



A Fuzzy Neural Network Control of SOFC based system in Distributed Generation

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Abstract-This research paper proposes a new controller for the control of Active and Reactive power of Solid Oxide Fuel Cell (SOFC) based system. The SOFC is coupled with a micro-grid through Voltage Source Inverter (VSI). The switches used in VSI are IGBT and the switching technique is Current Hysteresis. The Fuzzy Neural Network (FNN) controller is used to guide the power conditioning unit to deliver the active and reactive power to the micro-grid. It is found that the Fuzzy Neural Network (FNN) controller is capable to control the SOFC based system and outperforms conventional controller. Furthermore, the mathematical modeling of the system is presented. The whole mechanism is simulated in MATLAB/Simulink.

Keywords: Fuzzy Neural Network (FNN), Solid Oxide Fuel Cell (SOFC), Distributed Generation (DG).

1. INTRODUCTION

A country's development index is measured particularly by the strength of its energy sector. In this developmental progress, the Distributed Generation (DG) is considered to be the power paradigm for the new millennium. The knowledge based and the environment conscious world, today, has convinced the researchers to develop the technologies which have no or less effect on the environment and are efficient. Therefore renewable technologies like Photovoltaic, wind and fuel cell caught the eye of the researchers.

Solid Oxide Fuel Cell (SOFC) is a static device that utilizes an electrochemical process which converts the chemical energy of a hydrogen fuel into electric energy and heat. Among the different DG sources, SOFC is considered to be more suitable as these are modular in structure, efficient and having no or less harmful emissions (Vaishampayan *et al.*, 2014).

In the literature, several controllers and control strategies have been proposed but an independent control of active and reactive power using SAM based FNN has never been reported in the literature. The FNN controller used here track the demand more quickly than the conventional controllers.

2. MATERIAL AND METHODS

2.1 Technical Background

The Simulink model presented here consists of SOFC rated at 50 KW which is equal to 1 p.u in a micro-grid connected environment. The simulation is carried for 1 hour. The whole setup consists of inverter, transformer, RL filter, controller and the micro-grid.

The assumptions considered in this model is given below:

1. Nernst's equation is applied
2. The gasses are ideal
3. The temperature of the SOFC is invariant

The parameters used for the design of SOFC are given in (Table 1).

Table 1: SOFC operating data

Parameters	Values
Rated Power	50 KW
Absolute Temperature (K)	1273
Initial Current (A)	105
Universal gas constant	8315
Ideal Standard Potential	1.19
Number of cells in series	440
Maximum, Minimum and Optimal Consumption of fuel	0.91, 0.81 and 0.84
Response time for H, H ₂ O and O flows.	26.2, 78.4 and 2.92
Electrical response time (s)	0.81
Fuel processor response time (s)	5
Ratio of Hydrogen to Oxygen	1.144
Faraday's constant	96.47×10^6
Valve molar constant for Hydrogen, Water and Oxygen	8.44×10^{-4} , 2.82×10^{-4} and 2.53×10^{-3}
Ohmic loss per cell (ohms)	3.29×10^{-4}

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2.2 Related Work

A SOFC can be coupled with the grid or directly to the load through inverter. In the literature, conventional controllers and control strategies have been proposed. A decoupling scheme for the control of active and reactive power based on Takagi-Sugeno (TS) model is proposed in (Bhuyan *et al.*, 2011).

(Abinayasaraswathy *et al.*, 2013) has studied the operation of SOFC using D Q control strategy where the control action is performed using Proportional Integral (PI) controller. The power to the load i.e. 50KW, 30KW and 70 KW have been delivered.

(Nayak *et al.*, 2012) have simulated the voltage and current waveform of SOFC in DG mode for the control of active power only. In their work the power quality is enhanced by using DC link capacitor and RL filter but the reactive power control is ignored.

2.2 Proposed Model

In this research work, the FNN controller is used with the dq0/abc transformation which is based on the key concept that active power is proportional to d-axis current and reactive power is proportional to q-axis current. The diagram of the proposed model is shown in (Fig. 1).

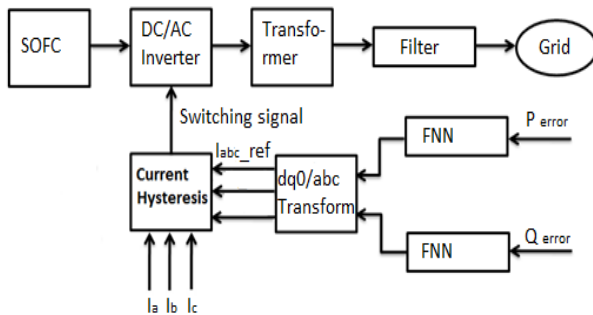


Fig. 1: Proposed model for the control of SOFC system in DG

The overall vector is the composition of D and Q component. Therefore by changing any component changes both the magnitude and angle. The active power can be controlled by varying the modulation index and reactive power can be controlled by varying the phase angle. Here, the P and Q error is given to the FNN (shown in Figure 1) which is the difference between the inverter output and the demand of micro-grid. The two output of the controller are given to direct axis current component (d-axis) and quadrature axis (q-axis). Finally the dq0/abc transformation is used to transform the currents Id and Iq from synchronously rotating frame into the three phase current using equation 1. The three phase currents are then fed to the current hysteresis (Diab *et al.*, 2012).

$$\begin{bmatrix} I_a(ref) \\ I_b(ref) \\ I_c(ref) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \times \begin{bmatrix} I_d \\ I_q \end{bmatrix}$$

Equation 1

The voltage source inverter (VSI) and Current Hysteresis in Figure 1 forms the power conditioning unit. This unit performs the control switching and transforms the DC output of the SOFC into AC.

The current hysteresis technique is used in this research work because this technique is commonly applied for inverter with low power ratings. In this method, the limits are defined which restrict the current in the desired band. Using this technique, the switching of the inverter not only depends upon the external control signal but on the circulating current in the bus of the grid as well. The basic implementation of this technique is to derive the switching signal by comparing the current error with a predefined band.

The Fuzzy Neural Network (Nauck *et al.*, 1997) implements a fuzzy system into neural network, which in this case has four layers shown in Figure 4. The architecture of FNN and its learning algorithm for Standard Additive Model are described below and shown in (Fig. 2).

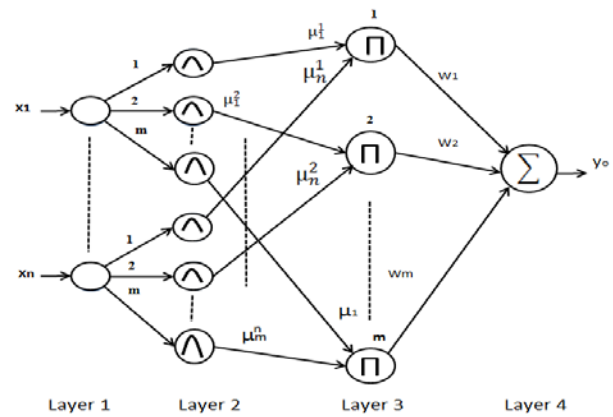


Fig. 2: Fuzzy Neural Network (FNN) Architecture

This algorithm contains four layers. Layer 1 is the input layer, layer 2 is the fuzzification layer which contains Gaussian functions, layer 3 is the rule layer having two rules and the final layer is defuzzification which is output. The rules in the controller are two having “If” part as antecedent and “then” part as consequent.

(Kosko, 1997) has proposed a model that gets the fuzzy inferences and is known as Standard Additive Model (SAM). The SAM is used for the approximation of the fuzzy function as;

$$F(x) = \text{Centroid}(\sum_{i=1}^m h_i w_i(x) B_j) = \frac{\sum_{i=1}^m h_i w_i(x) V_i c_i}{\sum_{i=1}^m h_i w_i(x) V_i} = \sum_{i=1}^m p_i(x) c_i \quad \text{Equation 2}$$

Where,

h_i is the i_{th} weight

V_i is the volume of the consequent

c_i is the centroid of consequent

$w_i(x)$ is the antecedent membership function

$p_i(x)$ is the degree of fire.

The supervised learning is used to tune the parameters. The equations of parameters are derived using gradient descent method which is basically the chain rule. The aim is to minimize the square of error.

$$E_k = \frac{1}{2} (y_k - t_k)^2 \quad \text{Equation 3}$$

2.3 Analysis and Mathematical Models

The voltage, active power and reactive power are delivered to the micro-grid on the basis of three main equations given below.

The mathematical model of output voltage as a function of modulation index can be given as;

$$V_{ac} = m V_{cell} \angle \delta \quad \text{Equation 3}$$

Where,

V_{ac} is the AC output voltage of inverter

m is the modulation index of inverter

δ is the phase angle of the alternating voltage V_{cell} .

While the mathematical models of Active and Reactive power can be represented as;

$$P_{ac} = \frac{m V_{cell} V_s}{X} \sin \delta \quad \text{Equation 4}$$

$$Q = \frac{(m V_{cell})^2 - m V_{cell} V_s \cos \delta}{X} \quad \text{Equation 5}$$

Where,

P_{ac} is the AC output power from the inverter

Q is the reactive power from the converter

V_s is the terminal voltage of load

X is the reactance of the line between SOFC and grid.

4. RESULTS AND DISCUSSION

The active and reactive power supplied by SOFC using is shown in Figure 3 and 4, which meets the reference demand of the micro-grid. The controller employs the supervised learning by using the gradient descent method. It tunes its parameters to minimize the square of the error which is the deference between reference demand and actual value of power flowing in the grid. Initially, the requirement of micro-grid is 0.25 p.u and at 0.4 hour, the demand increases to its maximum. While tracking the reference, the slight difference between the reference and actual power is due to the time taken by the controller to update its

parameters and the time taken by the SOFC to adjust its chemical reaction to deliver power to the load.

The output three phase voltage and corresponding current waveforms of the inverters after RL filtering is shown in Figure 5 and 6 respectively. The controlled current is injected into the grid with its peak varied at 0.4 thus keeping the peak value of the voltage at constant. Thus, when the demand is increased at 0.4, the current delivered is also increased. The controller guides the inverter to feed the controlled current into the micro-grid in order to follow the reference demand.

The above data was tested using both PI and SAM based FNN controllers. The comparative performance of PI and SAM based FNN controller is shown in Figure 7. The performance is shown with a step reference at 0.1. From figure, it is clear that the SAM based FNN catch the reference demand more quickly than the PI, thus the SAM based FNN controller outperforms the PI controller.

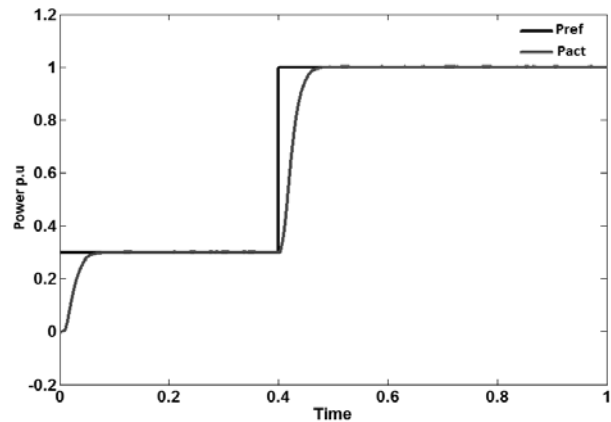


Fig. 3: Control of active power delivered of the micro-grid

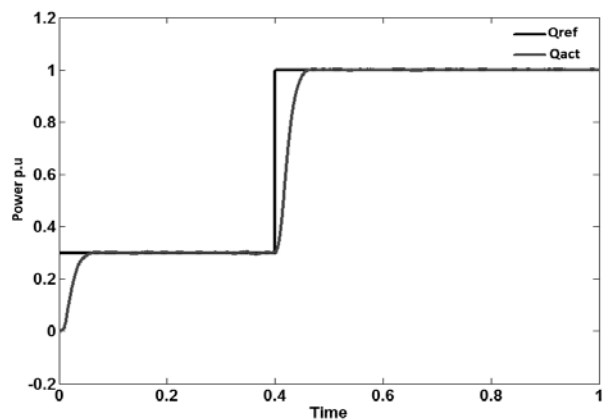


Fig. 4: Control of reactive power delivered of the micro-grid

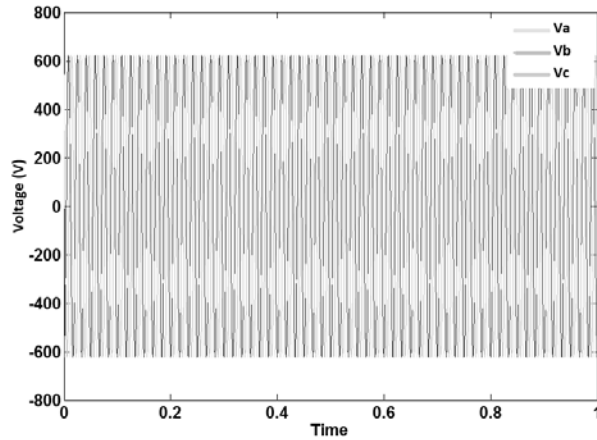


Fig. 5: Output voltage waveform of Inverter

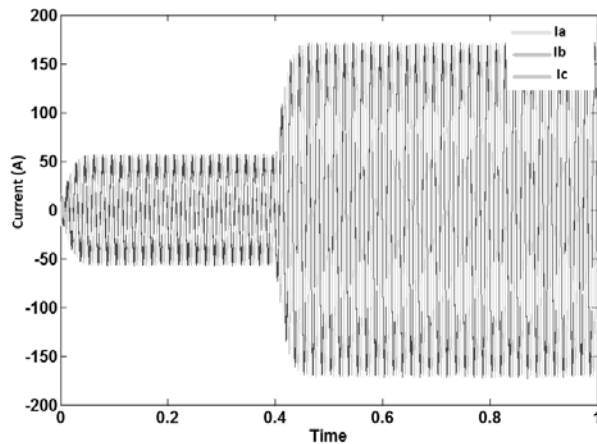


Fig. 6: Current injected to the micro-grid

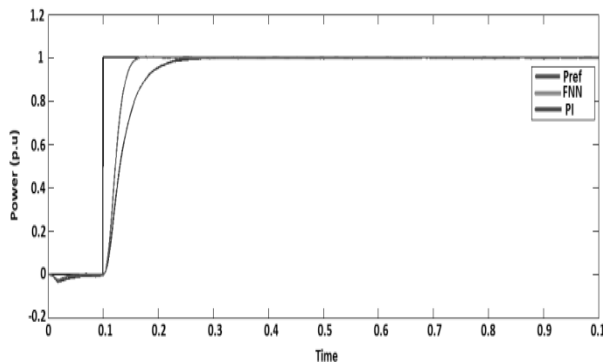


Fig. 7: Performance comparison of PI and SAM based FNN

5.

CONCLUSION

In this research paper, the active and reactive power is delivered to the micro-grid using SAM based

FNN and PI controller. The active power is controlled by changing the modulation index and reactive power is controlled by changing the phase angle which in turn varies the peak of current to follow the reference demand. The controllers and control strategy was able to control the active and reactive power and the SAM based FNN outperforms PI. With the RL filtering, the output voltage of the inverter is free of harmonics, and thus feasible for coupling with the micro-grid.

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