FPGA based intelligent FDI system for proton exchange membrane fuel cell PEMFC

Hussein M. H. Al-Rikabi[1], Abbas H. Issa[2]

[1] Imam Al-Kadhum University College, Najaf, Iraq.
[2] Department of Electrical Engineering, University of Technology, Baghdad, Iraq.

Abstract
A Fault Detection and Isolation (FDI) system for proton exchange membrane fuel cell (PEMFC) has been presented in this paper. Artificial Neural Network (ANN) is used to detect the faults. An Input\output data set have been acquisitioned from PEMFC and used to design an ANN model. The model designed gives a steady state prediction for a given input. The output of the PEMFC is compared to the output of the model, then a residual signal is monitored and used to detect the faults. Three types of faults have been studied in the presented work, which are: Abrupt, Incipient and Intermittent faults. The steady state model designed and simulated using Matlab. Then the ANN model has been downloaded to a hardware platform which is Spartan3 starter FPGA kit. The challenge of this study is to convert the FDI system to VHDL code to be downloaded to the FPGA. Due to the hardware limitation, the performance decreased by 5% and using an advanced features FPGA kit could remove that limitation.

Keywords: Fuel cells; Artificial neural network; Fault detection and isolation; FPGA.

1. Introduction
Detecting faults immediately is one of the most important factors in increasing the lifetime of the fuel cells. For the detection, diagnosis and correction an intelligent and automated systems are so important lately [1]. Fuel cells convert chemical energy to electricity, heat and water [2]. There are many types of fuel cells but the PEMFCs are the best since they give great start-up and shutdown curves and they are compact, low weight and temperature [3].
The Proton Exchange Membrane Fuel Cell (PEMFC) is very popular because of its low temperature range and solid membrane that makes it an easy start-up device compared with other generating sources [4]. Artificial Neural Network (ANNs) are computational or mathematical models which are inspired from biological networks [5]. Back Propagation Neural Network (BPNN) is a supervised algorithm, most popular and the feed forward ANN proposed by [6].
Field Programmable Gate Arrays (FPGAs) are a medium that can be used for reconfigurable computing and offer flexibility in design with performance speeds closer to Application Specific Integrated Circuits (ASICs) [7]. A model based fault detection and diagnosis (FDD) presented by T. Escobet et al. [8] designed with computing residuals and comparing the parameters. Rana D. [9] constructed fully parallel neural network hardware architecture using Matlab program for training and simulation and FPGA Virtex2 for

implementation. Marcian [10] presented an optimized holistic digital control system design, with its rapid prototyping using Xilinx Virtex II FPGA, for holistic modeling approach of a combined Photovoltaic and Wind power system.

In this work BPNN architecture proposed and used to form a black box model that predicts the parameters of the system without knowing the equations of this system. This feature gives a great ability to represent nonlinear complex systems by Field programmable gate array (FPGA) which accepts only linear systems. The algorithm used to train the network is Levenberg- Marquardt algorithm. The program language used to simulate this study is Matlab\Simulink. And the hardware platform used is Spartan 3 FPGA starter kit.

This paper is outlined as follows: in section 2, fuel cell fundamentals are presented. Section 3 describes the fault detection and isolation (FDI) concept. Section 4 shows the ANN training method. Section 5 gives a brief FPGA overview. Section 6 shows the simulation results. Section 7 gives and shows the presented method of conversion of the designed model to adapt the hardware platform, hardware results presented in this section too. Section 8 contains the conclusions.

2. Fuel cell

Among all types of fuel cells the PEMFC have been selected to be studied and controlled due to its advantages over the other types. The PEMFC model inside Matlab used in this work is (6kw-45Vdc) proposed by [11] and [12] which has been first added to Matlab in the version Matlab2014.

The Input\Output data set acquisition is done by the connection shown in Figure 1, more than hundred readings taken to form the data set.
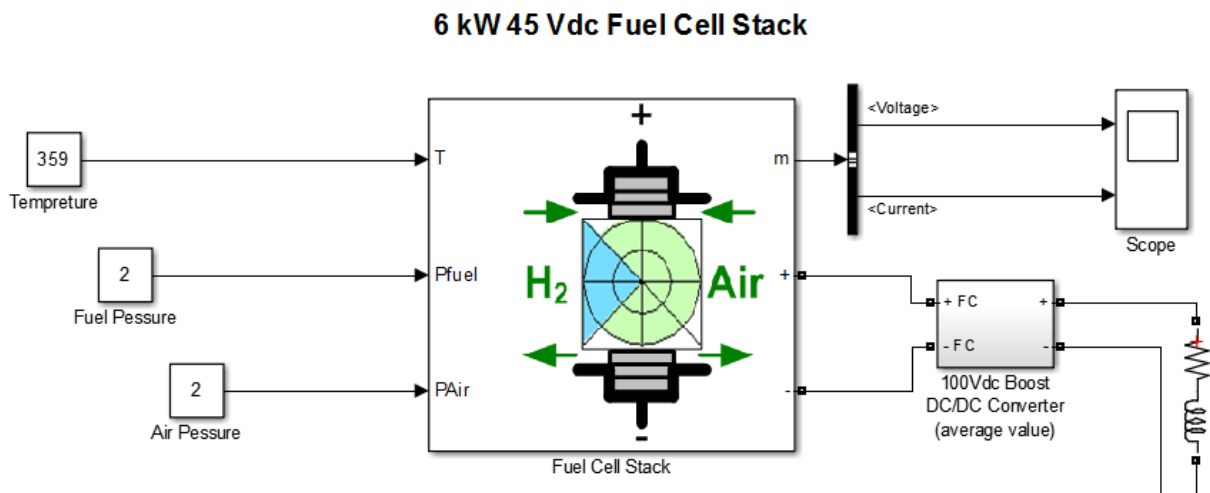

Figure 1. Data acquisition connection.

3. Fault detection and isolation (FDI)

Productivity and performance of the system is effected majorly by faults. So FDI is required to handle these faults to minimize the maintenance and cost and hence optimize the operation of the system [13]. Figure 2 shows a simple FDI block diagram.

For FDD problem, the best way is the model based fault terminology where the outputs are compared and a residual signal is generated. The decision making is based on the threshold which can be changed and adjusted to adapt the required sensitivity and hence the cost of the system [1].

Three kinds of faults considered in this study: Abrupt, Incipient and Intermittent faults. Three input parameters (Temperature, fuel pressure and Air pressure) and two output parameters (Voltage and current). The LMA is used in many software applications for solving generic curve-fitting problems. The algorithm was first published in 1944 by Kenneth Levenberg [14].

4. Artificial neural network training

The best algorithm\activation function pair is: first hidden layer: 10, second hidden layer: 4, activation function: softmax, training algorithm: trainlm (Levenberg- Marquardt algorithm), that gives the smallest error for train, test and validation (0.029229) as shown in Figure 3.
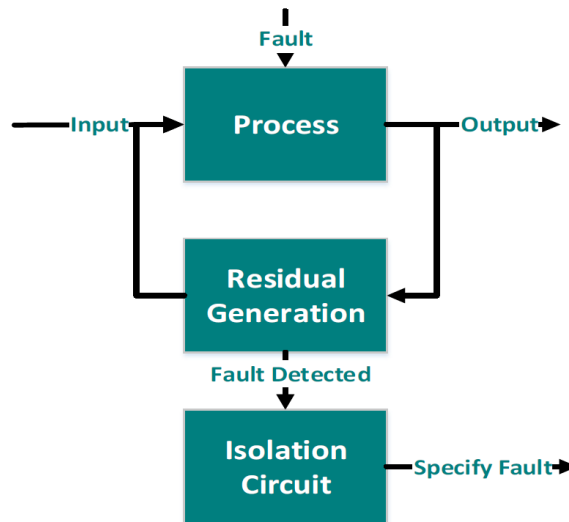
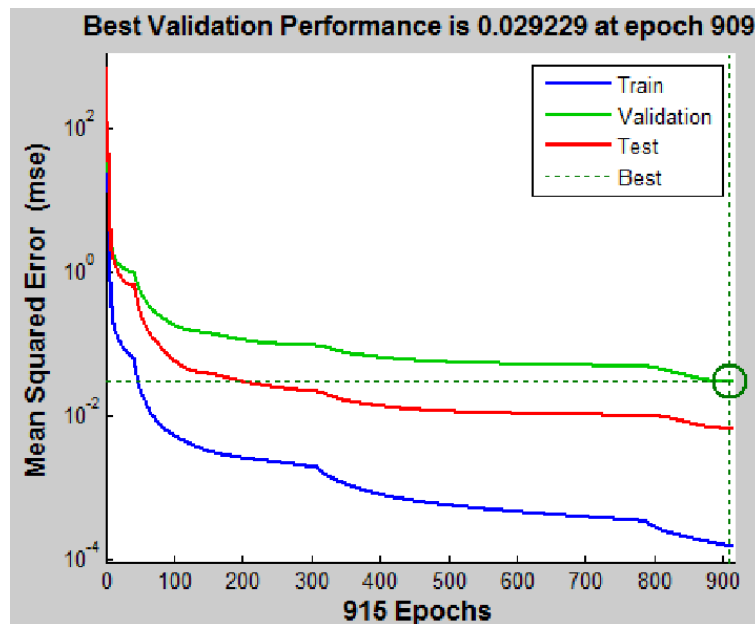Figure 2. Model based FDI block diagram.

Figure 3. ANN training.

Softmax regression is a generalized form of logistic regression. The function is given by equation (1:(15) (

$$\sigma\{z\}_j = \frac{e^{zj}}{\sum_{k=1}^{M} e^{zk}}$$

(1)

where: j=1…M

After the neural network model is designed it can be used to simulate all types of faults, first it is connected with the Matlab model for testing. Then the fault incarnation follows the acquisition.

5. Field programmable gate array (FPGAs)
They are pre-fabricated silicon devices that can be electrically programmed to become almost any kind of digital circuit or system. They provide a number of compelling advantages over fixed-function Application Specific Integrated Circuit (ASIC) technologies such as standard cells [15, 16].

6. Simulation results

Intermittent type of fault can be represented in simulation by Random signal that is added to the input signal of the PEMFC. The fault is added to the Air pressure input. The shape of the random and the other signals are shown in Figure 4. Also other types of faults to any input can be injected to the system.

After detecting the fault it should be isolated, so an isolation circuit is designed to specify and identify the location of the fault.

The isolation circuit compares the inputs to the PEMFC, which is faulty, and the inputs of the NN model which is healthy. This circuit enabled by the fault index signal shown in scope 5 of Figure 4.

The output of the Isolation circuit defines the fault according to Table 1. These codes are proposed in this work to be used in the diagnosis circuit which could be a future work.
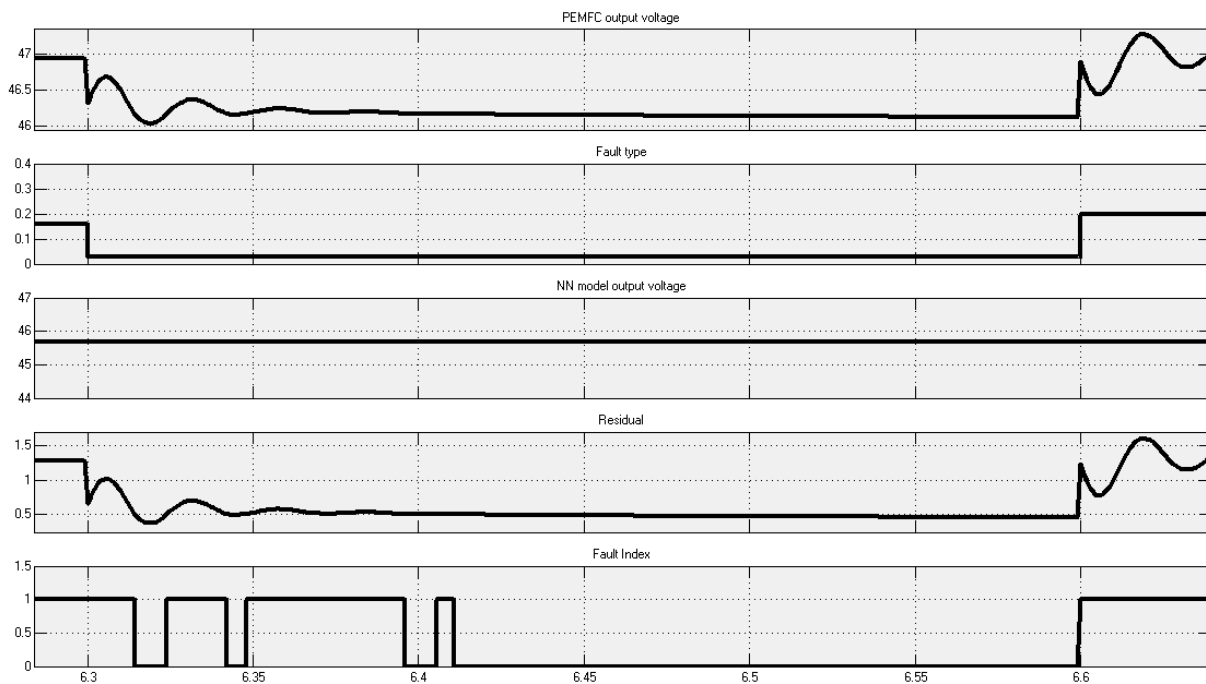

Figure 4. Intermittent fault addition signals.

Table 1. The output of the Isolation circuit.

Isolation output (F1F0) code	Description
11	Core temperature fault
10	Fuel pressure fault
01	Air pressure fault
00	Fault free

7. Conversion to adapt the hardware platform

The output of the Isolation circuit defines the fault according to Table 1. These codes are proposed in this work to be used in the diagnosis circuit which could be a future work.

The model designed in earlier contains a lot of blocks that are not compatible with the FPGA and have no valid VHDL codes. So a new NN model has been created using only linear activation functions (satlin, satlins, hardlim and purelin … etc).

A new smaller NN model have been created with eight neurons in a single hidden layer with "satlin" activation function. The performance is shown in Figure 5.

There were many challenges when converting this model to VHDL because it contain many blocks that are not supported by Xilinx programs and hardware platforms.

The first problem is that the 'dot product' Block inside each neuron is not valid in VHDL, so it has been replaced by 'product' and 'sum of elements' which has the same function as seen in Figure 6.
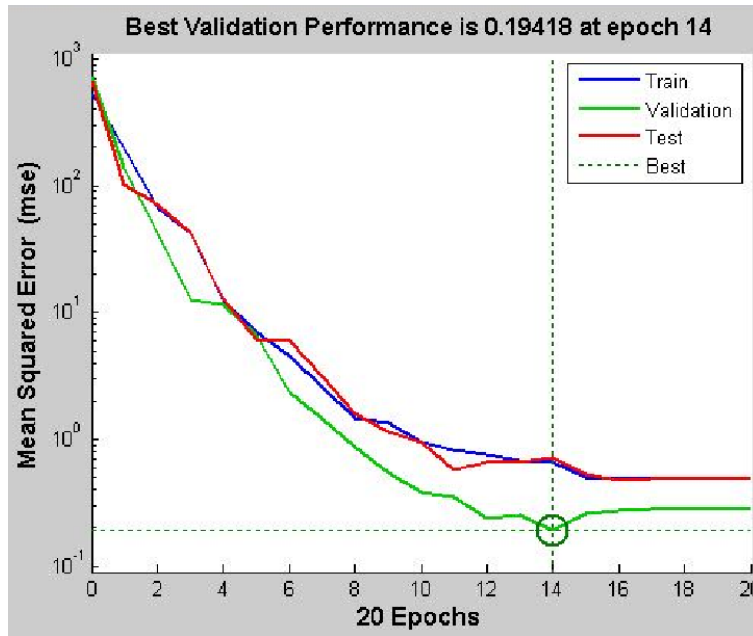
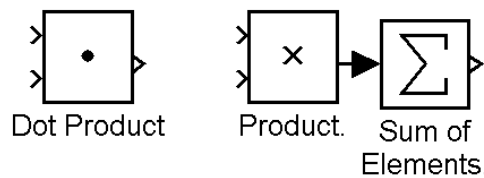Figure 5. Performance of the new small NN.

Figure 6. Replacing the Dot product by two blocks.

The second problem is the Input and Output process blocks. The internal structures of Input process block is shown in Figure 7.
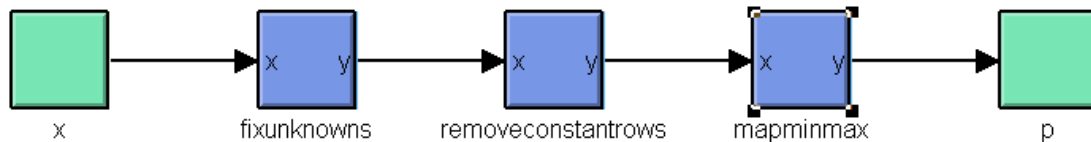

Figure 7. Input process block internal structure.

The blocks 'fixunknown' and 'removeconstantrows' can be removed if the inputs are separated and treated each alone. The third block 'mapminmax' is very important because it converts the input values to small values between "-1" and "1" according to the range of the input data set. The circuit inside this block is shown in Figure 8.
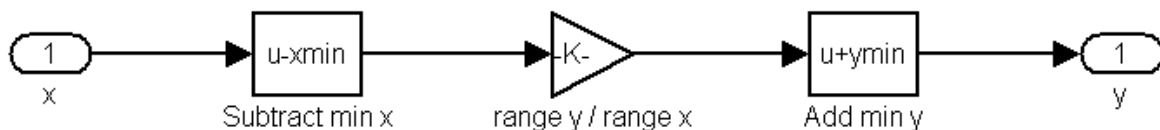

Figure 8. mapminmax internal structure.

The minimum and maximum values that are used in these blocks are taken from the data set and specified in the parameter window of the 'mapminmax' block window.

The whole input process block has been extracted to the circuit shown in Figure 9 after evaluating all the gains and constants.
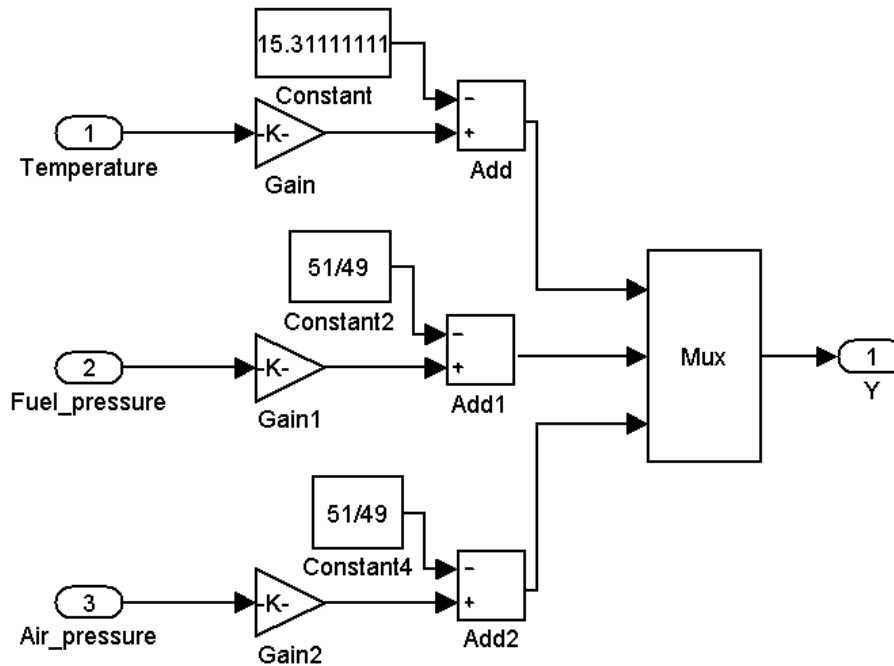

Figure 9. Input process block after modification.

Circuit in Figure 9 has been checked manually that it substitutes the original block. The purpose of the input process in the first place is to make sure that the values stay small and later they will be converted back by the same ratio.

After the conversion, no warning appear from the Matlab HDL coder report shown in Figure 10.

Figure 10. Matlab HDL coder report for the modified input process block.

A similar procedure has been used to convert the output process and the extracted circuit is shown in Figure 11.
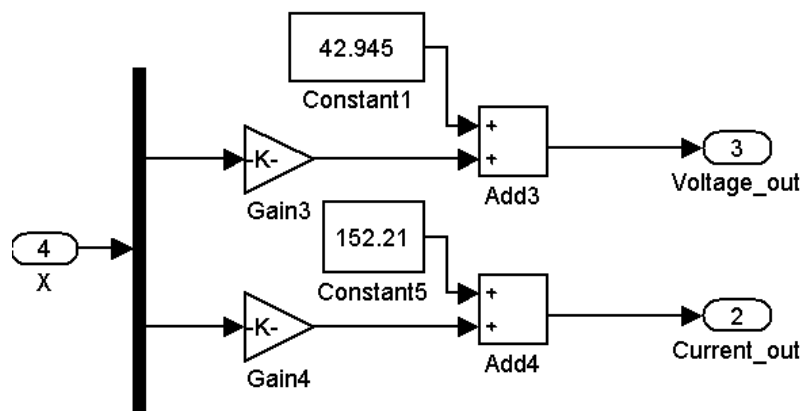

Figure 11. Output process block after modification.

The input of the output process block comes from the output layer which is referred to by "layer 2". After changing all incompatible blocks the whole Simulink model has been connected as seen in Figure 12.
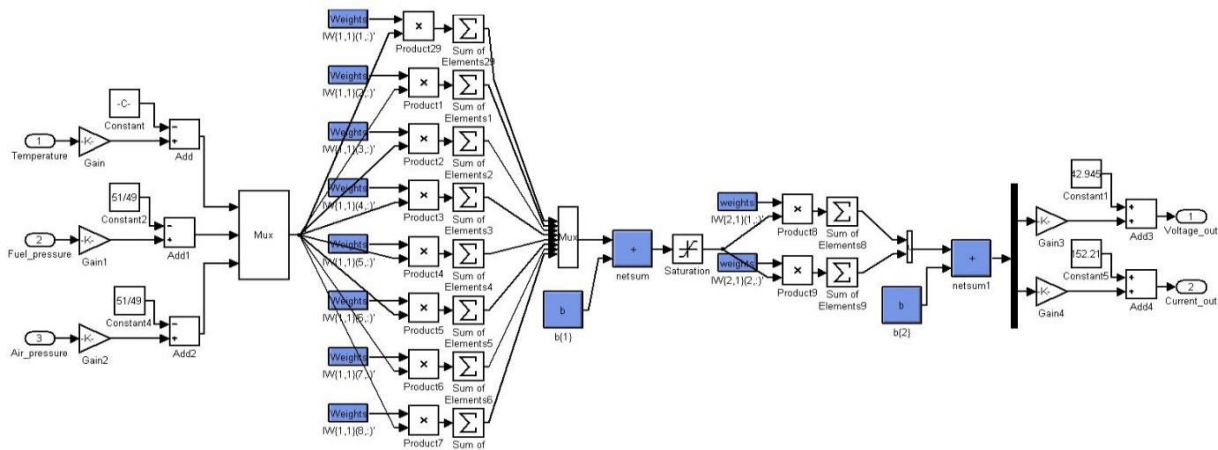

Figure 12. Final NN model to be converted to VHDL.

The NN model has many subsystems, and generating the VHDL for a model with many subsystems complicates the conversion since many (.vhd) files would be generated with a map to connect them in the configuration m-file.
So making the whole model all together without subsystems, simplifies the VHDL code generation where only two (.vhd) files have been generated (model.vhd and model_pkg.vhd).
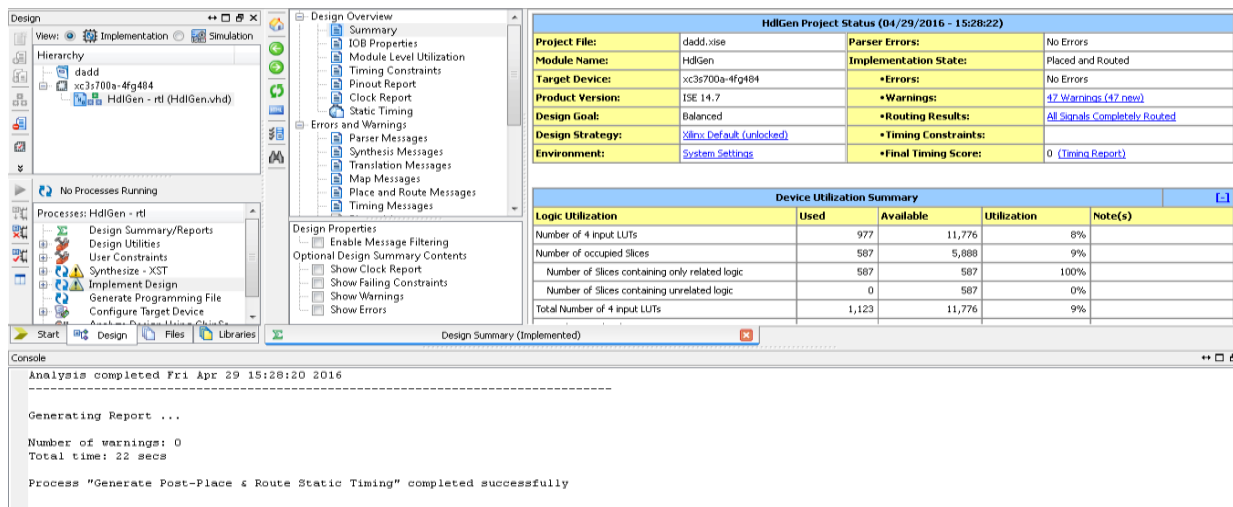Figure 13 shows ISE Design Suite report for the new model.

Figure 13. ISE Design Suite report for the Final NN model.

The NN model, fault index and isolation circuits are all connected together as shown in Figure 14. As seen in Figure 14 the "Geteway" blocks (the yellow ones) are renamed According to the inputs of the FDI system that will be created from the "system generator" token later. The signals of the scope is shown in Figure 15.
As seen in Figure 15 whenever the Residual signal gets higher than the threshold which is one (i.e. -1 to +1) the fault index activates the isolation which gives the reason behind this fault. F0F1=11 means it's Core temperature fault as mentioned before. The startup of the fuel sell has been neglected for four seconds as seen the first Fault index pulse has been neglected.
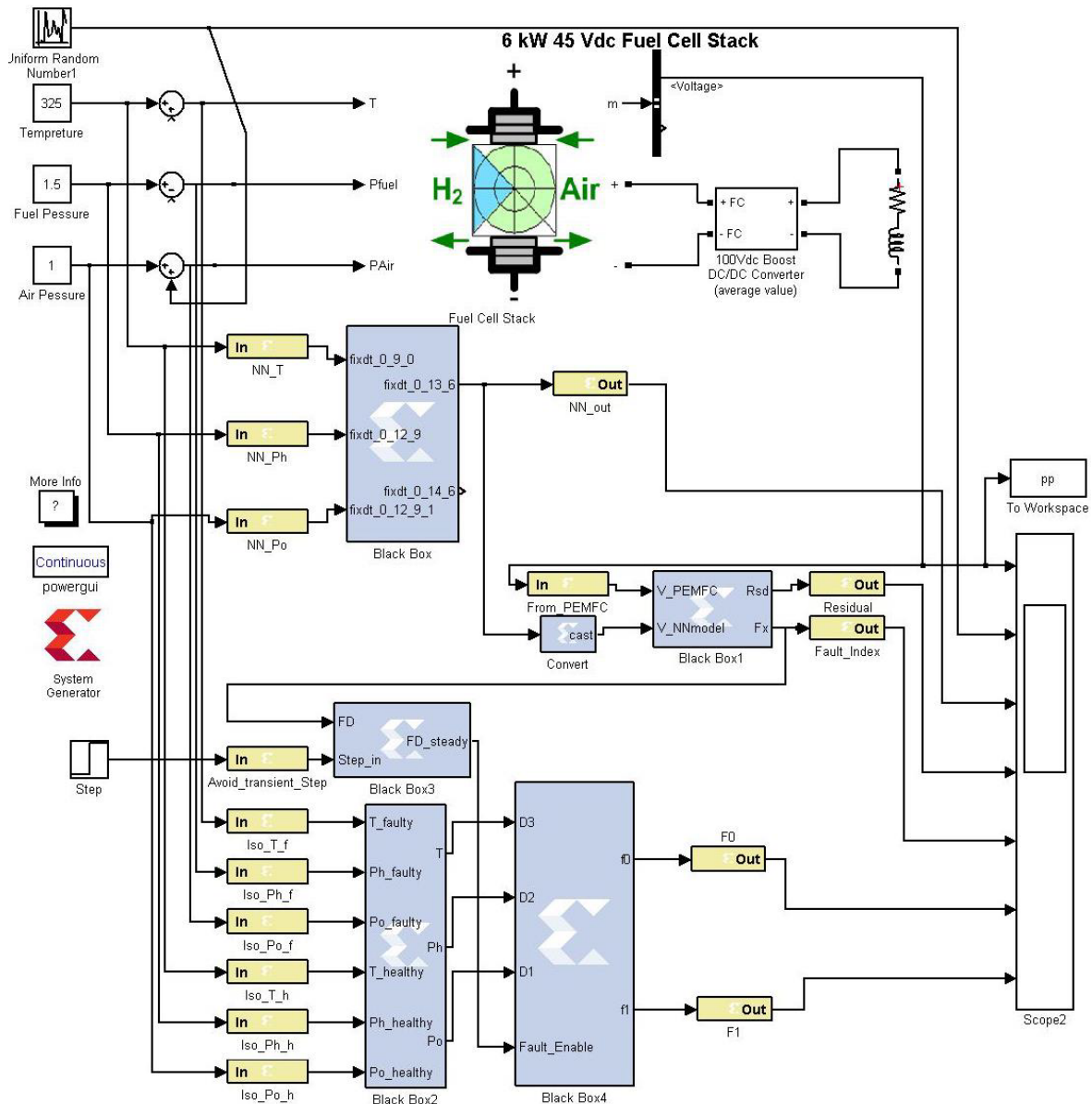
Figure 14. Whole system connection with FPGA hardware in the loop combined

8. Conclusions

A black box neural network model has been designed for a 6kw 45V PEMFC in this paper. This model is used to detect faults then the fault can be isolated by the isolation circuit designed. The model is used and designed only for steady state analysis (i.e. the transient or start up changes of the parameters are neglected). The proposed system gives good results to do the detection and the isolation. And it can be modified and adjusted for the level of sensitivity and cost required. The system has been converted to VHDL code then downloaded to an FPGA hardware platform. Hardware co-simulation prototyping method has been used in this work. The proposed system can be re-designed using other intelligent techniques. A diagnosis circuit can be added to the system utilizing the code produced by the isolation circuit also adding a Graphical Unit Interface (GUI) to the system as a facility to monitor all system parameters.
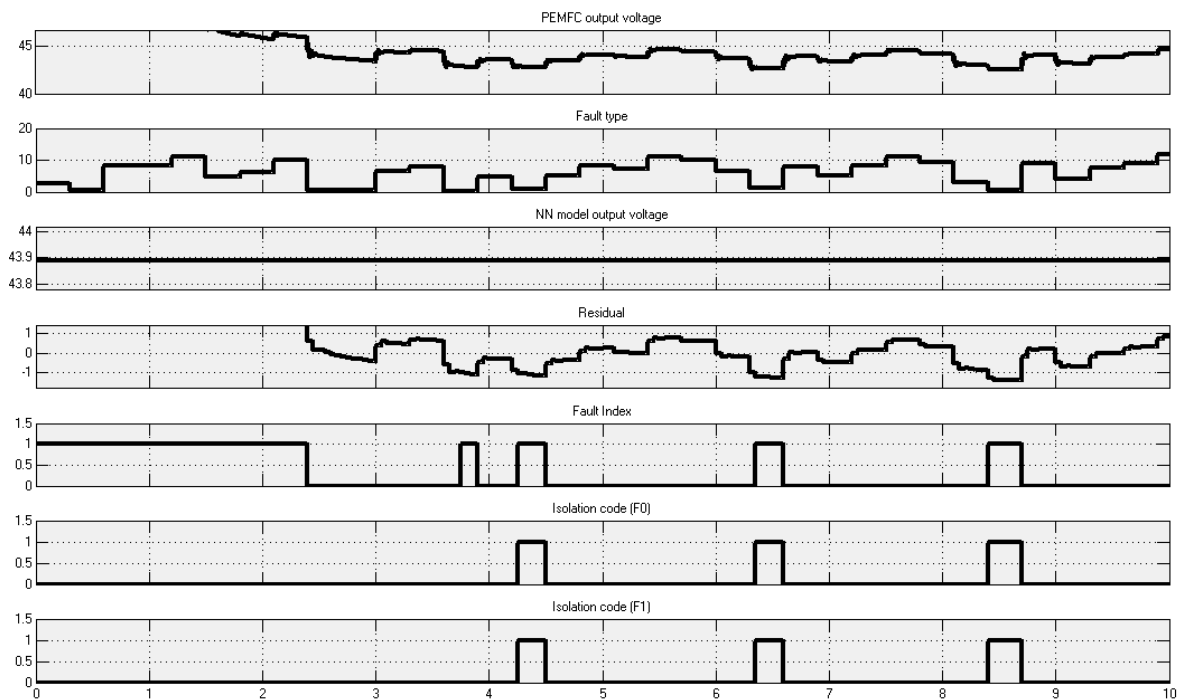
Figure 15. Signals of scope of Figure 14.

References

[1]   M.M. Kamal, D.W.Yu, D.L.Yu, "Fault Detection and Isolation for PEM Fuel Cell Stack with Independent RBF Model", Elsevier Inc., Engineering Applications of Artificial Intelligence, Volume 28, February 2014, Pages 52-63.

[2]   Pruthiraj Swain and Debashisha Jena, "Modeling, Simulation & Optimal Control of Non-Linear PEM Fuel Cell with Disturbance Input", IEEE Sponsored 2nd International Conference on Innovations in Information Embedded and Communication Systems, 2015.

[3]   Damien Guilbert, Abdoul N'Diaye, Arnaud Gaillard, Abdesslem Djerdir "Fuel cell systems reliability and availability enhancement by developing a fast and efficient power switch open-circuit fault detection algorithm in interleaved DC/DC boost converter topologies", Elsevier Inc., International Journal of Hydrogen Energy, Volume 41, Issue 34, 14 September 2016,Pages 15505-15517.

[4]   In-Su Han and Chang-Bock Chung, "Performance prediction and analysis of a PEM fuel cell operating on pure oxygen using data-driven models: A comparison of artificial neural network and support vector machine", Elsevier Inc., International Journal of Hydrogen Energy, Volume 41, Issue 24, 29 June 2016, Pages 10202-10211.

[5]   Saduf and Mohd Arif Wani, "Comparative Study of Back Propagation Learning Algorithms for Neural Networks", International Journal of Advanced Research in Computer Science and Software Engineering 3 (12), December, 2013.

[6]   David E. Rumelhart, James L. McClelland and the Pdp Research Group, "Parallel Distributed Processing: Explorations in the Microstructure of Cognition", MIT Press, 1986.

[7]   B. Vasumathi, S. Moorthi, "Implementation of hybrid ANN–PSO algorithm on FPGA for harmonic estimation", Elsevier Inc., Engineering Applications of Artificial Intelligence, Volume 25, Issue 3. April 2012, Pages 476-483.

[8]   T. Escobet , D. Feroldi , S. de Lira, V. Puig, J. Quevedo, J. Riera and M. Serra, "Model-based fault diagnosis in PEM fuel cell systems", Elsevier Inc., Journal of Power Sources, Volume 192, Issue 1, 1 July 2009, Pages 216-223.

[9]   Rana D. Abdu-Aljabar, "Design and Implementation of Neural Network in FPGA", Journal of Engineering and Development, Vol. 16, No.3, Sep. 2012.

[10] Marcian Cirstea and Alberto Parera-Ruiz, "An FPGA Controller for a Combined Solar / Wind Power System", 12th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2010.

[11] Njoya, S. M., O. Tremblay, and L. -A. Dessaint, "A generic fuel cell model for the simulation of fuel cell vehicles", Vehicle Power and Propulsion Conference, 2009, VPPC '09, IEEE®. Sept. 7-10, 2009, pp. 1722-29.

[12] Motapon, S.N., O. Tremblay, and L. -A. Dessaint, "Development of a generic fuel cell model: application to a fuel cell vehicle simulation." Int. J. of Power Electronics. Vol. 4, No. 6, 2012, pp. 505-22.

[13] W. Chine, A. Mellit, V. Lughi, A. Malek, G. Sulligoi and A. Massi Pavan," A novel fault diagnosis technique for photovoltaic systems based on artificial neural networks", Elsevier Inc., Renewable Energy, Volume 90, Pages 501-512, May 2016.

[14] Kenneth Levenberg. "A Method for the Solution of Certain Non-Linear Problems in Least Squares". Quarterly of Applied Mathematics 2: 164-168, 1944.

[15] Christopher M. Bishop.," Pattern Recognition and Machine Learning", Springer, 2006.

[16] E. Won, "A hardware implementation of artificial neural networks using field programmable gate arrays", Elsevier Inc., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 581, Issue 3, Pages 816-820, 1 November 2007.

Hussein M. H. Al-Rikabi is a M.Sc. degree graduate from the Department of Electrical and Electronic Engineering, University of Technology, Baghdad, Iraq and he completed the B.Sc. degree at 2013 in Electrical Engineering Department, College of Engineering, University of Kufa, and Najaf, Iraq. He worked as a lab engineer at the college of engineering, University of Kufa, 2014. Currently he is working as a lecturee at Imam Al-Kadhum University College, Najaf, Iraq. Mr. Hussein interested in DSP applications and algorithms, medical systems and communication engineering, all implemented on FPGA, and Embedded systems.
E-mail address: Hyper.hus@gmail.com

Abbas H. Issa is an Assist Prof. of Control and Automation Engineering. Currently he works as lectuere at the Department of electrical and electronics engineering, University of Technology, Baghdad, Iraq.
E-mail address: 30050@uotechnology.edu.iq