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Design and Control of PEM Fuel Cell Diffused Aeration System using Artificial Intelligence Techniques

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Abstract**—**Fuel cells have become one of the major areas of research in the academia and the industry. The goal of most fish farmers is to maximize production and profits while holding labor and management efforts to the minimum. Risk of fish kills, disease outbreaks, poor water quality in most pond culture operations, aeration offers the most immediate and practical solution to water quality problems encountered at higher stocking and feeding rates. Many units of aeration system are electrical units so using a continuous, high reliability, affordable, and environmentally friendly power sources is necessary. Aeration of water by using PEM fuel cell power is not only a new application of the renewable energy, but also, it provides an affordable method to promote biodiversity in stagnant ponds and lakes. This paper presents a new design and control of PEM fuel cell powered a diffused air aeration system for a shrimp farm in Mersa Matruh in Egypt. Also Artificial intelligence (AI) techniques control is used to control the fuel cell output power by control input gases flow rate. Moreover the mathematical modeling and simulation of PEM fuel cell is introduced. A comparison study is applied between the performance of fuzzy logic control (FLC) and neural network control (NNC). The results show the effectiveness of NNC over FLC.

Keywords**—**PEM fuel cell, Diffused aeration system, Artificial intelligence (AI) techniques, neural network control, fuzzy logic control

I. INTRODUCTION

HYDROGEN is the most abundant element in the universe, and hydrogen fuel cells are seen by some experts as the solution to our future energy needs. In a hydrogen fuel cell, gaseous hydrogen and air are fed in. The hydrogen gas atoms then get split into protons and electrons by a catalyst, and the protons travel through a membrane which prevents the electrons from getting through. This forces the electrons to find another way of getting back to the protons, and this is via a wire. When the electrons travel through the wire they produce an electric current which can be used to power vehicles or to run household appliances. Fuel cells are simply devices that convert fuel such as hydrogen, methane, propane, etc., directly into electricity. The process is an electrochemical reaction that is similar to the reaction in a battery operation. However, fuel cells, unlike batteries, do not store the energy internally. Instead, they use a continuous supply of fuel from an external storage. A large number of FC systems for stationary power generation have been installed worldwide for use in hospitals, hotels, office buildings, schools, utility power plants and even airport terminals. Fuel cells are also being tested for use at landfill and wastewater treatment plants. Fuel cells are of critical importance to manned space missions [1, 2]. Fuel cells are being used for portable electronics like laptop computers, cellular phones or even hearing aids. A FC produces electricity and significant amount of heat, so it is possible to heat water and help to generate heat without using any additional energy.

Aeration means addition of oxygen to the water. This process is accomplished either by exposing the water to air or by introducing air into the water. Aerators also circulate water so fish can find areas with higher oxygen concentrations. Circulation reduces water stratification and increases oxygen transfer efficiency by moving oxygenated water away from the aerator. Artificial intelligence (AI) techniques are becoming useful as alternate approaches to conventional techniques or as components of integrated systems. They have been used to solve complicated practical problems in various areas and are becoming more and more popular nowadays. AI have been used and applied in different sectors, such as engineering, economics, medicine, military, marine, etc. They have also been applied for modeling, identification, optimization, prediction, forecasting, and control of complex systems [3-5].

II. DIFFUSED AERATION SYSTEM

The aeration system can be used for improvement of water bodies for use in aquaculture systems, reservoirs, water storage tanks, fish tanks, artificial ponds and lakes. The proposed aeration system does not require connection to the electrical power grid and may be used in any location. One of the practical limitations of conventional aeration systems is the requirement for a power source. For location away from the electrical power grid, the cost of supplying power in these location. Moreover using photovoltaic system as a power source is not recommended because of the need for aeration is during the night period which has low dissolved oxygen concentration in water. Fuel cells are of the most promising technologies for delivering clean and efficient power for many applications. With increased urgency in reducing pollution and greenhouse gas emissions, a resurgence of interest in fuel cells has occurred. Fuel cells are very useful as a power sources in remote locations due to high reliability and no moving parts. Diffused aeration system require continuous electrical source for using in any time according to the dissolved oxygen concentration in the pond.

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III. PROPOSED ELECTRICAL SYSTEM

The proposed aeration system consists of PEM fuel cell to supply the system with the electrical power, a control unit to control the system operation, a blower unit to supply the required air to diffused aeration system, diffuser unit which use to diffuse air into the pond. The proposed aeration system configuration is depicted in fig. 1.

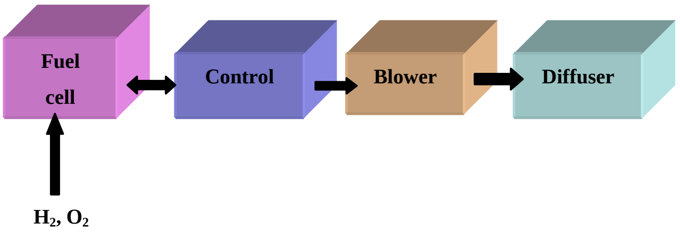


Fig. 1 Block diagram of the proposed aeration system

IV. MATHEMATICAL MODELING

A. Mathematical Modeling of Fuel Cell

The dynamic model of the fuel cell is the electrochemical model with the component material balance equations. The model is also based upon the voltage activation, concentration and Ohmic losses (the Nernst voltage equation). Table 1 shows the parameters used to validate the PEM fuel cell model. The total cell potential can be obtained as [6, 7]

$$V_{fc} = V_n - V_{ac} - V_{oh} - V_{con} \tag{1}$$

$$V_n = V_{ref} + \frac{R^{'}T}{nF} \ln\left(\frac{p_{H2}\, p_{O2}^{0.5}}{p_{H2O}}\right) \tag{2}$$

$$V_{ac} = \frac{R^{'}T}{\alpha nF} \ln\left(\frac{I_{fc}}{I_o}\right)$$

(3)

$$V_{oh} = RI \tag{4}$$

$$V_{con} = \frac{R^{'}T}{nF} \ln\left(1 - \frac{I_{fc}}{I_L}\right) \tag{5}$$

$$p_{H_2} = 0.5\left(\frac{P_{H_2}}{\exp\left(1.653\; i \big/ T_K^{1.334}\right)}\right) - P_{H_2O} \tag{6}$$

$$p_{O_2} = \left(\frac{P_{air}}{\exp\left(4.192\; i \big/ T_K^{1.334}\right)}\right) - P_{H_2O} \tag{7}$$

TABLE I
PARAMETERS USED FOR MODEL VALIDATION.

symbol	value
Cell temperature T	353 K
Standard voltage of fuel cell V_r	1.229 V
Ideal gas constant R	8.314 $J/mol\ K$
Faraday's constant F	96487 C/mol
Number of electrons transferred in the reaction n	2
Exchange current density J_o	10^{-4} A/cm^2
Internal resistance R_{ohm}	0.19 Ω/cm^2
Anode pressure P_{H2}	3 atm
Cathode pressure p_{air}	3 atm
Limiting current density J_L	1.4 A/cm^2
Charge transfer coefficient of reaction α	0.239

B. Mathematical Modeling of Blower

Blowers and compressors are the dominant sources of energy consumption of a diffused aeration device. Appropriate selection of blowers and compressors can therefore lead to substantial energy and cost savings. From the various types of blowers and compressors manufactured, basically only two groups are applied in aeration system. These include

- The positive displacement blower (PD-blower).
- The dynamic or centrifugal blower or compressor [8].

For the diffused aeration system, centrifugal blower is used. The electrical system in the blower is DC motor, DC motor drives are used for many speed and position control systems where their excellent performance, ease of control and high efficiency are desirable characteristics. Permanent magnet DC motors are limited in terms of power capability and control capability. A linear model of a simple DC motor consists of a mechanical and electrical equation as determined in the following equations, the steady state operation of the motor is described by [9, 10]:

$$V_a = E + I_a R_a + L_a \frac{dI_a}{dt} \tag{8}$$

$$T_e = T_L + B_m \omega_m + J \frac{d\omega_m}{dt} \tag{9}$$

Where R_a is Armature Resistance (Ω), L_a is Armature Inductance (H), V_a is terminal voltage (V), J is Motor of inertia (kg m^2), B is damping factor of mechanical system (N ms). I_a is armature current (A), T_L is load torque (N m), T_e is developed torque (N m), and ω is speed of rotation (rpm).

C. The Thermostatic Valve Modeling

The required characteristic of this valve must be linear, such that controlling the valve input signal, will directly control the mass flow rate of water. Therefore, the transfer function of the used valve will be considered to be a first order one, as

$$G_v(s) = \frac{1}{0.5s + 1} \tag{10}$$

V. SIZING OF PEM FUEL CELL

The sizing of a fuel cell stack is very simple; there are two independent variables that must be considered - voltage and current. The known requirements are the maximum power, voltage, and/or current. Recall that power output is a product of stack voltage and current [7]:

$$P_{fc} = V_{st}\ I \tag{11}$$

$$I = A_{cell}\ i \tag{12}$$

Most fuel cell developers use a nominal voltage of 0.6 to 0.7 V at nominal power. The total stack potential is a sum of the stack voltages or the product of the average cell potential and number of cells in the stack, Table 2 shows the results of PEM fuel cell sizing.

$$V_{st} = V_{cell}\ N_{cell} \tag{13}$$

TABLE II
FUEL CELL SIZING RESULTS

symbol	value
Load power P_L	823.4 W
Load voltage V_L	24 V
Cell area A_{cell}	1.7 cm^2
Number of cells N_{cell}	40 cell

VI. ARTIFICIAL INTELLIGENCE CONTROL TECHNIQUES

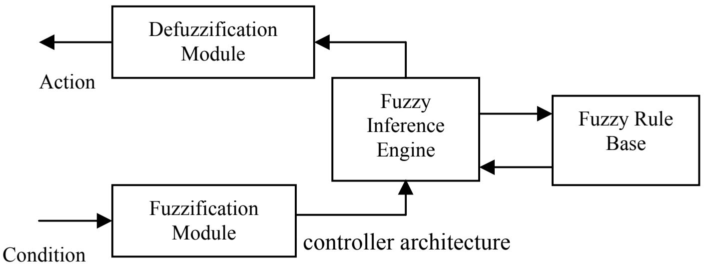
Artificial intelligence (AI) is a term that in its broadest sense would mean the ability of a machine to perform similar kinds of functions that characterize human thought [11]. Artificial intelligence (AI) techniques are becoming useful as alternate approaches to conventional techniques or as components of integrated systems. They have been used to solve complicated practical problems in various areas and are becoming more and more popular nowadays.

A. FLC Algorithm

Fuzzy logic controller (FLC) techniques have been found to be a good replacement for conventional control techniques, owing to their low computational burden and ease of implementation using microcomputers [12]. The fuzzy-logic based controller overcomes system ambiguities and parameter variations by modeling the control objective based on a human operator experience, common sense, observation and understanding how the system responses, thereby eliminating the need for an explicit mathematical model for the system dynamics[13]. FLC in the last few years, fuzzy logic has met a growing interest in many control applications due to its non-linearity handling features and independence of the plant modeling. FLC operates in a knowledge-based way, and its knowledge relies on a set of linguistic if-then rules, like a human operator.

B. FLC Control Structure

Fuzzy systems (FS) are based on fuzzy set theory and associated techniques [14, 15]. A goal of this approach is to mimic the aspect of human cognition that can be called approximate reasoning. Fuzzy systems may be less precise than conventional systems but are more like our everyday experiences as human decision-making. Fuzzy logic (FL) is used mainly in control engineering. It is based on fuzzy logic reasoning which employs linguistic rules in the form of if–then statements. Fuzzy logic and fuzzy control feature are relative simplification of a control methodology description. Fuzzy logic systems (FLS) are rule-based systems in which an input is first fuzzified (i.e., converted from a crisp number to a fuzzy set) and subsequently processed by an inference engine that retrieves knowledge in the form of fuzzy rules contained in a rule-base. The fuzzy sets computed by the fuzzy inference as the output of each rule are then composed and defuzzified (i.e., converted from a fuzzy set to a crisp number). A fuzzy logic system is a nonlinear mapping from the input to the output space. A schematic representation of a FLS is presented in Fig. 2. The operation of a FLS is based on the rules contained in the rule base [16-18].



controller architecture

The commonly used defuzzification method is the centroied (COA) method. This method gives a faster defuzzification process and a fairly reliable estimate of the centroid point uo, as given by

$$u_o = \frac{\sum_{i=1}^{n} u_i \cdot \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)} \tag{14}$$

Where n is the number of fired rules, ui is the centroid of the ith clipped fuzzy set. μ(ui) is the height of the ith clipped fuzzy set or the strength of the rule i.

C. Neural Network Control Algorithm

Neural networks are massively parallel processors that have the ability to learn patterns through a training experience. Traditionally, modeling of equipment and controller algorithms consists of computer programs that rely on complicated mathematics tailored for a specific application, and are generally not portable to other systems. An alternative to traditional models is through the use of neural networks (NN), from a branch of artificial intelligence. Neural networks are nonlinear computer algorithms that learn with feedback, and can model the behavior of complicated nonlinear processes. Within pattern association networks there are many types of configurations, each with a specific architecture useful for solving different types of problems. In all cases, however, the goal is to map input to output while minimizing an error function. Nodes in each of the other layers collect information from the weighted upstream node outputs (usually by summation) and process the information with an activation function. A value computed from the activation function is then available to be sent to the next layer using more weights [19- 23].

D.Multi-layer neural network

A schematic diagram of typical multilayer feed forward neural network architecture is shown in Fig.3. The network usually consists of an input layer, some hidden layers and an output layer. In its simple form, each single neuron is connected to other neurons of a previous layer through adaptable synaptic weights. Knowledge is usually stored as a set of connection weights.

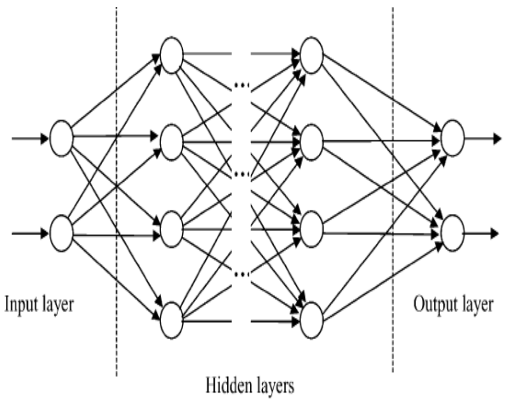


Fig. 3 Schematic diagram of a multilayer feed forward neural network

E. The Error Back-Propagation Algorithm

The most popular supervised training algorithm is the one named 'error back-propagation', or simply 'back-propagation'. It involves training a FFANN structure made up of activation function neurons. The back-propagation algorithm is a gradient method aiming to minimize the total operation error of the neural network. The process is intended to minimize the Error between the network output and the output actual output for the same input. The total error is a function defined by

$$RMS = \frac{1}{2} \sum_{j} \left| t_j - o_j \right|^2 \tag{15}$$

Where *t* is target value, and *o* is output value [19- 23]

VII. Proposed Control System

The AI control is utilized to provide the system with the required control action. The control signal is used to control the operation of thermostatic valve to control the mass flow rate of input gases to fuel cell as depicted in Fig.4.

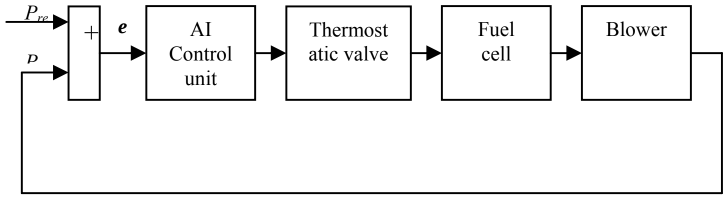


Fig. 4 Block diagram of AI control for PEM fuel cell

A. FLC System Design

Fuzzy logic control offers a way of dealing with modeling problems by implementing linguistic. Table 3 shows possible control rule base which are used. The rows represent the rate of the error change (ce) and the columns represent the error (e). Each pair (e, ce) determines the output level from NL to PL corresponding to output. Here NL is negative large, NM is negative medium, NS is negative small, ZE is zero, PS is positive small, PM is positive medium and PL is positive large. The triangular type membership function is chosen because of its linearity. The collections of the reference fuzzy set for the error, the change of error, and the control input are the same, but their scale factors are different, as shown in Fig. 5, seven fuzzy subsets. The continuity of input membership functions, reasoning method, and defuzzification method for the continuity of the mapping ufuzzy (e, ce) are necessary. The max-min reasoning method and the center of gravity defuzzification method are used, as those methods are most frequently used in many literatures. Figure 6 shows the MATLAB SIMULINK of FLC system.

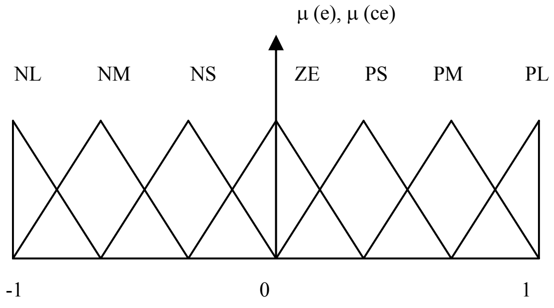


Fig. 5 membership functions of error change of error, and output signal

TABLE III
RULE BASE OF FUZZY LOGIC CONTROLLER.

		CHANGE OF ERROR (CE)						
		NL	NM	NS	ZE	PS	PM	PL
Error (e)	NL	NL	NL	NL	NL	NS	NS	ZE
	NM	NL	NL	NL	NM	NS	ZE	PS
	NS	NL	NL	NL	NS	ZE	PS	PS
	ZE	NL	NM	NS	ZE	PS	PM	PL
	PS	NS	NS	ZE	PS	PL	PL	PL
	PM	NS	ZE	PS	PM	PL	PL	PL
	PL	ZE	PS	PS	PL	PL	PL	PL

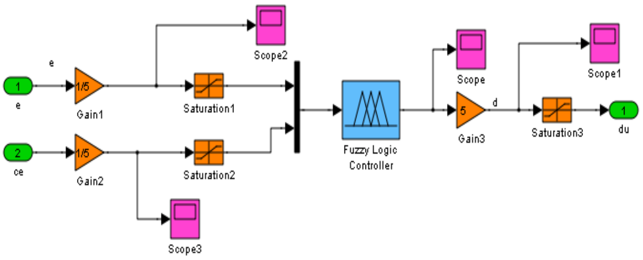


Fig. 6 FLC architecture

The goal of tuning is to shape the nonlinearity that is implemented by the fuzzy controller. This nonlinearity called the control surface which is affected by all the main fuzzy controller parameters. The control surface for the FLC which is suggested in this work is shown in Fig. 7 (Gain1 = 0.2, Gain2 = 0.2, and Gain3 = 5), where the output of the fuzzy controller is plotted against its two inputs. The surface represents in a compact way all the information in FLC.

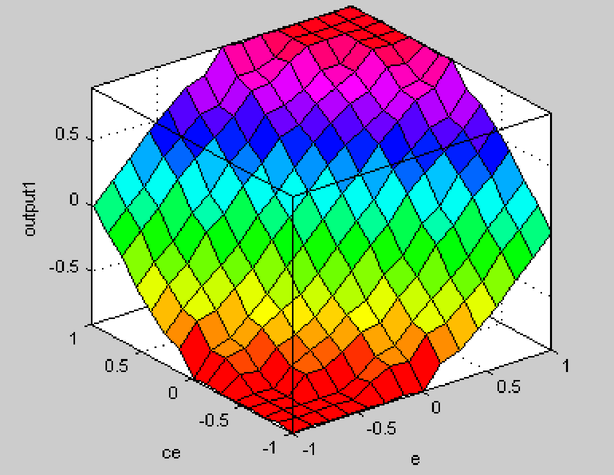


Fig. 7 Control surface of FLC

B. NNC System Design

On the other hand the proposed NN control after many trials eventually employed three layers which are the input layer, hidden layer, and output layer. The input layer consists of one neurons, hidden layer consists of three neurons, and output layer of one neurons. The activation function used in this work is "logsig" for hidden layer, and "purelin" for output layer. The NNC is trained using a back propagation with Levenberg–Marquardt algorithm. The back propagation is a form of supervised learning for multi-layer nets. Error data at the output layer is back propagated to earlier ones, allowing incoming weights to these layers to be updated. It is most often used as training algorithm in current neural network applications. Figure 8 presents the mean square error between the network output and the target. The network response analysis is depicted in Fig. 9. As shown in this figure the regression "R" is approximately one which means that the output tracks the target in a correct way.

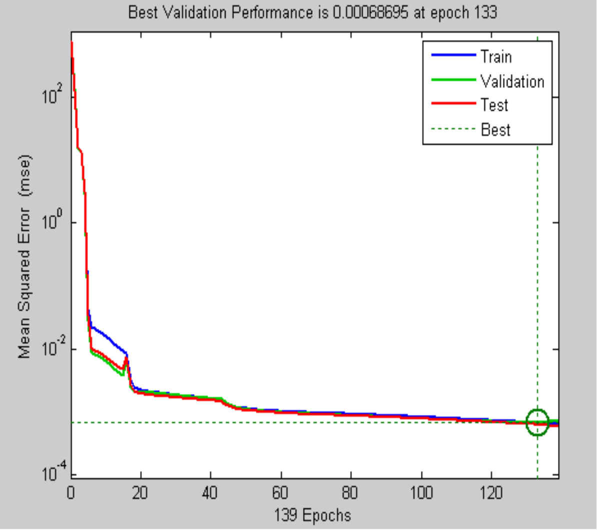


Fig. 8 Mean square error

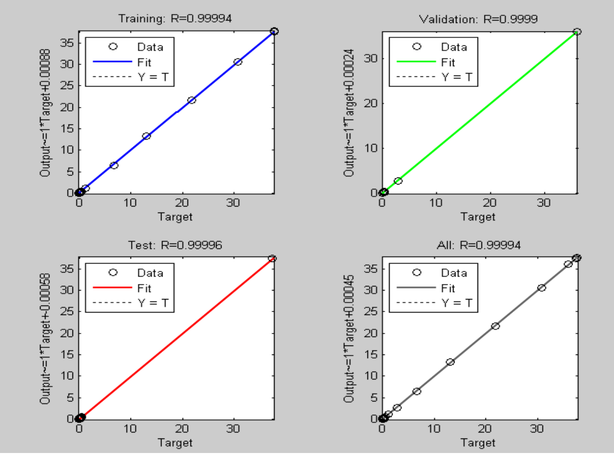


Fig. 9 Regression between the network output and target

VIII. SYSTEM SIMULATION USING MATLAB

In this section the MATLAB SIMULINK model of PEM fuel cell system using for diffused aeration system is introduced. Figure 10, and Fig. 11 show the system component using FLC, and NNC respectively. The system consists of PEM fuel cell subsystem, control subsystem to control gases flow rate, and diffuser subsystem. Figure 12 introduces the PEM fuel cell subsystem, the input signals are gases flow rate, and the outputs are current, voltage, and power.

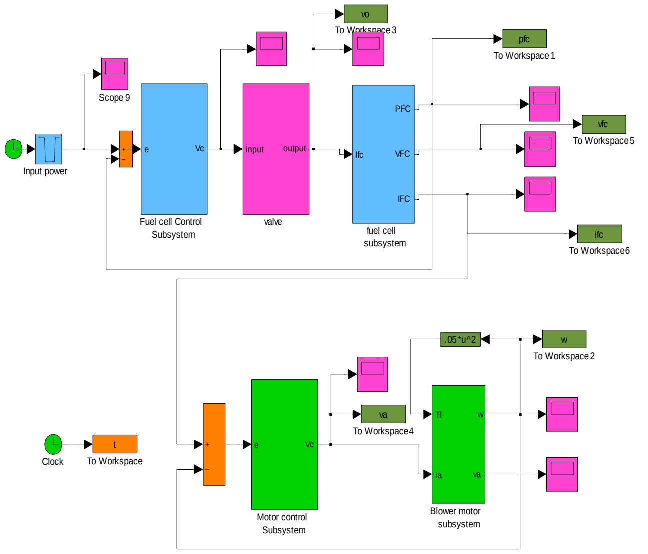


Fig. 10 Electrical system of diffused aeration system using FLC

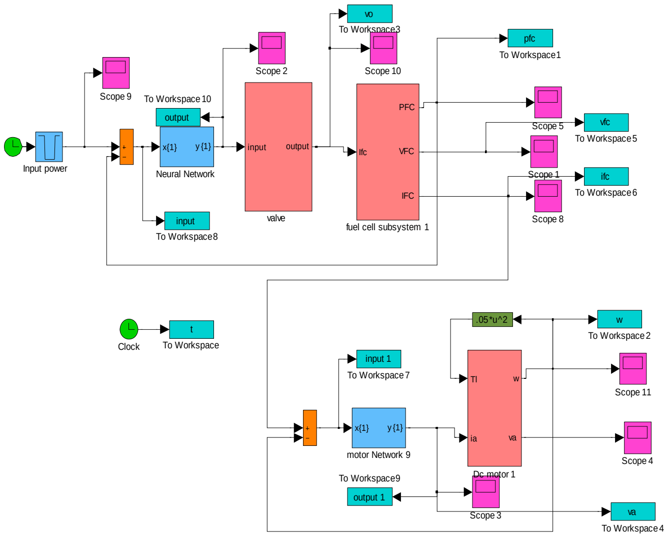


Fig. 11 Electrical system of diffused aeration system using NNC

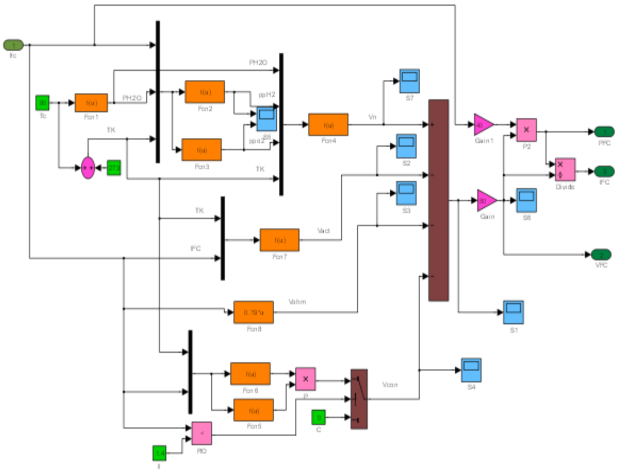


Fig. 12 PEM Fuel cell subsystem

IX. RESULTS AND DISCUSSION

A. FLC Results

Figure 13 presents the output power of PEM fuel cell with the reference power using FLC. It is clear that the controller success in making output power flow the variation of reference power. The output current of PEM fuel cell is depicted in Fig. 14.

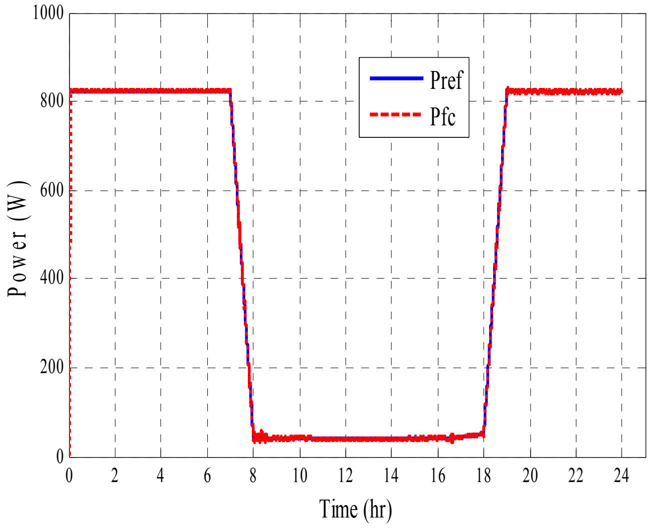


Fig. 13 PEM fuel cell power using FLC

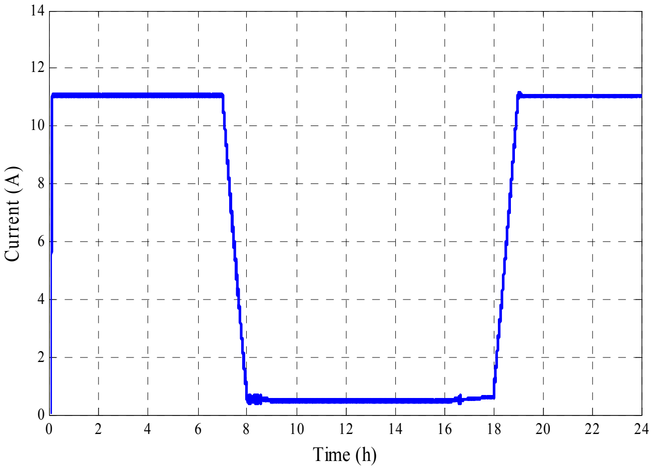


Fig. 14 PEM fuel cell current using FLC

B. NNC Results

One of the important aspects of applying a NNC to any particular problem is to formulate the inputs and outputs of the NN structure under study. Off line training for the proposed NNC was applied. Data for off-line training can be obtained either by simulation or experiment. In the present work, the data is obtained by simulating the proposed system in an open-loop system. Figure 15 shows output power of PEM fuel cell with the reference power using NNC. It is clear that the controller success in making output power flow the variation of reference power. The output current of PEM fuel cell is depicted in Fig. 16.

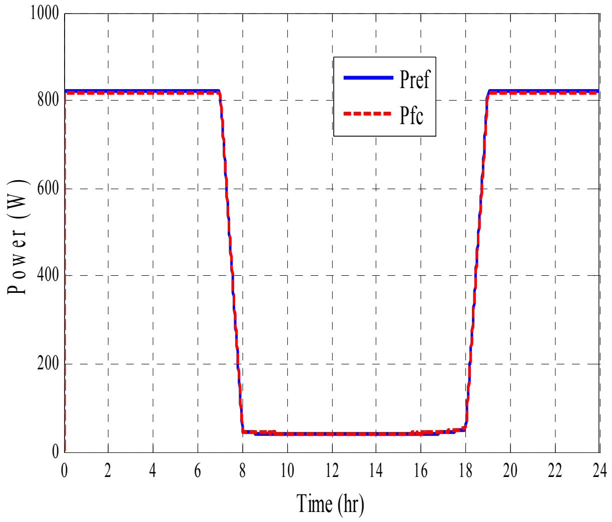


Fig.15 PEM fuel cell power using NNC

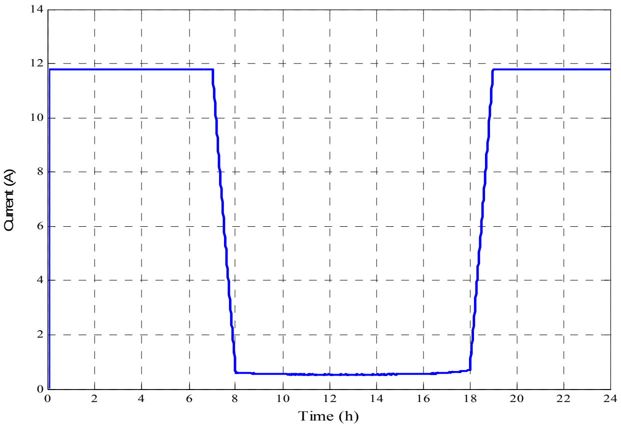


Fig. 16 PEM fuel cell current using NNC

X. COMPARISON BETWEEN FLC AND NNC

From the pervious output signals of the two controls, the NNC output power is smoother than using FLC as depicted in Fig.17. Figure 18 and Fig. 19 show the error signal using NNC and FLC respectively , it is clear that the error signal using FLC is larger than in NNC, it means that NNC is more suitable in this application than FLC.

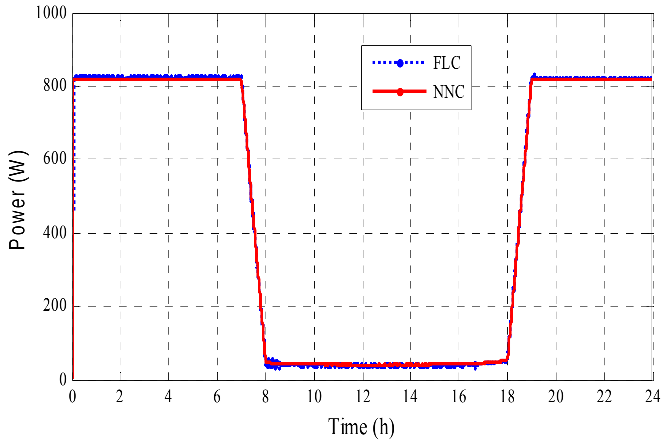


Fig. 17 PEM fuel cell power using AI control

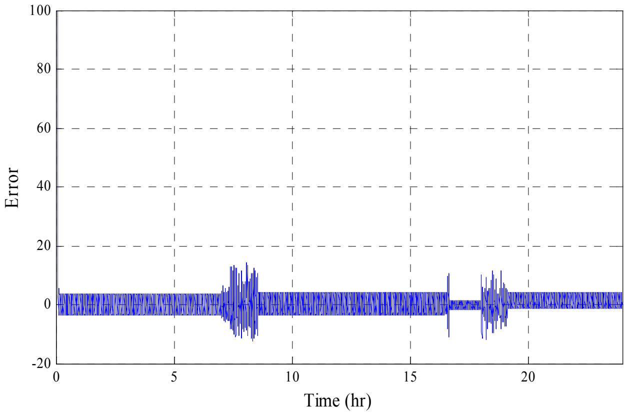


Fig. 18 Error signal using FLC

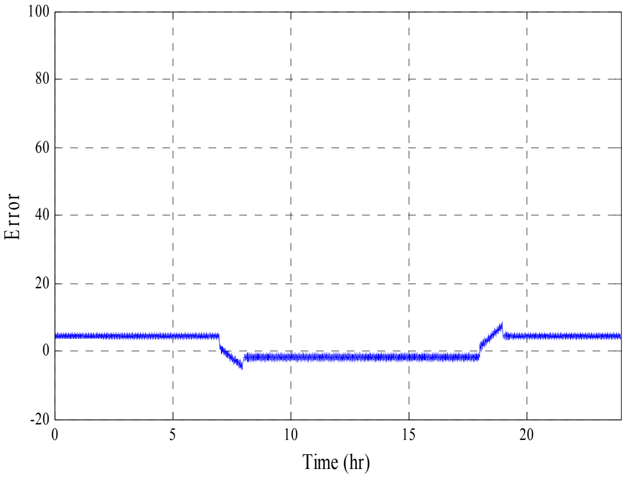


Fig. 19 Error signal using NNC

XI. CONCLUSION

The most important parameters to be monitored and controlled in an aquaculture system are related to water quality, since they directly affect animal health. In this paper, a new application of PEM fuel cell for diffused aeration system has been presented. A complete mathematical modeling and MATLAB SIMULINK model for the PEM fuel cell are developed and a control system, which includes either the NNC or the FLC controller, is developed for controlling input gases flow rate. Neural networks offer one such method with their ability to map complex nonlinear functions. Offline training are applied with the BP algorithm has been used. The simulation results show that the feasibility of NN control. FLC with the three main components; Fuzzification, fuzzy rule base, and Defuzzification are introduced also and applied to control input gases flow rate. The performance of the system is evaluated by comparing its performance using NNC and FLC. The response of output generation using NNC is more accurate and better than using FLC.

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