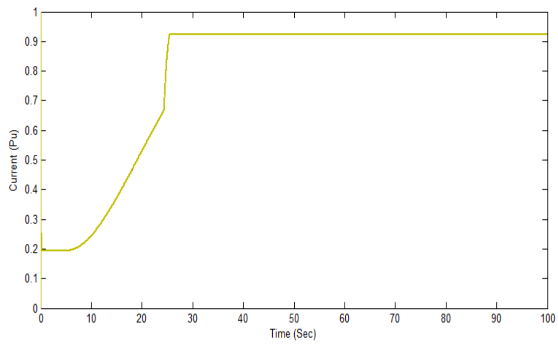

Figure 5: Response of 3-phase current at normal or healthy state

Case 2: Response of turbine at L-G fault

A single line to ground (L-G) fault has been applied on B400 (terminal of the generators) at time t = 45 sec. and lasts to time of t = 0.2 sec. for 50Hz. The power system and wind speed the value of current increases since the value of voltage decreases as shown. This is the most common fault, which occurs in the system. The voltage and current responses of this case are shown in Figures 6 and 7 respectively.

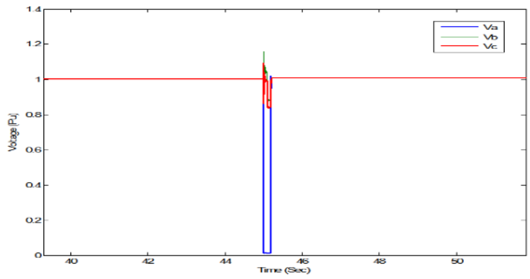

Figure 6: Response of 3-phase voltage at (L-G) fault

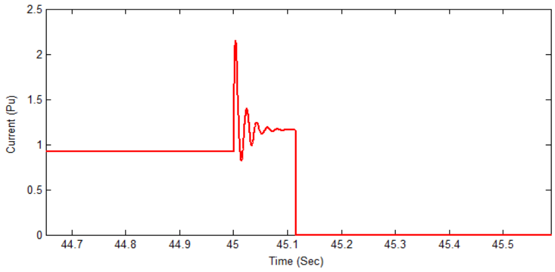

Figure 7: Response of 3-phase current at (L-G) fault

Case 3: Response of turbine at (L-L-G) fault

A double line to ground (L-L-G) fault has been applied on B400 (terminal generators) at time t= 45 sec and lasts for time t = 0.2 sec. Figures 8 and 9 respectively illustrate the responses of voltage and current waves of this case.

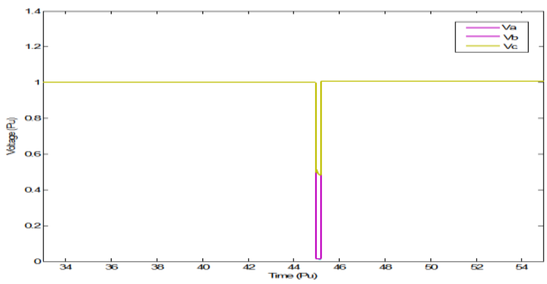

Figure 8: Response 3-phase voltage at (L-L-G) fault

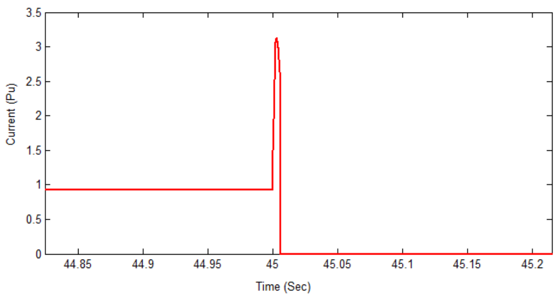

Figure 9: Response 3-phase current at (L-L-G) fault

Case 4: Response of turbine at (3L-G) fault

A three line to ground (3L-G) fault has been applied on B400 at time t = 45 sec and lasts for time t = 0.2 sec. The voltage decreases and drops to zero. This type of fault represents the most dangerous fault compared with other types of faults where its magnitude is too high. The voltage and current responses of this are shown in Figures 10 and 11respectively.

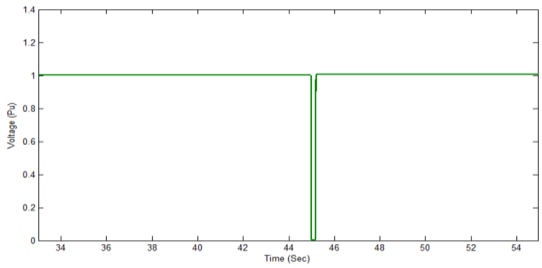

Figure 10: Response of 3-phase voltage at (3L-G) fault

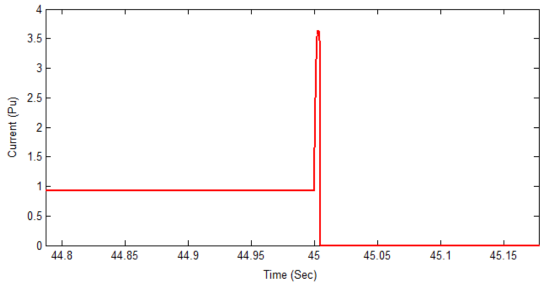

Figure 11: Response of 3-phase current at (3L-G) fault

Figure 12 shows the accuracy of training data with Mean Square Error (10^{-24}).The performance of each ANN with PSO techniques is shown in Figure 13. There is a difference in epoch (iteration) of each network, where each network has been trained on different data according to the input. The best trained network has the Error (10^{-2}).

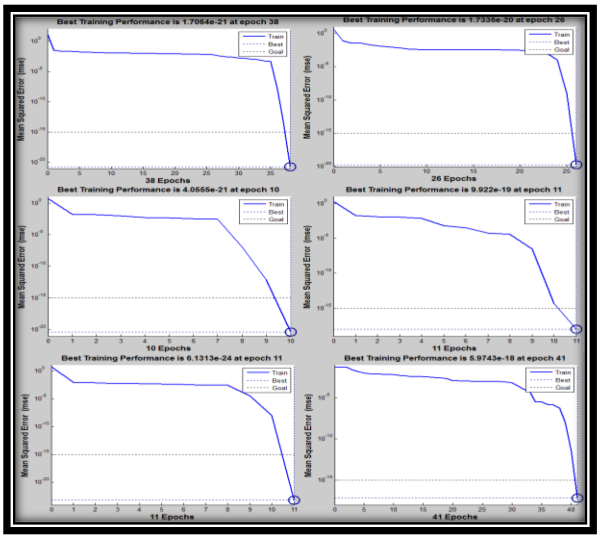

Figure 12: ANNs performance of the proposed model

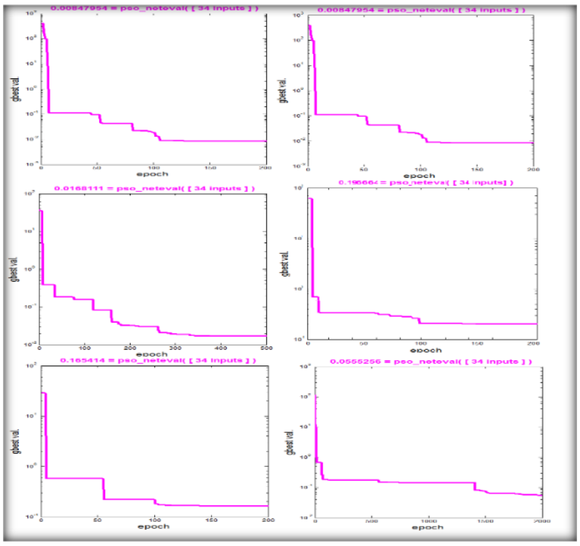

Figure 13: ANNs performance of the proposed model based on PSO

7. Experimental Results of Fault Detection and Diagnosis

The experimental results are displayed by using array of LEDs, which exist at FPGA card as shown in Figures 14 - 17, where four LEDs have been used to represent state of the system as illustrated in Table 1

1-PC computer for downloading the design.
2- Supply voltage for analog to digital convertor (ADC).
3-Supply as voltage data.
4-Supply as current data.
5- Two ADCs.
6- Four LEDs for digital current data.
7-Four LEDs for digital voltage data.
8-LEDs of FPGA card.
9-Zoom picture of FPGA LEDs.
10-LED No. one.
11-LED No. two.
12-LED No. three.
13-LED No. four.

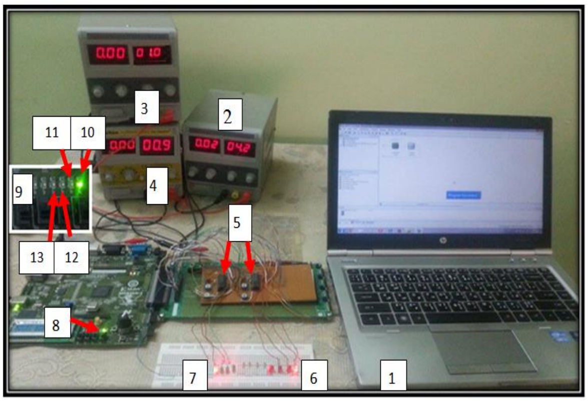

Figure 14: Normal state of the induction generator

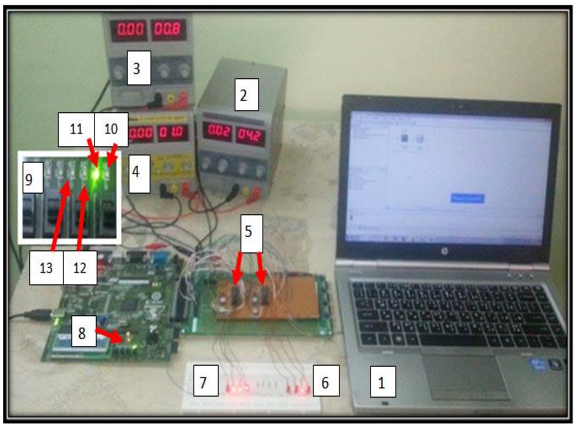

Figure 15: Single line to ground (L-G) fault state of Doubly-Fed Induction Generator

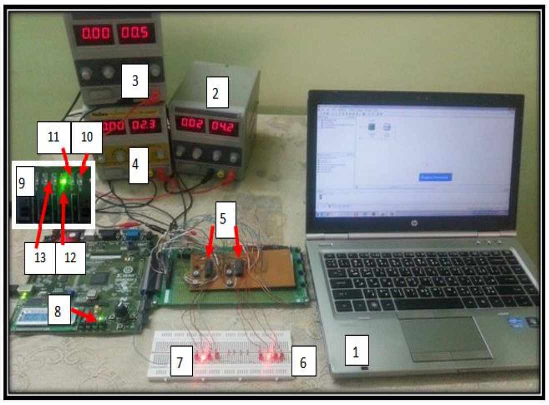

Figure 16: Double line to ground (L-L-G) fault state of Doubly-Fed Induction Generator

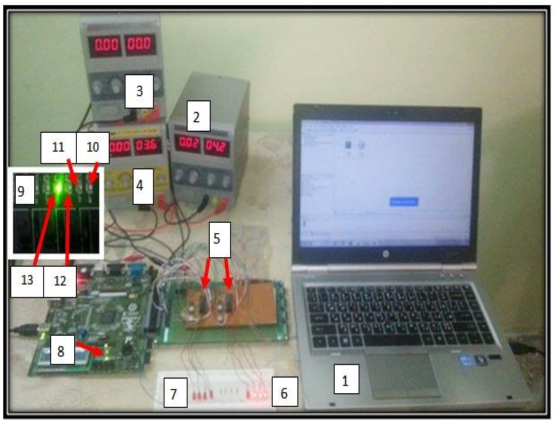

Figure 17: Three line to ground (3L-G) fault state of Doubly-Fed Induction Generator

Table 1: States of the systems based on four LEDs

Turbine state	Output
Normal	LED1
L-G Fault	LED2
L-L-G Fault	LED3
3L-G Fault	LED4

8. Conclusions

In this paper, a fault detection and diagnosis of induction generator type Double Fed Induction Generator (DFIG) in a wind power system has been proposed. The model of Wind Energy Conversion System (WECS) was proposed using MATLAB/Simulink. Different types of electrical faults are applied on the terminals of DFIG to study and analysis the performance of such generator and then detection and diagnosis these faults. Particle Swarm Optimization (PSO) and Artificial Neural Networks (ANNs) are the aid software, which is used for training the data of the applied faults for improving the convergence rate and processing speed. The performance of Artificial Neural Networks (ANNs) was better than the performance of Particle Swarm Optimization (PSO) in term of fitness (training accuracy) and the time taken in training process, while Particle Swarm Optimization (PSO) takes longer time than Artificial Neural Networks (ANNs). Spartan 3A FPGA card is used for healthy and faulty state detection of DFIG for characterizing fast response of fault detection and diagnosis, which enhances the performance of wind power systems and increases their operational life.

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Appendix:

Swarm size (number of birds)	5
Number of iterations	9
Cognitive coefficient (0 < c_1 >2)	1.2
Social coefficient (0<c_2>2)	1.2
Inertia weight (W)	0.8

Authors Biography

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