Intelligent Control of Fuel Cell Distributed Generation Systems

A.Hajizadeh, M.A.Golkar

***Abstract*—This paper presents modeling, controller design, and simulation study of a Solid Oxide Fuel Cell (SOFC) distributed generation (DG) system. The overall configuration of the SOFC DG system is given, dynamic models for the SOFC power plant and its power electronic interfacing are briefly described, and controller design methodologies for the power conditioning units to control the power flow from the fuel cell power plant to the utility grid are presented. A MATLAB/Simulink simulation model is developed for the SOFC DG system by combining the individual component models and the controllers designed for the power conditioning units. Simulation results are given to show the overall system performance including active power control and voltage regulation capability of the distribution system.**

***Index Terms*— Distributed Generation, Intelligent Control, Fuel Cell, Active power, Power Quality**

I. Introduction

DISTRIBUTED Generation (DG) systems, powered by microsources such as fuel cells, photovoltaic cells, and microturbines, have been gaining popularity among the industry and utilities due to their higher operating efficiencies, improved reliabilities, and lower emission levels. The introduction of DG to the distribution system has a significant impact on the flow of power and voltage conditions at the customers and utility equipment [1]-[2]. These impacts might be positive or negative depending on the distribution system operating characteristics and the DG characteristics. Positive impacts include, voltage support and improved power quality, diversification of power sources, Reduction in transmission and distribution losses, transmission and distribution capacity release and improved reliability. Among the distributed generators, fuel cells are attractive because they are modular, efficient, and environmentally friendly [3]. Fuel Cell DG (FCDG) systems can be strategically placed at any site in a power system (normally at the distribution level) for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency. Therefore, proper controllers need to be designed for a FCDG system to make its performance characteristics as desired [4]-[5]. Stevandic J. Jiang [6] develop a standalone, reduced-order, dynamic model of fuel cell power plant connected to a distribution grid via dc/ac converter. Sedghisigarchi and Feliachi [7] proposed a model includes the electrochemical and thermal aspects of chemical reactions inside the fuel-cell stack (i.e., temperature and chemical species dynamics are considered) but the dynamics model of DC/DC and DC/AC Converters are not considered. In [8] a novel hierarchical control architecture for a hybrid distributed generation system that consists of dynamic models of a battery bank, a solid oxide fuel cell and power electronic converters has been presented. But in this paper the voltage regulation capability and reactive power control of FCDG have not been addressed. So it is important to develop a proper modeling of FCDG system and design suitable control strategies for all components to attain good performances such as optimal operation of fuel cell stack and power quality improvement. Hence, in this paper the intelligent control structure has been developed for a FCDG system with active power management and reactive power control capability. The fuel cell power plant is interfaced with the utility grid via boost dc/dc converters and a three-phase pulse width modulation (PWM) inverter. A validated SOFC dynamic model, reported in [9], is used in this paper. The models for the boost dc/dc converter and the three-phase inverter together are also addressed. The controller design methodologies for the dc/dc converters and the three-phase inverter are also presented for the proposed fuel cell DG system. Based on the individual component models developed and the controllers designed, a simulation model of the SOFCFC DG system has been built in MATLAB/Simulink environment. Simulation results show that the active power control and voltage sag mitigation by FCDG system.

II. Dynamic Modeling of Fuel Cell Distributed Generation Systems

The dynamic modeling of a Fuel Cell Distributed Generation (FCDG) system is an important issue that needs to be carefully addressed. To study the performance characteristics of FCDG systems, accurate models of fuel cells are needed. Moreover, models for the interfacing power electronic circuits in a FCDG system are also needed to design controllers for the overall system to improve its

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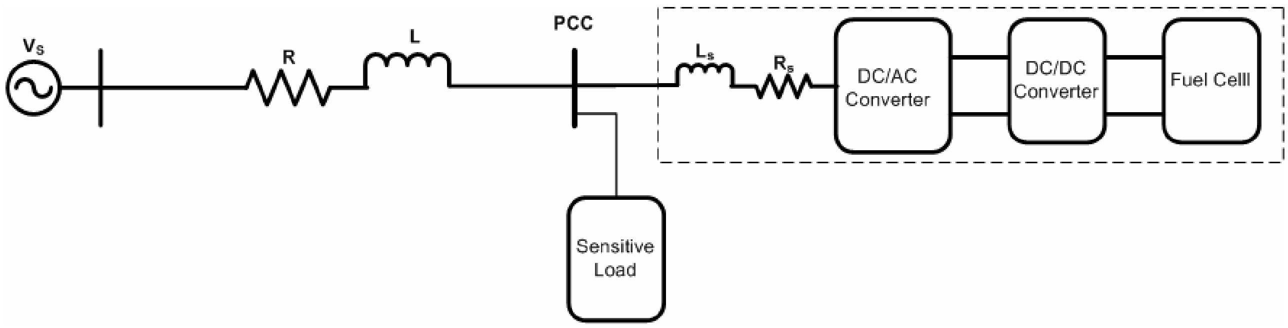

Fig.1. Fuel Cell Distributed Generation System Structure

performance and to meet certain operation requirements [10]. To meet the system operational requirements, a FCDG system needs to be interfaced through a set of power electronic devices. Fig. 1 shows the block diagram of the FCDG system proposed in this paper that connected to main grid in Point Common Coupling (PCC). The electric components of the FCDG system used in this paper comprise a battery, DC/DC and DC/AC converters, while the electrochemical component is a Solid Oxide Fuel Cell system (SOFC). The mathematical models describing the dynamic behavior of each of these components are given below.

A. Fuel Cell Model

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy. They show great promise to be an important DG source of the future due to their many advantages, such as high efficiency, zero or low emission (of pollutant gases), and flexible modular structure. The model of SOFC power plant used in this study is based on the dynamic SOFC stack model developed and validated in [9]. The performance of FCs is affected by several operating variables, as discussed in the following. Decreasing the current density increases the cell voltage, thereby increasing the FC efficiency. One of important operating variable is the reactant utilization, Uf, referring to the fraction of the total fuel (or oxidant) introduced into a FC that reacts electrochemically:

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} \quad (1)$$

Where   is the hydrogen molar flow.

High utilizations are considered desirable (particularly in smaller systems) because they minimize the required fuel and oxidant flow, for a minimum fuel cost and compressor load and size. However, utilizations that are pushed too high result in significant voltage drops. The SOFC consists of hundreds of cells connected in series and parallel. Fuel and air are passed through the cells. By regulating the level, the amount of fuel fed into the fuel cell stacks is adjusted, and the output real power of the fuel cell system is controlled. The Nernst's equation and Ohm's law determine the average voltage magnitude of the fuel cell stack [11]. The following equations model the voltage of the fuel cell stack:

$$V_{fc} = N_0(E_0 + \frac{RT}{2F}(\ln(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}})) - rI_{f0} \quad (2)$$

where:
N_0 is the number of cells connected in series;
E_0 is voltage associated with the reaction free energy;
R is the universal gas constant;
T is the temperature;
I_{f0} is the current of the fuel cell stack;
F is the Faraday's constant.
P_{H2}, P_{H2O}, P_{O2} are determined by the following differential equations:

$$\begin{aligned} \dot{P}_{H_2} &= -\frac{1}{t_{H_2}}(P_{H_2} + \frac{1}{K_{H_2}}(q_{H_2}^{in} - 2K_r I_{fc})) \\ \dot{P}_{H_2O} &= -\frac{1}{t_{H_2O}}(P_{H_2O} + \frac{2}{K_{H_2O}} K_r I_{fc})) \\ \dot{P}_{O_2} &= -\frac{1}{t_{O_2}}(P_{O_2} + \frac{1}{K_{O_2}}(q_{O_2}^{in} - K_r I_{fc})) \end{aligned} \quad (3)$$

Where, $q_{H_2}^{in}$ and $q_{O_2}^{in}$ are the molar flow of hydrogen and oxygen and where the Kr constant is defined by the relation between the rate of reactant hydrogen and the fuel cell current

$$q_{H_2}^{r} = \frac{N_0 I}{2F} = 2K_r I \quad (4)$$

B. DC/DC Converter Model

To connect a fuel cell to an external power system, it is necessary to boost the fuel cell voltage or to increase the number of cells. The role of the DC/DC booster converter is to increase the fuel cell voltage, to control the fuel cell power, and to regulate the voltage. Fig. 2 shows the DC/DC converter model. This boost converter is described by the following two non-linear state space averaged equations [12]:

$$\begin{aligned} \rho X_1 &= \frac{(1-d)}{L.X_2} + \frac{d}{L.U} \\ \rho X_2 &= \frac{-(1-d)}{C.X_1} - \frac{X_2}{RC} \end{aligned} \quad (5)$$

Where ''d'' is the on time of the switching device, ''U'' is the input voltage, ''X_1'' is the inductor current and ''X_2'' is the output voltage.

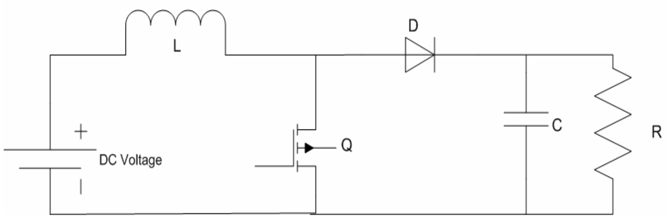

Fig.2. DC/DC Converter Model

C. DC/AC Converter Model

Far the mostly used converter nowadays is the Voltage Source Converter (VSC). The power rating of most DG units is not higher than a few MW. So most VSC's will be based on IGBT switches. The action of the power electronics devices in such an inverter is much faster than the mechanical valve. Thus, for fast response, DC/AC inverter is the first choice. A dynamic model of voltage source inverter has been developed. A three-phase equivalent circuit of DC/AC converter is shown in Fig. 3. To reduce these harmonics, filters are connected between the converter and the grid. A first-order filter, represented by the L_s and the R_s in Fig. 3, is used. In Fig. 4, v_{ia}, v_{ib}, v_{ic} are the three-phase AC voltage outputs of the inverter, and i_a, i_b, i_c are the three-phase AC current outputs of the inverter. The bus voltages of the grid are v_{sa}, v_{sb}, v_{sc}. The dynamic model of three-phase VSC is represented in [13].

$$\frac{di_k}{dt} = -\frac{R_s}{L_s} i_k + \frac{1}{L_s}(v_{ik} - v_{sk}) \tag{6}$$

Where k= {a, b, c}.

To develop the dynamic model, the state equations (6) are transformed to the system synchronous reference frame as:

$$\frac{di_q}{dt} = \frac{-R_s\omega_s}{L_s} i_q - \omega_s i_d + \frac{\omega_s}{L_s} m \sin(\delta + \theta_s) V_{dc} - \frac{\omega_s}{L_s}\sin(\theta_s) V_s$$
$$\frac{di_d}{dt} = \frac{-R_s\omega_s}{L_s} i_d + \omega_s iq + \frac{\omega_s}{L_s} m \cos(\delta + \theta_s) V_{dc} - \frac{\omega_s}{L_s}\cos(\theta_s) V_s \tag{7}$$

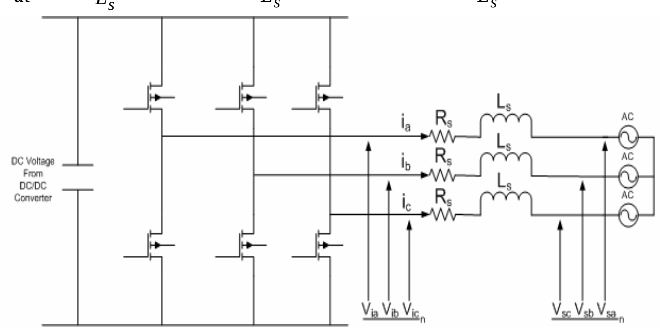

Fig. 3. Three-phase dc/ac voltage source inverter

III. CONTROL STRATEGY FOR FCDG SYSTEM

There is a high demand for utility DG installations due to their advantages of deferment or upgrading t he distribution infrastructure. Most DG units are connected to the distribution system through a shunt nonlinear link such as a Voltage Source Inverter (VSI) or a Current Source Inverter (CSI). The main function of the shunt connection is to control the amount of active power drawn from the DG source. This link can emulate DSTATCOM devices by controlling the reactive power, as well as the active power. Hence, it is necessary to design a control structure to manage active power and reactive power simultaneously. Moreover, the control strategy must be designed to mitigate different power quality problems. Also, the suitable control is presented to regulate the input fuel flow in order to meet a desirable output active power demand and to prevent transient conditions in fuel cell stack. The control structure that has been proposed in this paper has been shown in Fig. 4. As shown, this structure has been composed of different local units. Using of distributed fuzzy logic controllers in this structure makes that it has adaptive properties in distribution systems [14]. Fuzzy control is a practical alternative for a variety of challenging control applications since it provides a convenient method for constructing nonlinear controllers via the use of heuristic information. A fuzzy logic controller used in this research consists of the rule base, fuzzification, inference engine, and defuzzification. The rule base collects the control rules which describe experts' knowledge and experience in the fuzzy set. In the fuzzification process, the numerical inputs are converted into linguistic fuzzy values. Then, from the fuzzy values and the already established rule base, linguistic control values are generated in the inference engine. Because these linguistic inference results cannot be used in the actuator directly, they should be converted into numerical output again in the defuzzification process. MAX-MIN composition and the center of gravity method are used in the inference engine and defuzzification of this fuzzy logic, respectively.

A. DC/AC Converter Controller

Power quality has attracted considerable attention from both utilities and users due to the use of many types of sensitive electronic equipment, which can be affected by harmonics, voltage sag, voltage swell, and momentary interruptions [15]. These disturbances cause problems, such as overheating, motor failures, inaccurate metering, and misoperation of protective equipment. Voltage disturbance is the common power quality problem in industrial distribution systems. The voltage disturbance mainly encompasses voltage sags, voltage swells, voltage harmonics, and voltage unbalance. The voltage disturbance notoriously affects voltage-sensitive equipment that eventually leads to malfunction. Voltage sag is one of the most severe power quality problems because of its adverse financial impact on customers. The power quality control unit, as shown in Fig. 5, has been formed of two parts, voltage processing unit and fuzzy logic controllers.

A.1 Voltage Processing Unit

This unit is based-on Adaptive Linear Neuron structure (ADALINE). Recent years, with the development of artificial intelligence technique, ADALINE has been used to analyze the power quality [16]. The idea behind using the ADALINE in detection of power quality disturbances is to represent the

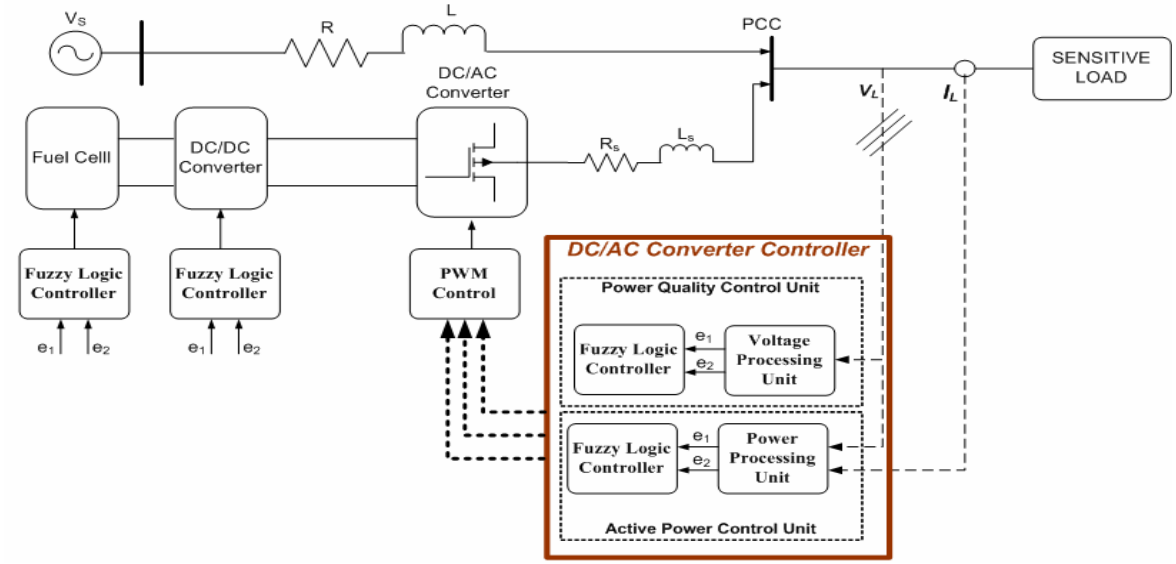

Fig.4. Control Structure of Fuel Cell Distributed Generation System

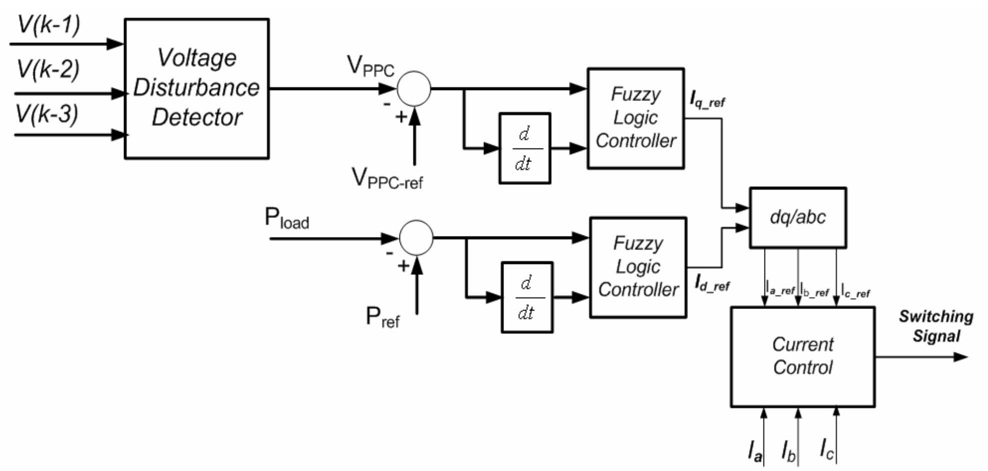

Fig. 5. DC/AC Converter Controller

ADALINE as an adaptive signal predictor [17]. The input to this predictor is time-delayed samples of the signal and the output of the ADALINE is the predicted value of the signal. The ADALINE algorithm possesses a highly tracking capability. Yet when a power quality disturbance occurs, the abrupt change in the signal gives rise to the error signal generated by the ADALINE and the weight values experience variation until it settles down to the new values. Both the alterations in the error signal and the sum of the variation of the weight values can aid in the detection of power quality events. To achieve the voltage regulation task, the current $i_{q\text{-ref}}$ is assigned to the output of the FLC. The actual inputs to the fuzzy system are scaled versions of both the rms voltage error and its derivative. Seven uniformly distributed triangle membership functions are used for the fuzzification of the inputs [14].Each of the FLC input signals and output signals are fuzzy variables and are assigned seven linguistic variables, namely, NB, NM, NS, Z, PS, PM, and PB, which stand for negative big, negative medium, negative small, zero, positive small, positive medium and, positive big, respectively. The rule base is designed so that the actual rms voltage can reach its command value as quickly as possible within the shunt compensator limitation without overshoot.

A.2 Active Power Control

A fuzzy logic controller has been designed to control active power drawn from load. The actual inputs to the fuzzy system are scaled versions of both the active power error and its derivative and the current id-ref is assigned to the output of the FLC [14]. Seven uniformly distributed triangle membership functions are used for the fuzzification of the inputs. Each of the FLC input signals and output signals are fuzzy variables and are assigned seven linguistic variables, namely, NB, NM, NS, Z, PS, PM, and PB, which stand for negative big, negative medium, negative small, zero, positive small, positive medium and, positive big, respectively.

B. DC/DC Converter Controller

The unregulated output voltage of the FC is fed to the dc/dc boost converter. Being unregulated it has to be adjusted to a constant average value (regulated dc voltage) by adjusting the duty ratio to the required value. The voltage is boosted depending upon the duty ratio. The duty ratio of the boost converter is adjusted with the help of a fuzzy logic controller (FLC). The duty ratio is set at a particular value for the converter to provide desired average value of voltage at the output, and any fluctuation in the FC voltage due to change in fuel flow, in the load or in the characters of FC due to the chemistry involved takes the output voltage away from the desired average value of the voltage. The FLC changes the duty ratio appropriately to get the desired average value. The boost converter responds fast to the changes in the duty ratio. The duty ratio of the converter is changed by changing the pulses fed to the switch in the dc/dc converter circuit by the PWM generator. The fuel flow also needs to be adjusted, which takes effect gradually and controls the output voltage. Thus, both the strategies have to be combined for the efficient control of voltage of the FC. This paper concentrates only on the boost converter control strategy. The response time of the dc/dc converter is very short compared to that of the reformer of the FC, which alters the fuel flow. Thus, for the fast system response, initially the converter is controlled for load variations and the average voltage is adjusted in the transitional period by the boost converter. The output of the dc/dc converter is the boosted voltage that is fed to the load or to the next stage of filter to eventually pass on to the inverter stage. This boosted voltage is compared with a reference dc voltage to generate an error signal. The change in error is calculated. The error and the change in error are fed as inputs to the Fuzzy Logic Controller (FLC) [14]. The FLC generates control signal based upon the inputs and rule base. The control signal is fed to the PWM generator. The PWM generator based upon the control signal adjusts the pulses of the switch of the boost converter. The boost converter generates output voltage based upon the duty ratio provided by the PWM generator.

C. Fuel Cell Controller

In order to operate the fuel cell stack at an optimal fuel utilization point (approximately 85%) [18], the control algorithm should observe the following operational constraints of the fuel cell system:

Underused fuel: If the fuel utilization drops below a certain limit, the cell voltage will rise rapidly.

Overused fuel: If the fuel utilization increases beyond a certain value, the cells may suffer from fuel starvation and be permanently damaged.

Under voltage: The fuel cell characteristic poses a lower cell voltage limit of approximately 0.5 V, beyond which the cell voltage decreases very steeply with increasing current. To meet the aforementioned usage requirements, the basic target of the fuel cell controller is to maintain optimal hydrogen utilization, $U_{f,\,opt}$, around 85%.

Eq. (4) shows that the reacting fuel quantity, $q^{r}_{H_2}$, is directly proportional to the output current, I, the factor Kr being a cell constant.

Hence, the desired utilization is translated to corresponding output current demand:

$$q^{in}_{H_2} = \frac{2K_r}{U_{f,opt}} I_{demand} \Rightarrow I_{demand} = \frac{U_{f,opt}}{2K_r} q^{in}_{H_2} \qquad (8)$$

A typical range of Uf is 80-90% ([18]), which ensures that the operational limits mentioned above are observed. The corresponding limitation for the demand current is then

$$\frac{0.8q^{in}_{H_2}}{2K_r} = I_{fc\_\min} \le I_{fc\_ref} \le I_{fc\_\max} = \frac{0.9q^{in}_{H_2}}{2K_r} \qquad (9)$$

Under these conditions, the cell output power is directly related to its fuel consumption at the selected optimum operating point of the V-I characteristic. Operating the fuel cell at different output power levels requires suitable variation of its input fuel flow rate, to be realized by the overall control system of the fuel cell. The power demand requirement of the fuel cell is translated into a current demand input by dividing with the stack output voltage:

$$I_{demand} = \frac{P_{demand}}{V_{fc}} \qquad (10)$$

To overcome the transient conditions in fuel cell, a fuzzy logic controller has been designed. The actual inputs to the fuzzy system are scaled versions of both the fuel cell current error and its derivative and the hydrogen molar flow $q_{H2\text{-}ref}$ is assigned to the output of the FLC [14]. Seven uniformly distributed triangle membership functions are used for the fuzzification of the inputs. Each of the FLC input signals and output signals are fuzzy variables and are assigned three linguistic variables, namely, S, M, L, N, Z and P, which stand for small, medium, large, negative, zero, positive respectively. However, for preventing transient condition on output voltage of fuel cell, the rule based of FLC must be designed correctly. The control structure for fuel cell system has been shown in Fig. 6.

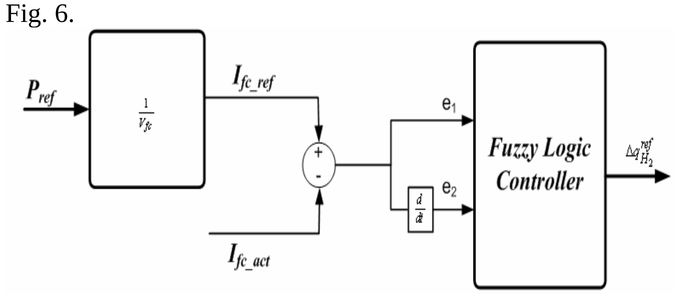

Fig. 6. Control structure for hydrogen molar flow of fuel cell system

IV. SIMULATION RESULTS

The performance of the proposed structure is assessed by a computer simulation that uses MATLAB Software. The parameters of the system under study are given in Table I. The study case is dedicated to test the dynamic performance of the proposed structure. A voltage sag will be used to examine the dynamical performance of the algorithm. It is assumed that the three phase voltages were balanced until a disturbance has occurred in the system at 0.25 second. The disturbance causes a voltage sag in the three voltages, as shown in Fig. 7. Before the disturbance, the system was balanced and, therefore, the negative component vanishes. The voltage at the PCC is equal to 1.0 pu during normal operation. At t=0.05 sec, the distributed energy source is switched on to correct the voltage profile. At 0.25 second, the voltage sag is initiated and the proposed algorithm succeeds to detect the disturbance in less than half of a cycle. The signal of voltage that predicted by ADALINE structure, has been presented in Fig. 8. As shown in Fig. 8, The ADALINE algorithm possesses a highly tracking capability. Fig. 9 demonstrates that the proposed control structure based Fuzzy Logic Control succeeds in regulating the PCC voltage at 1.0 pu, even when the load disturbance occurs at 0.25ses and 0.5s with fast dynamics and minimum overshoot. This result examines the disturbance rejection capabilities of the proposed FLC. It quickly returns the voltage at the PCC to its setting value. Fig. 10(a) indicates that the active power supplied from the DER is almost constant, and is equal to its input command value (1pu) from the control circuit. Finally, Fig. 10(b) shows the injected reactive power from the distributed energy sources to compensate for the voltage. It is clear from figures 10(a) and 10(b) that the control of the active and reactive power is independent of the other. Fig. 11 shows the output voltage changes of fuel cell. As depicted in this figure, the voltage rises when the voltage sag occurs.

V. Conclusion

Modeling, control, and simulation study of a SOFC DG system is investigated in this paper. A validated SOFC dynamic model is used to model the fuel cell power plant. The state space models for the boost dc/dc converter and the three-phase inverter are also discussed. Then by designing proper intelligent controllers the capability of FCGD for active power control and voltage disturbance mitigation has been demonstrated. The proposed control method is insensitive to the parameter variation of the distribution system, because it is adaptive in nature. This is an absolute necessity in distribution systems, since there is no dependence on the parameter of the electrical network.

TABLE I
FUEL CELL DISTRIBUTED GENERATION SYSTEM PARAMERTERS

Fuel Cell Parameters			
Rated Voltage=210[V]		Rated Power= 100[KW]	
N_0 = 384	K_{H2}=8.43e-4	K_{H2O}=2.81e-4	K_{O2}=2.52e-3
t_{H2}=26.1	t_{H2O}=78.3	t_{O2}=2.91	r=0.126
DC/DC Converter Parameters			
Rated Voltage=200V/480V		Rated Power=100KW	
R [Ω]=14	C [mF]=1.5	L [μH]=415	
DC/AC Converter Parameters			
Rated Voltage=480V dc/ 220V ac		Rated Power=100KW	
R_s [Ω]=0.9	L_s [mH]=0.01	V_s [Volt]=220	f_s [Hz]=50

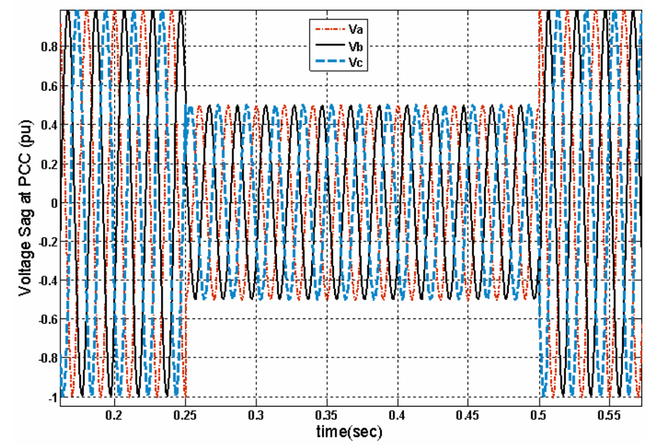

Fig.7. Three-phase supply voltage during a sag

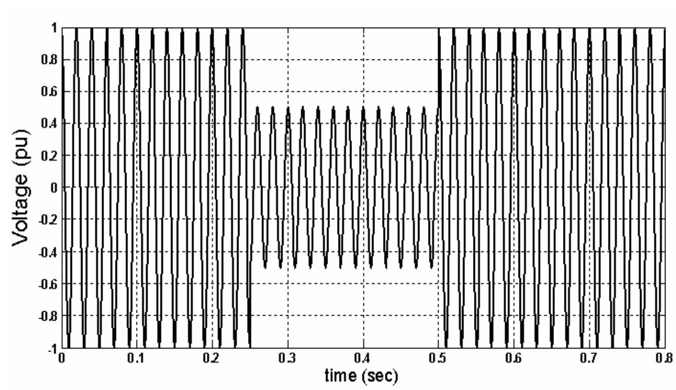

Fig. 8. Predicted Voltage Sag by ADALINE

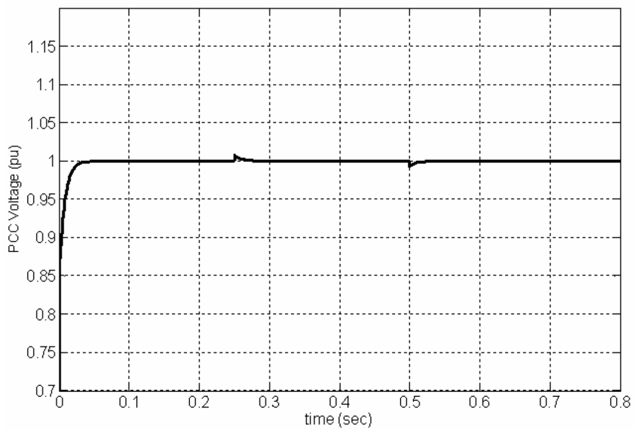

Fig.9. Regulated Voltage (pu) at PCC

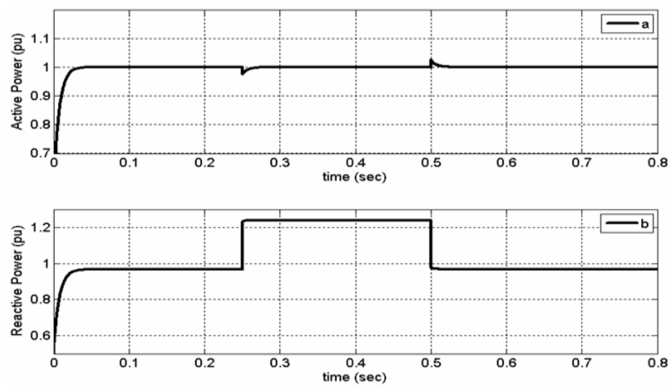

Fig.10. Produced Active and Reactive Power by FCDG

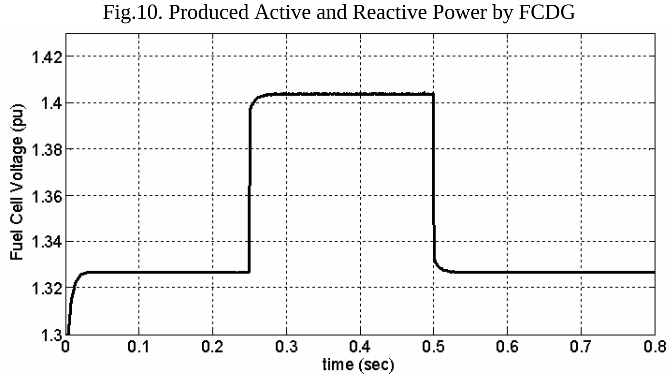

Fig.11. Fuel Cell Voltage during voltage sag

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VII. Biographies

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