Power Flow Control of Grid-Connected Fuel Cell Distributed Generation Systems

Amin Hajizadeh† **and Masoud Aliakbar Golkar***

Abstract – This paper presents the operation of Fuel Cell Distributed Generation (FCDG) systems in distribution systems. Hence, modeling, controller design, and simulation study of a Solid Oxide Fuel Cell (SOFC) distributed generation (DG) system are investigated. The physical model of the fuel cell stack and dynamic models of power conditioning units are described. Then, suitable control architecture based on fuzzy logic and the neural network for the overall system is presented in order to activate power control and power quality improvement. 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.

Keywords: Distributed Generation, Fuel Cell, Power Flow Control, Power Quality

1. Introduction

Recently, power market liberalization has resulted in an increase in the number of smaller power producers participating in the electricity market giving rise to a renewed interest for distributed generation (DG). This led to a considerable increase in the proportion of DG in the network [1, 2]. The introduction of DG to the distribution system has a significant impact on the flow of power and voltage conditions to the customers and utility equipment. 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 [3]. The integration of DG with the utility distribution network offers a number of technical, environmental, and economical benefits. Moreover, such integration allows distribution utilities to improve the network performance by reducing its losses. The existing DG units are utilized to supply active power to either the network or the customers. Although DG units such as fuel cell, photo voltaic, micro turbine, and storage devices, which are linked via a nonlinear interface, represent a small portion of the installed DG capacity, they will potentially grow. Usually, this interface consists of a current controlled Voltage Source Inverter (VSI). With the new era of system restructuring, the quality of power gains increasing attention. [4]. Among the new forms of DG, the natural-gas-fed fuel cell that converts chemical energy directly to dc shows a promising future. Several types of FCs for a variety of applications are under active research [5, 6]. 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 [7, 8]. A great deal of research has been done on power electronic devices for grid-connection of FCDG systems in distribution systems [9-13]. However, most of the related papers have not addressed in detail the modelling and control of power converters and fuel cell distributed generators. In [14] 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 the power electronic converters has been presented. But in this paper the voltage regulation capability and reactive power control of FCDGs have not been addressed. Also in [15] the flexible control strategy for grid-connection of fuel cell distributed generation to improve the power quality and active power control in distribution systems has been presented. Nevertheless, for practical analysis of the fuel cell systems, a first/second order model [16] is used to realize the slow dynamics of the fuel cells.

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So it is important to develop a proper modeling of the 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 [17], 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 SOFC DG system has been built in MATLAB/Simulink environment. Simulation results show the active power control and voltage sag mitigation by FCDG system.

2. Dynamic Modeling of FCDG System

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 called for to design controllers in order for the overall system to improve its performance and to meet certain operational requirements [14]. Concerning 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. 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.

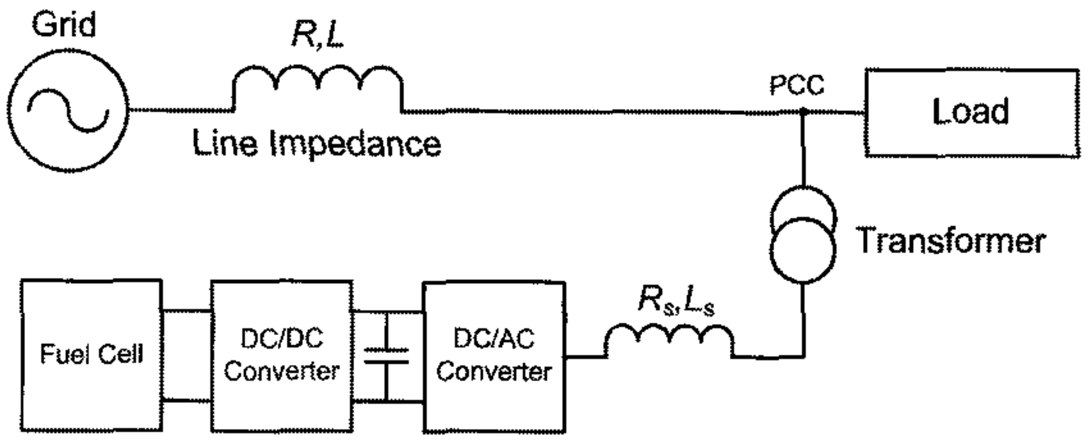

Fig. 1. Fuel Cell Distributed Generation System Structure

2.1 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 numerous 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 [17]. 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 the important operating variables is the reactant utilization, Uf, referring to the fraction of the total fuel (or oxidant) introduced into a FC that reacts electrochemically:

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} \tag{1}$$

Where q_{H2} 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 [18]. The following equations model the voltage of the fuel cell stack:

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

where:

N_0 is the number of cells connected in series;
E_0 is the 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:

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

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:

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

2.2 DC/DC Converter Model

Usually 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 boost 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 [14]:

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

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.

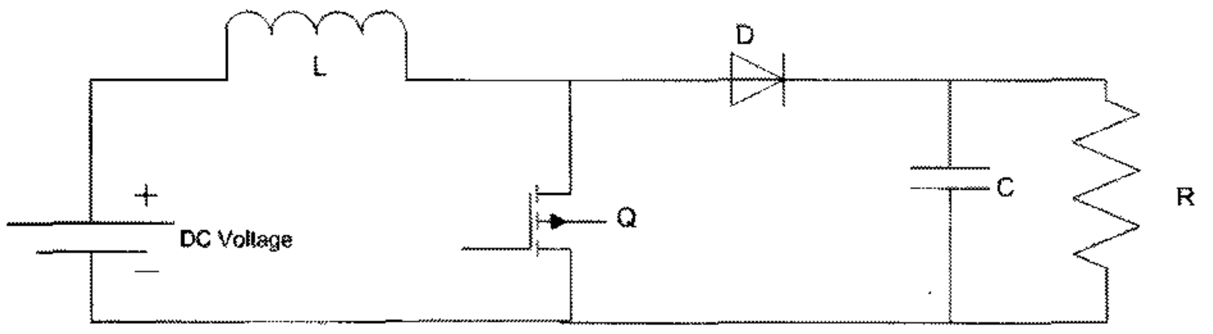

Fig. 2. DC/DC Converter Model

2.3 DC/AC Converter Model

By far the mostly used converter nowadays is the Voltage Source Converter (VSC). A dynamic model of the voltage source inverter has been developed. A three-phase equivalent circuit of DC/AC converter is shown in Fig. 3. To reduce 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. 3, v_{ia}, v_{ib} and 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} and v_{sc}. The dynamic model of the three-phase VSC is represented in [19].

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

Where k= {a, b, c}.

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

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

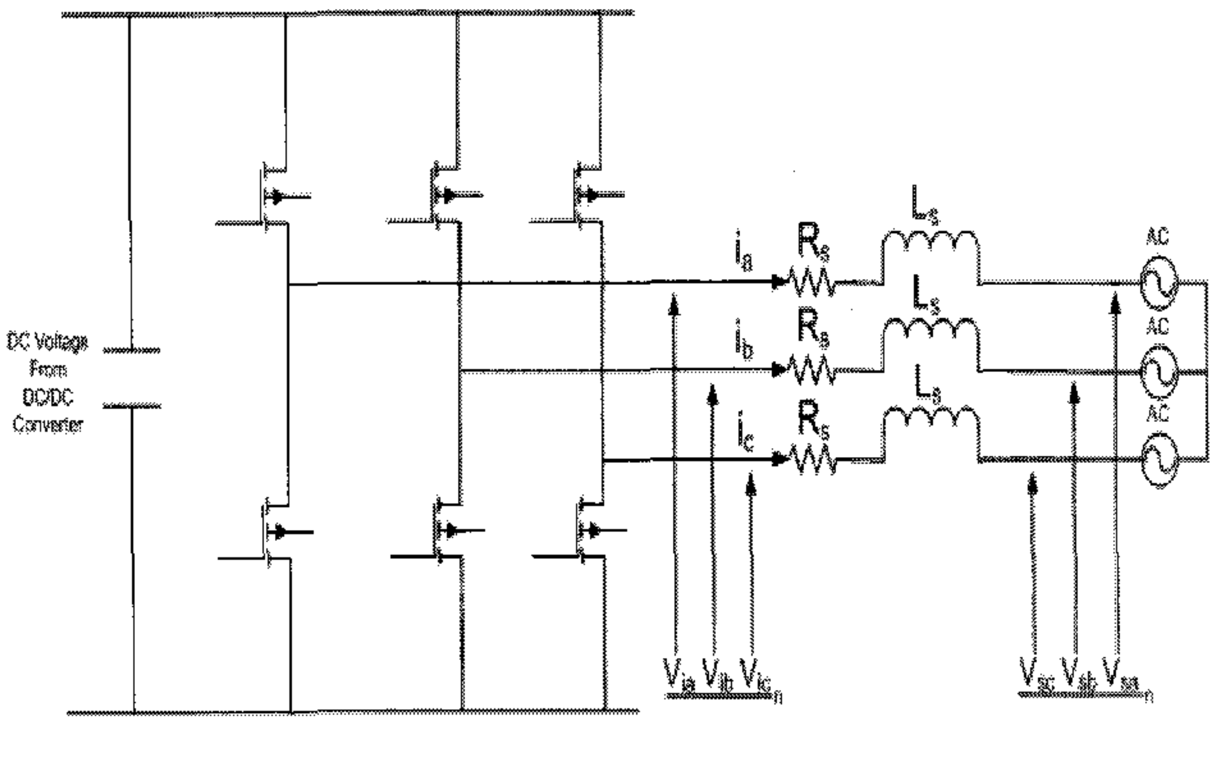

Fig. 3. Three-phase dc/ac voltage source inverter

2.4 Distribution System Model

To study the dynamic impact of the fuel cell power plant on the power distribution system, the three-phase system has been represented by a single line equivalent system.

3. Control Strategy for FCDG System

There is a high demand for utility DG installations due to their advantages of deferment or upgrading the 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, a 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 the fuel cell stack. The control structure that has been proposed in this paper has been presented in Fig. 4. As indicated, this structure has been composed of different local units.

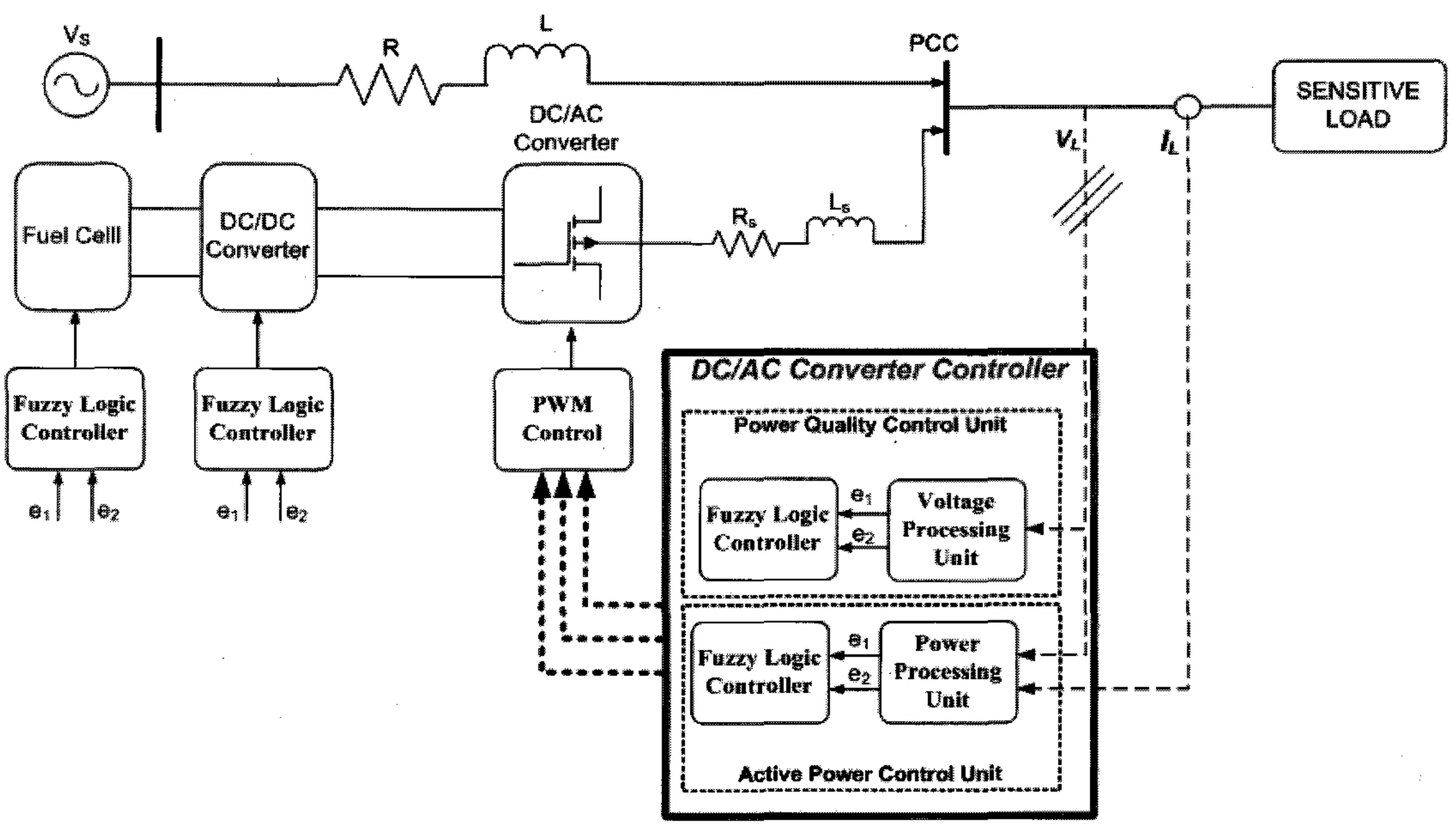

Fig. 4. Control Structure of Fuel Cell Distributed Generation System

Usage of distributed fuzzy logic controllers in this structure causes it to have adaptive properties in distribution systems [15]. The superiority of FLC is the result of its ability to manage the nonlinear behavior of many practical systems of complex control structures by taking advantage of heuristics and expert knowledge of the process being controlled. The fuzzy logic controller used in this research consists of rule base, fuzzification, inference engine, and defuzzification. The rule base collects the control rules which describe the 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 utilized in the inference engine and defuzzification of this fuzzy logic, respectively.

3.1 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 [19]. These disturbances cause problems, such as overheating, motor failures, inaccurate metering, and misoperation of protective equipment. Voltage disturbance is the most common power quality problem in industrial distribution systems. The voltage disturbance mainly encompasses voltage sags, voltage swells, voltage harmonics, and voltage unbalances. 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, the voltage processing unit and fuzzy logic controllers.

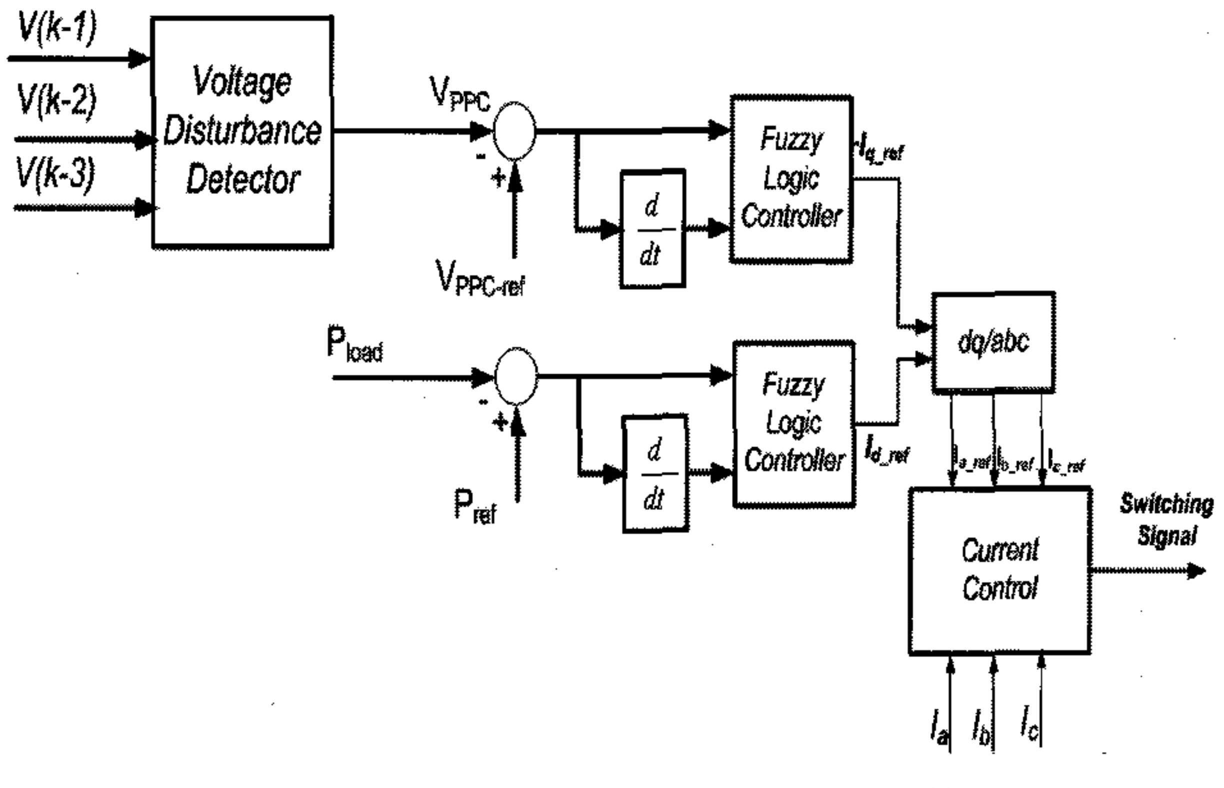

Fig. 5. DC/AC Converter Controller

3.1.1 Voltage Processing Unit

This unit is based on Adaptive Linear Neuron structure (ADALINE). In recent years, with the development of artificial intelligence techniques, ADALINE has been used to analyze the power quality [20]. The idea behind using the ADALINE in detection of power quality disturbances is to represent the ADALINE as an adaptive signal predictor [21]. The inputs to this predictor are 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 they settle 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 Fuzzy Logic Controller (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. Each of the FLC input 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. This leads to the rules as listed in Table I.

Table 1. Fuzzy Rule Base for Voltage Regulation

Δ_{iq_ref}		e_2						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e_1	**NB**	PB	PB	PB	PM	PM	PM	PS
	NM	PB	PB	PM	PM	PM	Z	NB
	NS	PB	PM	PM	PM	PS	NS	NB
	Z	PB	PM	PS	Z	NS	NM	NB
	PS	PB	PS	NS	NM	NM	NM	NB
	PM	PB	Z	NM	NM	NM	NB	NB
	PB	NS	NM	NM	NM	NB	NB	NB

3.1.2 Active Power Control

A fuzzy logic controller has been designed to control active power drawn from the load. The actual inputs to the fuzzy system are scaled versions of both the active power error and its derivative and the current $i_{d\text{-ref}}$ is assigned to the output of the FLC. Seven uniformly distributed triangle membership functions are used for the fuzzification of the inputs. Each of the FLC input 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 fuzzy rule base has been shown in Table 2.

Table 2. Fuzzy Rule Base for Active Power Control

Δ_{id_ref}		e_2						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e_1	**NB**	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PM	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

3.2 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 must also be adjusted, which takes effect gradually and controls the output voltage. Thus, both 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. Consequently, for 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 FLC. The FLC generates a control signal based upon the inputs and the 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.

The fuzzy rule base for duty ratio control of the DC/DC converter has been presented in Table 3.

Table 3. Fuzzy Rule Base for Duty Ratio Control of DC/DC Converter

Δd		e₂						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e₁	**NB**	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PM	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

3.3 Fuel Cell Controller

In order to operate the fuel cell stack at an optimal fuel utilization point (approximately 85%) [22], the control algorithm should observe the following operational constraints of the fuel cell system:

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

Overused fuel: If 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 [14]. 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%.

Equation (3) shows that the reacting fuel quantity, $q^r_{H_2}$, is directly proportional to the output current, I, being the factor K_r, which is a cell constant.

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

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

A typical range of U_f is 80-90% ([22]), which ensures that the operational limits mentioned above are observed. The corresponding limitation for the demand current is then:

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

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 by the stack output voltage:

$$I_{demand} = \frac{P_{demand}}{V_{fc}} \tag{10}$$

To overcome the transient conditions in the 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. Seven uniformly distributed triangular membership functions are used for the fuzzification of the inputs. This leads to the rules as listed in Table IV. 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, and positive, respectively. However, for preventing transient condition on the output voltage of the fuel cell, the rule base of the FLC must be designed correctly. The control structure for the fuel cell system has been shown in Fig. 6.

Table 4. Fuzzy Rule Base for the Hydrogen Molar Flow of the Fuel Cell

$\Delta q_{H2\text{-}ref}$		e₂		
		N	**Z**	**P**
e₁	S	NL	Z	PS
	M	NS	Z	PS
	L	NS	PS	PL

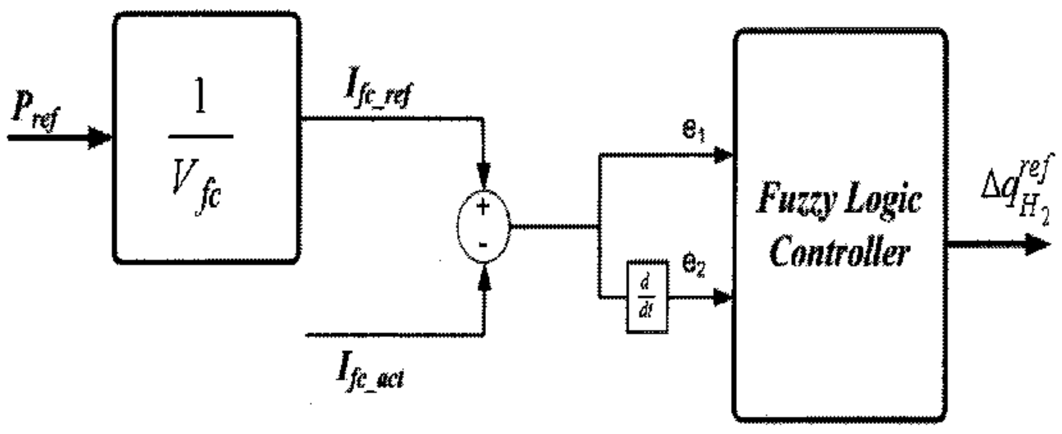

Fig. 6. Fuel Cell Controller

4. Simulation Results

The topology used in this study for the fuel cell system, power condition unit, and utility grid is shown in Fig. 7. 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 5.

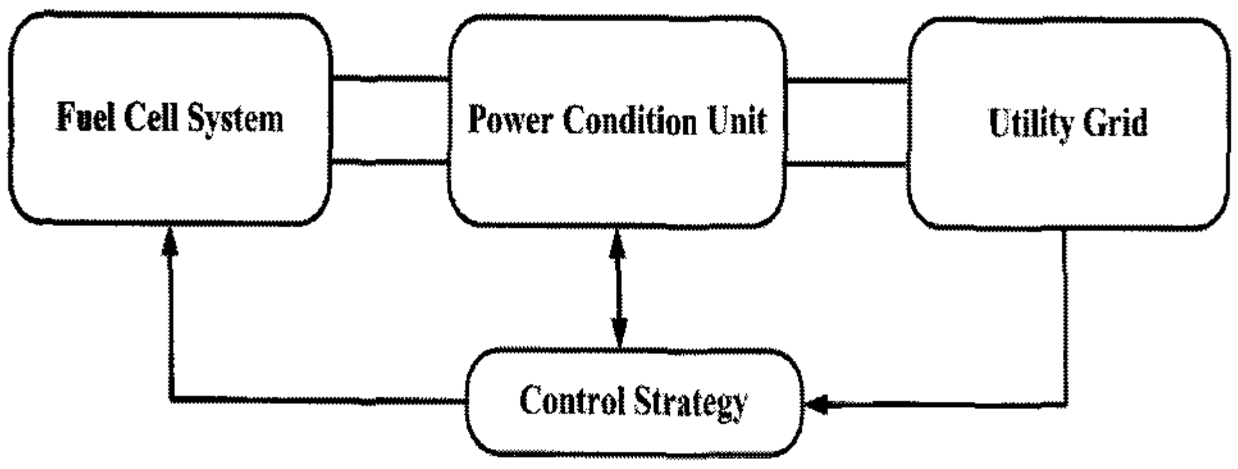

Fig. 7. Block diagram of proposed model

The case study is dedicated to test the dynamic performance of the proposed structure.

In a fuel cell DG system, a certain amount of power may be scheduled to be delivered to a load center from the utility grid with the rest to be supplied by the fuel cell system. In this case study the fuel cell power is set to 100 kW (1 p.u.). 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 seconds. The disturbance causes a voltage sag in the three voltages, as shown in Fig. 8. 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 seconds, 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 predicted by the ADALINE structure has been presented in Fig. 9. As shown in Fig. 9, The ADALINE algorithm possesses a high tracking capability. Fig. 10 demonstrates that the proposed control structure based on Fuzzy Logic Control succeeds in regulating the PCC voltage at 1.0 pu, even when the load disturbance occurs at 0.25sec and 0.5sec 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. 11(a) indicates that the active power supplied from the fuel cell DG is almost constant, and is equal to its input

Table 5. Fuel Cell Distributed Generation System Parameters

Fuel Cell Parameters	
Faraday's constant (*F*)	96484600[C/kmol]
Hydrogen time constant (t_{H2})	26.1 [sec]
Hydrogen valve molar constant(K_{H2})	8.43×10^{-4}
k_r Constant=$N_0/4F$	9.9497×10^{-7}
No Load Voltage (E_0)	0.6 [V]
Number of Cells (N_0)	384
Oxygen time constant (t_{O2})	2.91[sec]
Oxygen valve molar constant (K_{O2})	2.52×10^{-3}
FC internal resistance *(r)*	0.126 [Ω]
FC absolute temperature *(T)*	343 [K]
Universal gas constant *(R)*	8314.47 [J/(kmol K)]
Utilization Factor (U_f)	0.8
Water time constant (t_{H2O})	78.3 [sec]
Water valve molar constant (K_{H2O})	2.81×10^{-4}
DC/DC Converter Parameters	
Rated voltage (V)	200V/540V
Resistance (R)	2.3 [Ω]
Capacitance (C)	1.5 [mf]
Inductor (L)	415 [μH]
DC/AC Converter Parameters	
Rated Voltage (V)	540V dc/220V ac
Rated Power (W)	100KW
R_s (Ω)	0.9(mΩ)
L_s (H)	0.01(mH)
f_s (Hz)	50(Hz)

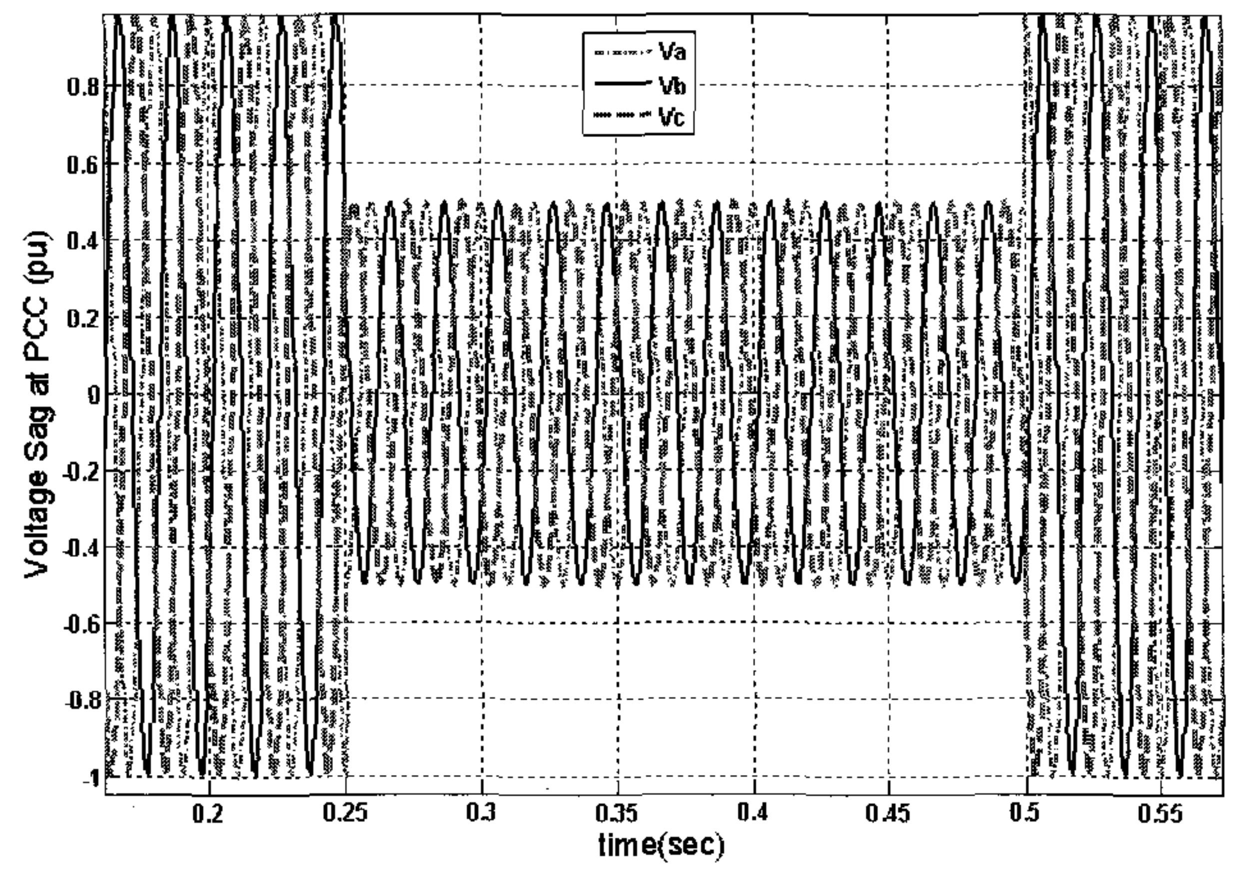

Fig. 8. Three-phase Supply Voltage During a Sag

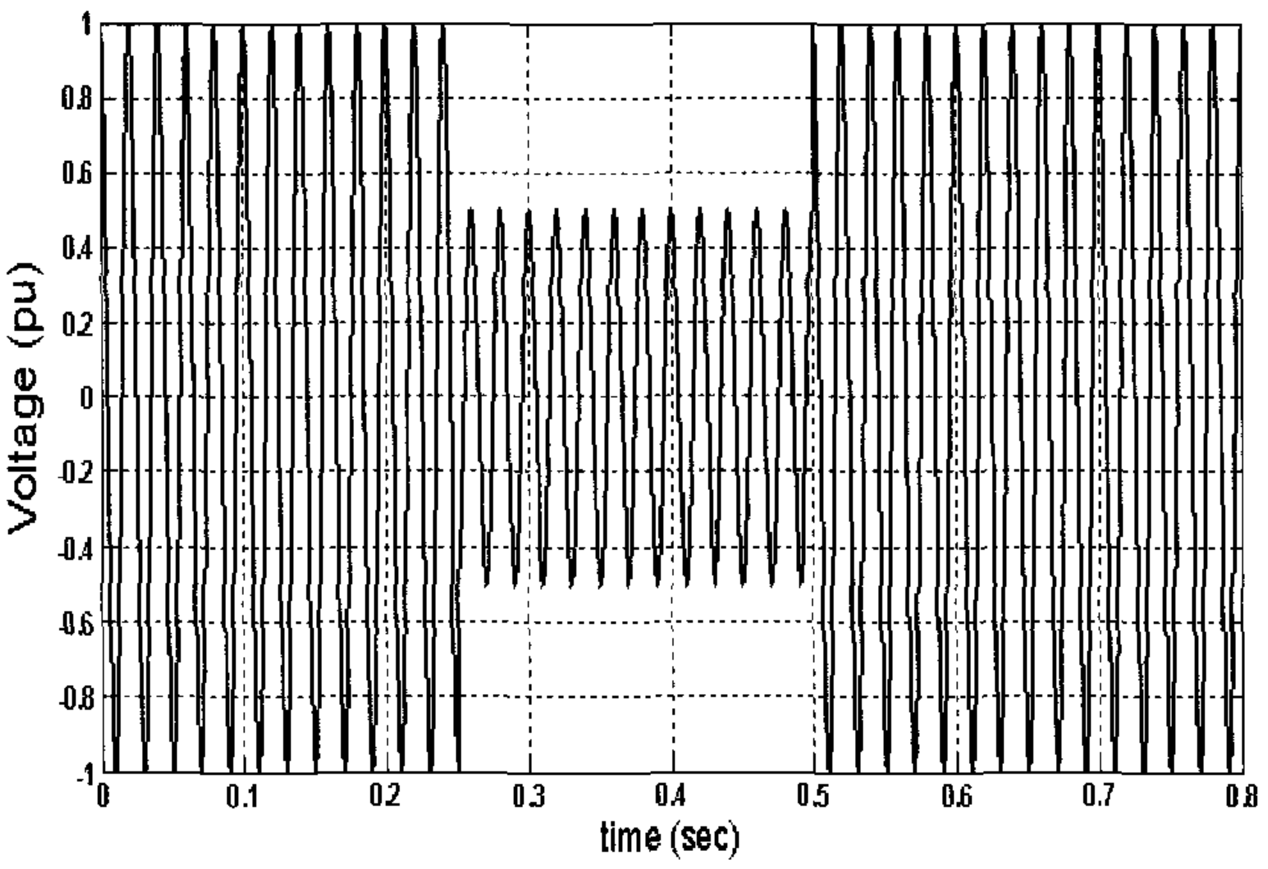

Fig. 9. Predicted Voltage Sag by ADALINE

command value (1pu) from the control circuit. Finally, Fig. 11(b) shows the injected reactive power from the FCDG system to compensate for the voltage. It is clear from Fig. 11(a) and 11(b) that the control of the active and reactive power is independent of each other. Fig. 12 shows the output voltage changes of the fuel cell. As depicted in this same figure, the voltage decreases when the active power increases. The fuel cell voltage has not been affected during the voltage sag.

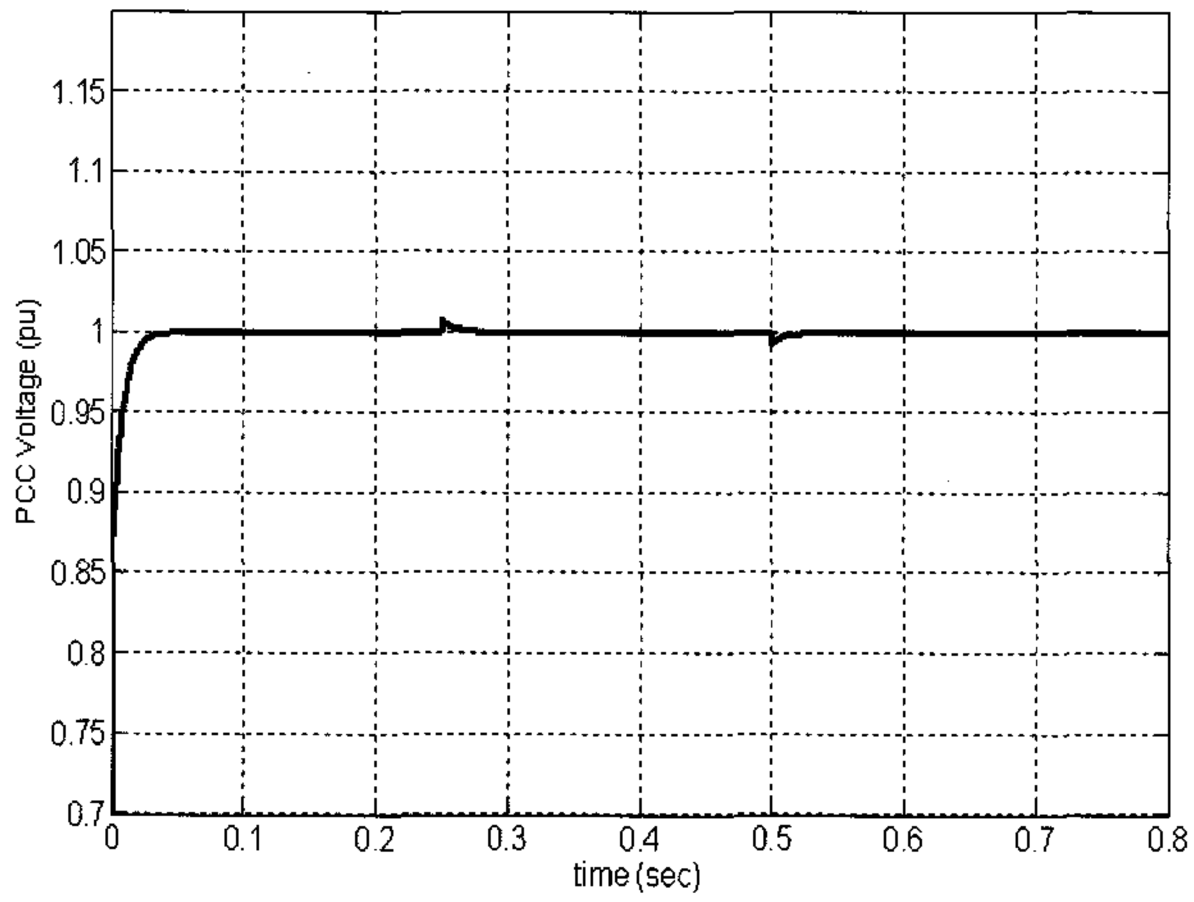

Fig. 10. Regulated Voltage (pu) at PCC

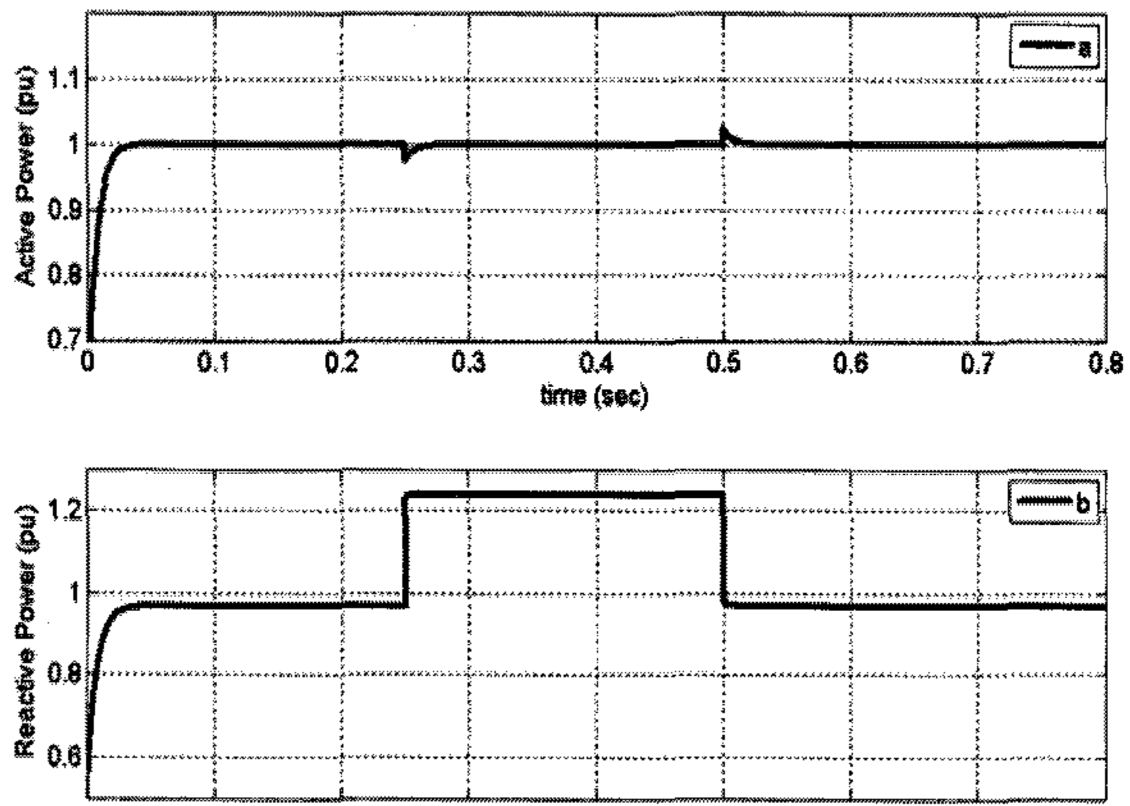

Fig. 11. Produced Active and Reactive Power by FCDG

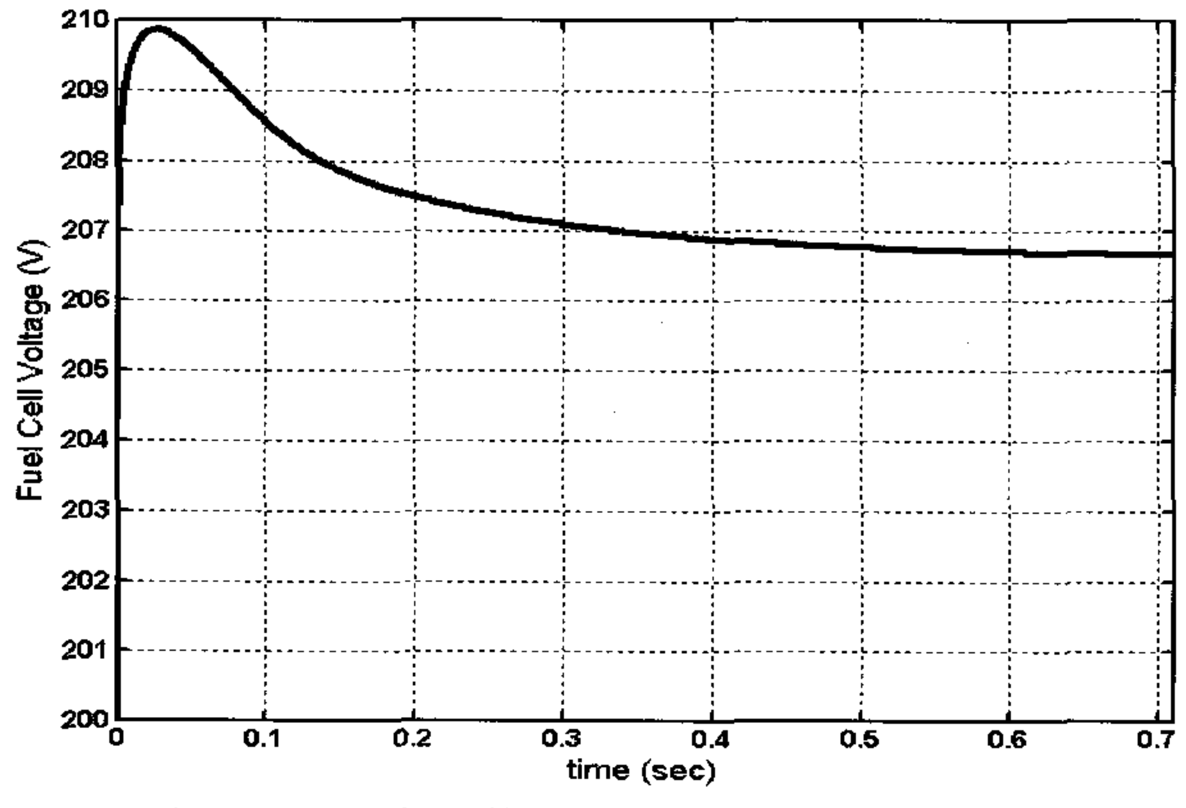

Fig. 12. Fuel Cell Voltage During Voltage Sag

5. Conclusion

This paper presents a new approach for active power control and power quality improvement in a fuel cell distributed generation system. Modeling, control, and simulation study of a SOFC DG system are 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 parameters of the electrical network.

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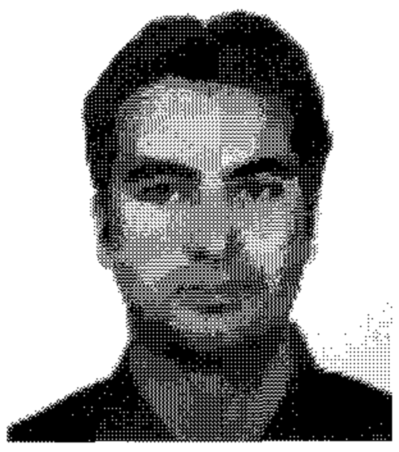

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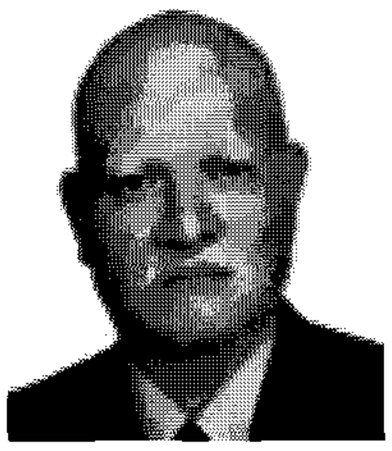

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