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Active Power Control & Voltage Regulation of FCDG Using FLC

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ABSTRACT: Of late, the electrical power utilities are undergoing rapid restructuring process worldwide. Indeed, with deregulation, advancement in technologies and concern about the environmental impact, competition is particularly fostered in the generation side thereby allowing increased interconnection of generating units to the utility networks. The operation of Fuel Cell Distributed Generation (FCDG) systems in distribution systems is introduced by modeling, controller design, and simulation study of a Solid Oxide Fuel Cell (SOFC) distributed generation (DG) system. 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 control for the overall system is presented in order to active 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, Fuzzy Control, Power Quality, Voltage Regulation.

1. INTRODUCTION

Distributed Generation (DG) systems, powered by micro sources such as fuel cells, photovoltaic cells, and micro turbines, 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. 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. 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.

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. The models for the boost dc/dc converter and the three phase inverter together are also addressed. The dynamic model of fuel cell system and fuel flow controller has not been presented. Hence, in this paper the fuzzy control structure has been developed for a FCDG system with active power management and reactive power control capability.

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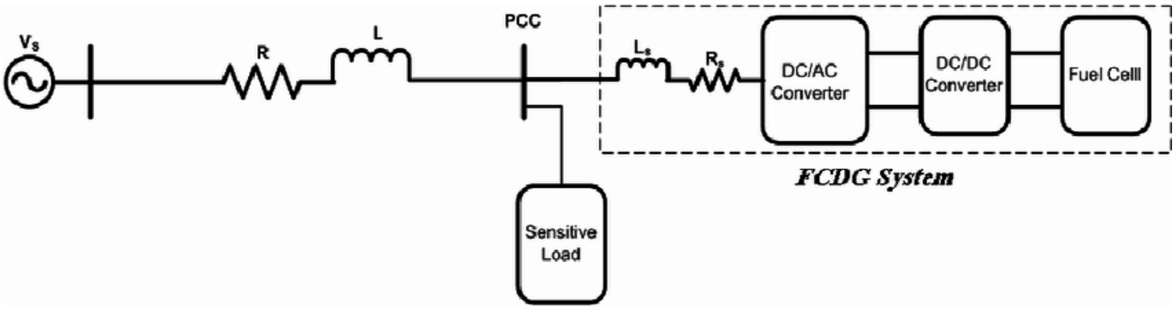

Fig. 1 Fuel Cell Distributed Generation System Structure

converters and a three-phase pulse width modulation (PWM) inverter. 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 and dc/ac inverters 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 that the active power control and voltage regulation in distribution systems by FCDG system.

II. MODELING OF SOLID OXIDE FUEL CELL BASED DISTRIBUTED GENERATION SYSTEM

Fuel cells based DG system is considered an alternative to centralized power plants due to their non-polluting nature, high efficiency, flexible modular structure, safety and reliability. At present, they are under extensive research investigation as the power source of the future, due to their characteristics. A fuel cell converts chemical energy directly to electrical energy through an electrochemical process. As opposed to a conventional storage cell, it can work as long as the fuel is supplied to it. There are many motivations in developing this method of energy generation and it needs further development to have a realistic system analysis combining various subsystems and components.

Among the various types of fuel cells discussed in the literature, PEMFC and SOFC fuel cells are in wide use and have been widely commercialized. A number of research have been undertaken in the modelling, control and performance of PEMFCs, which are best suited to mobile and residential applications. The control of an SOFC in stand-alone and grid connected mode with a DC/DC boost converter followed by a DC/AC inverter using fuzzy logic control were discussed in. The use of a flux-vector controlled inverter to connect the SOFC to the grid was explained in. Two control strategies namely constant utilization control which is accomplished by controlling the input fuel in proportion to the stack current and other using constant voltage control accomplished by incorporating an additional voltage control loop for the SOFC was discussed in while independent control of active and reactive power were elucidated in.

2.1 FUEL CELL MODEL

The basic components of a typical fuel cell include two electrodes, an anode and cathode where the reactions take place. An electrolyte is sandwiched between anode and the cathode which allows the ions to cross over, while blocking the electrons. The electrolyte also allows the ions that are formed to cross-over to the other electrode, which happens because of the tendency of charged particles migrating to regions of lower electrochemical energy. The electrical energy is produced when the electrons traverse the external circuit, flowing from the anode to the cathode. The end products of a fuel cell are heat and electricity, which make them suitable for CHP (Combined Heat and Power) applications. The most commonly used fuel in a fuel cell is hydrogen and the oxidant is usually oxygen and the product of chemical reaction is water which is produced either at the cathode or at the anode, depending on the type of fuel cell used.

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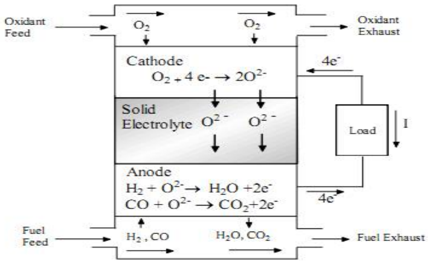

Fig.2.1 Basic Electrochemistry of an SOFC

The chemical reactions that take place inside the SOFC which are directly involved in the production of electricity are as follows.

At anode (fuel electrode):

$$2H_2 + 2O^{2-} \Rightarrow 2H_2O + 4e^- \quad (2.1)$$

$$2CO + 2O^{2-} \Rightarrow 2CO_2 + 4e^- \quad (2.2)$$

At cathode(air electrode):

$$O_2 + 4e^- \Rightarrow 2O_2^- \quad (2.3)$$

$$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O \quad (2.4)$$

2.2 OHMIC VOLTAGE LOSSES

These losses in SOFCs are caused due to the resistance both to flow of electrons through the electrodes and to the migration of ions through the electrolyte. In addition, the fuel cell interconnects or bipolar plates also contribute to the ohmic losses. Ohmic loss is given as

$$V_{ohmic} = rI_{fc} \quad (2.5)$$

Where, r is the internal resistance

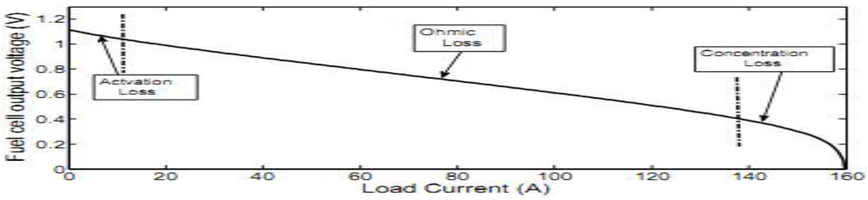

Fig.2.2 V –I characteristic of SOFC of a single cell

2.3 IMPLEMENTATION OF SOFC MODEL IN SIMULINK /MATLAB

A comprehensive dynamic model of a SOFC has been developed and simulated in the MATLAB / Simulink environment as shown in Fig.2.3.

Fuel cells can be operated in two basic modes, viz.

(i) Constant input mode
(ii) Constant utilization mode.

In this model, constant utilization mode is considered. The fuel utilization is defined as the ratio between fuel flow that reacts and the fuel flow injected to the stack and is expressed as:

$$U_f = \frac{q_{H_2}^r}{q_{H_2}^{in}} \quad (2.6)$$

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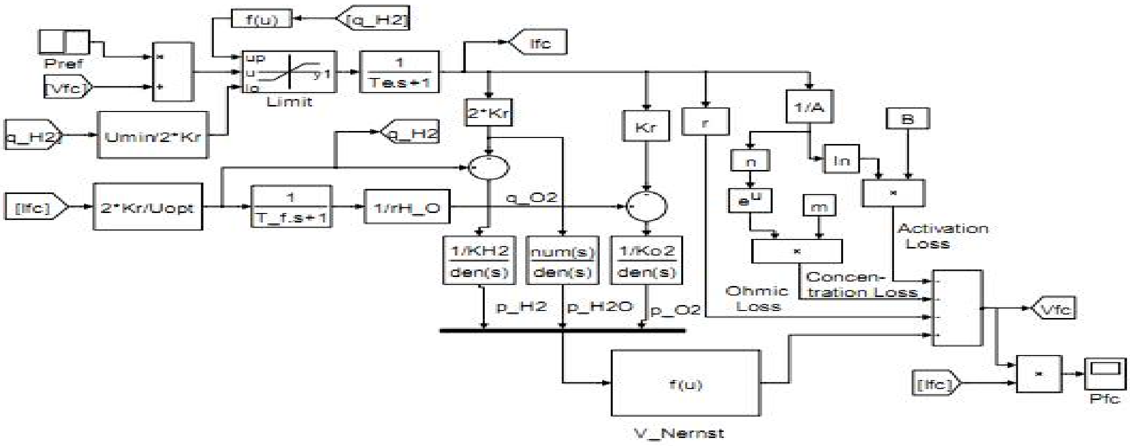

Fig. 2.3 Simulink diagram of a dynamic model of SOFC

It has been shown that the fuel utilization ranging from 0.8 to 0.9 yields better performance and prevents overused and underused fuel conditions. Considering the above specified fuel conditions, U f >0.9 can cause permanent damage to the cell because of fuel starvation and U f < 0.7 leads to higher cell voltage rapidly. For definite hydrogen input flow, the demand current of fuel cell system can be limited in the range given as:

$$\frac{0.8q^{in}_{H_2}}{2K_r} \le I_{fc} \le \frac{0.9q^{in}_{H_2}}{2K_r} \qquad (2.7)$$

$$q^{in}_{H_2} = \frac{2K_r I_{fc}}{0.85} \qquad (2.8)$$

2.4 POWER ELECTRONICS INTERFACE TOPOLOGIES

A variety of topologies have been discussed in the literature in order to utilize the power generated by a fuel cell. The power output of a fuel cell cannot be used directly, and needs to be properly conditioned before interfacing to the load or to the grid.

2.4.1 DESIGN OF DC – DC BOOST CONVERTER

In this work, the boost converter has been considered for providing a regulated dc output voltage at its terminals. DC–DC boost converter is the integral part of fuel cell power conditioning unit. A circuit diagram of boost converter is shown in Fig. 2.4.

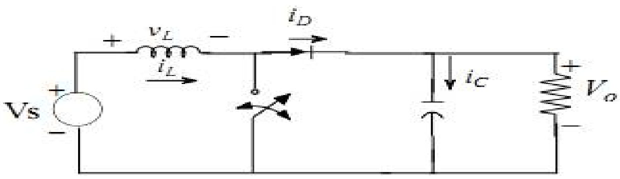

Fig.2.4 Boost converter circuit diagram

- **Analysis when switch is in closed condition**

Fig. 2.5 shows the equivalent circuit of the DC–DC boost converter during switch on time.

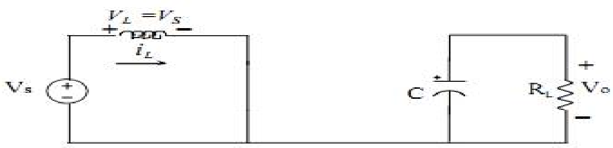

Fig.2.5 Equivalent for DC–DC boost converter during switch ON time

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During the time period DT, when the switch is closed, the inductor voltage can be written as

$$V_L = V_S = L\frac{di_L}{di} \quad \text{or} \quad \frac{di_L}{dt} = \frac{V_S}{L} \tag{2.9}$$

The change in inductor current is given as

$$(\Delta i_L)_{closed} = \frac{V_S DT}{L} \tag{2.10}$$

- **Analysis when switch is in open condition**

When the switch is open for time period (1-D)*T, the equivalent circuit is as shown in Fig.2.6.

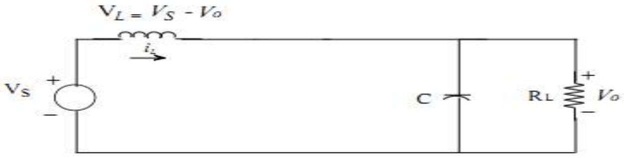

Fig.2.6 Equivalent circuit for DC–DC boost converter during switch off time

Assuming that the output voltage VO is a constant, the voltage across inductor is given as

$$V_L = V_S - V_O = L\frac{di_L}{dt} \quad \text{or} \quad \frac{di_L}{dt} = \frac{V_S - V_O}{L} \tag{2.11}$$

The change in inductor current while switch is open is given as

$$(\Delta i_L)_{open} = \frac{(V_S - V_O)(1-D)T}{L} \tag{2.12}$$

The net change in inductor current must be zero, from equations (2.11) and (2.12)

$$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\Rightarrow V_O = \frac{V_S}{1-D} \tag{2.13}$$

Equation (2.13) gives the expression of the output voltage as a function of the duty cycle. The average current inductor is determined by considering that the power supplied by source must be same as power absorbed by the load.

$$P_O = \frac{V_O^2}{R_L} \tag{2.14}$$

and $V_S I_S = V_S I_L$ (2.15)

Now from (2.13), (2.14) and (2.15), the inductor current is obtained as

$$I_L = \frac{V_S}{(1-D)^2 R_L} \tag{2.16}$$

Where, RL is the load resistance.

Maximum and minimum inductor currents are determined as

$$I_{max} = I_L + \frac{\Delta i_L}{2} = \frac{V_S}{(1-D)^2 R_L} + \frac{V_S DT}{2L} \tag{2.17}$$

$$I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_S}{(1-D)^2 R_L} - \frac{V_S DT}{2L} \tag{2.18}$$

And the minimum value of inductance, obtained from the limiting value of the current to ensure continuity in conduction is given as

$$L_{min} = \frac{D(1-D)^2 R_L}{2f_s} \tag{2.19}$$

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Where fs is switching frequency in hertz.
A ripple in the output will always be present whenever a capacitance is involved in the circuit. The voltage ripple due to the capacitor can be considered as

$$\frac{\Delta V_O}{V_O} = \frac{D}{R_L C f_s} \qquad (2.20)$$

The size of reactive elements of Boost converter can be determined from the rated voltage, voltage ripple and switching frequency of the converter based on the equations from (2.13) to (2.20) with voltage ripple < 0.1% and switching frequency fs =20000 hertz.

Parameters	Values
Voltage ripple	0.1%
Desired DC Output Voltage	776 V
Inductance: *L*	19.188
Capacitance : *C*	419.88
Switching frequency : fs	20KHz

Table 2.1 Boost converter parameters

III. PERFORMANCE ANALYSIS OF SOFC BASED DISTRIBUTED GENERATION SYSTEM FOR ISOLATED OPRATION

SOFC based distributed generation systems can become a dominant DG in future power supply network because of their efficiency, fuel diversity, modularity, and cleanness. They have the potential not only to penetrate into remote and premium power application, but also in combined heat and power (CHP) applications because of their high temperature characteristics. Thus the performance study of this kind of generation system in both isolated and grid connected modes becomes significant in dealing with the issues related to system planning, interconnected /isolated operation, security and management. Different researchers have worked and are still working in the field of SOFC with a view to improve their performance characteristics and their efficiencies. The creation of a simulation model of SOFC–based power plant, for use in power system analysis package was explained in. In this paper a first-order transfer function was used to simulate the electrical dynamic response of SOFC. However, this model did not include the thermal dynamics as well as the effect of concentration and activation losses. The dynamic performance of SOFC was analyzed in using simplified models showing the load-following services of fuel cells to enhance their economic values.

3.1 STEADY STATE CHARACTERISTICS OF SOFC

The V–I and P–I characteristics of SOFC stack model under constant fuel utilization of 85% are shown Fig. 3.1.

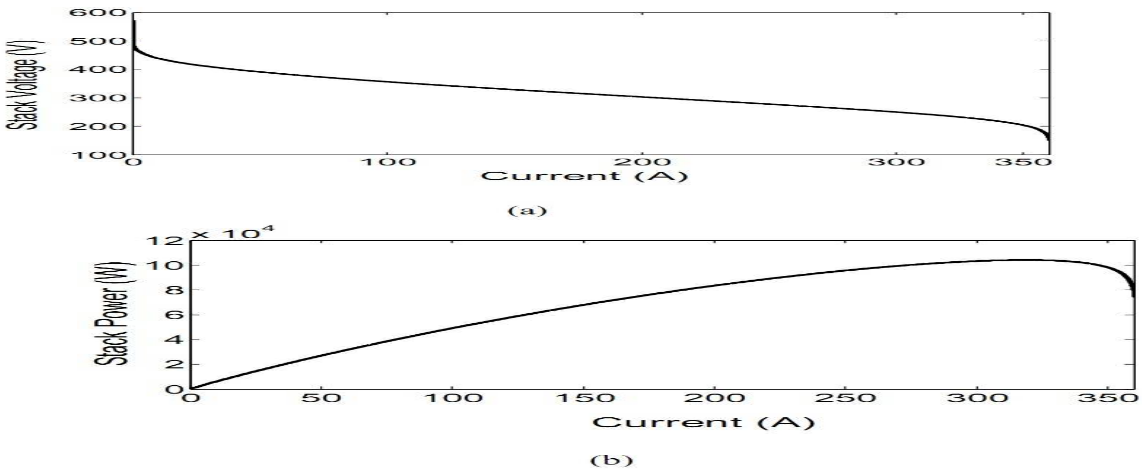

Fig. 3.1 (a) V-I (b) P–I Characteristics of SOFC

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Vol. 5, Issue 7, July 2016

3.2 SOFC CONNECTED TO AN ISOLATED LOAD

In this case study, the SOFC has been interfaced with an isolated three-phase step-changing balanced resistive load. The schematic diagram of the SOFC based DG connected to an isolated load is shown in Fig. 3.6.

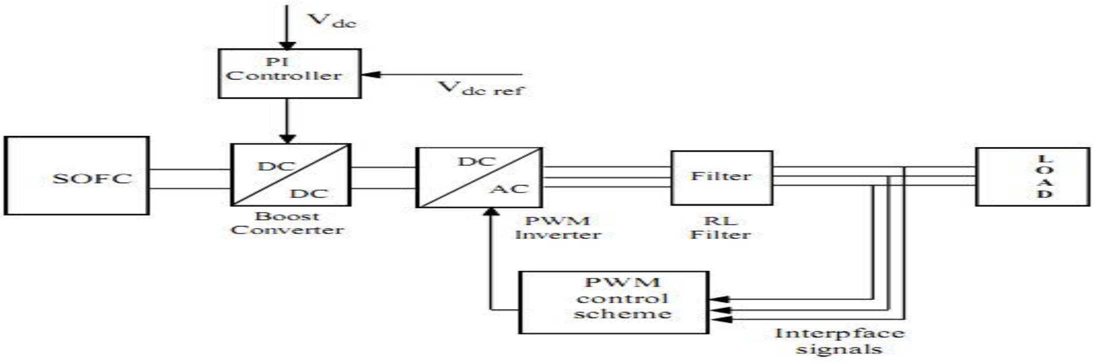

Fig.3.6 SOFC DGs connected to an isolated load

IV. PERFORMANCE STUDY OF SOFC WITH FUZZY LOGIC CONTROLLER FOR ISOLATED OPERATION

During the past several years, fuzzy control has emerged as one of the most active and fruitful area for research in the applications of fuzzy set theory. Fuzzy logic, which is the logic on which fuzzy control is based, is much closer in spirit to human thinking and natural language than the traditional logical systems. It provides an effective means of capturing the approximate, inexact nature of the real world. The literature in fuzzy control has been growing rapidly in recent years, for the wide range of engineering applications that have been made. Fuzzy logic controllers are increasingly employed for a wide range of applications in electric power system and they yield results superior to those obtained by conventional control algorithms. Being highly complex and nonlinear, power systems are very difficult to control with conventional methods and linearization techniques. They, very often fail to produce a model that has the actual characteristics of the system. Artificial intelligence based techniques such as fuzzy logic control can overcome these difficulties.

4.1 FUZZY LOGIC CONTROLLERS FOR SOFC

The output voltage of FC's at the series of stacks is uncontrolled DC voltage, which fluctuates with load variations as well as with the changes in the fuel input. It has to be controlled by a DC/DC converter. The controlled voltage thus obtained is then fed to the DC/AC inverter. The power obtained from the inverter is supplied to the load directly (isolated mode) or to the grid. The voltage at the inverter output needs to be conditioned for interfacing the FC to the isolated load.

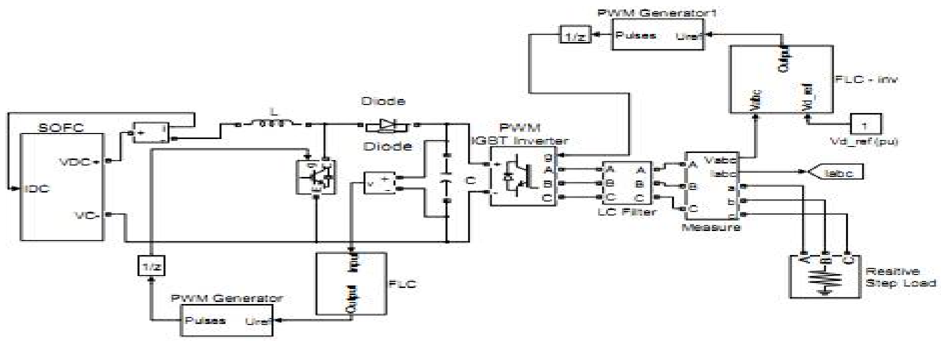

Fig 4.1 Simulink block diagram of SOFC with fuzzy logic controller for isolated operation

The Simulink block diagram of SOFC interfaced to isolated load using DC/DC Boost converter and PWM inverter

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topology with fuzzy logic controller is shown in Fig.4.1.

4.2 FUZZY BASED SIMULINK MODEL FOR BOOST CONVERTER

The fuzzy logic controller used in this work is of two input and single output Mamdani type. The input signal is the error (ΔV) between the voltage across the capacitor (Vdc) and reference voltage. The FLC used for Boost converter is shown in Fig. 4.2.

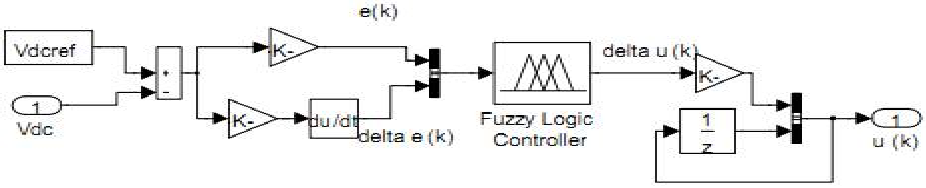

Fig. 4.2 Fuzzy controller for boost converter

The error, change of error and the output of the controller are given as follows:

$$e(k) = K_1(V_{dcref} - V_{dc}) \qquad (4.1)$$

$$\Delta e(k) = K_2(\frac{de(k)}{dt}) \qquad (4.2)$$

$$u(k) = u(k-1) + K_3 \Delta u(k) \qquad (4.3)$$

Where Vdcref is the reference DC Voltage, Vdc is the voltage across the capacitor, and $\Delta\ u(k)$ is the change in dutyratio. The output of the fuzzy controller is the change induty cycle $\Delta u(k)$ it is scaled by linear gain K3. The scaling factor k1, k2 have been tuned to obtained the required response. The value of scaling factor found to be k1 =2; k2 =102; and k3 =0.7

The basic fuzzy partition of membership functions for three variables is shown in Fig. 4.3.

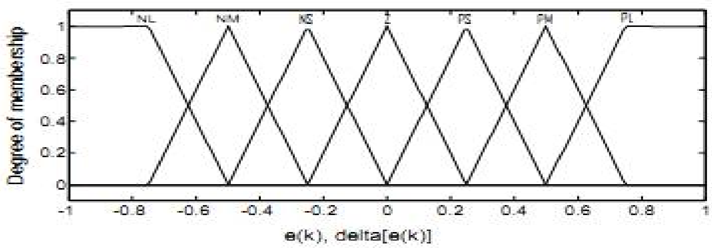

Fig. 4.3 Fuzzy membership function for $e(k)$, $\Delta\ e\ (k)$ and $\Delta u(k)$

The rule base for FLC is shown in Table 4.1.

	Error (e)							
Rate of change of error (Δe)		NL	NM	NS	Z	PS	PM	PL
	NL	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NL	NM	NS	Z	PS
	NS	NL	NL	NM	NS	Z	PS	PM
	Z	NL	NM	NS	Z	PS	PM	PL
	PS	NM	NS	Z	PS	PM	PL	PL
	PM	NS	Z	PS	PM	PL	PL	PL

Table 4.1 Fuzzy rule base for duty ratio control of DC-DC boost converter

Fig.4.4 illustrates the fuzzy rule viewer diagram for providing the change in duty ratio.

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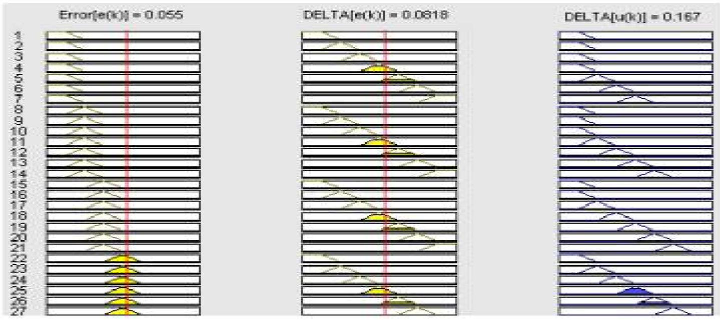

Fig.4.4 Fuzzy rule viewer diagram for fuzzy controller's output, delta [u (k)] Only a portion of rule viewer is shown.
Figure 4.5 shows the surf view of fuzzy controller for providing change in duty ratio.

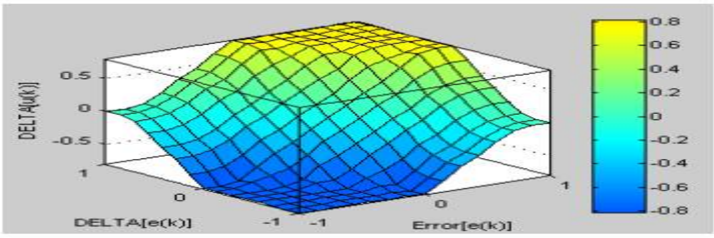

Fig.4.5 Surf view of fuzzy controller providing change in duty ratio

4.3 COMPLETE MATLAB/SIMULINK MODEL OF PROPOSED SYSTEM

The complete MATLAB/SIMULINK Model of Proposed System of a grid connected PV system is shown in figure 4.7.

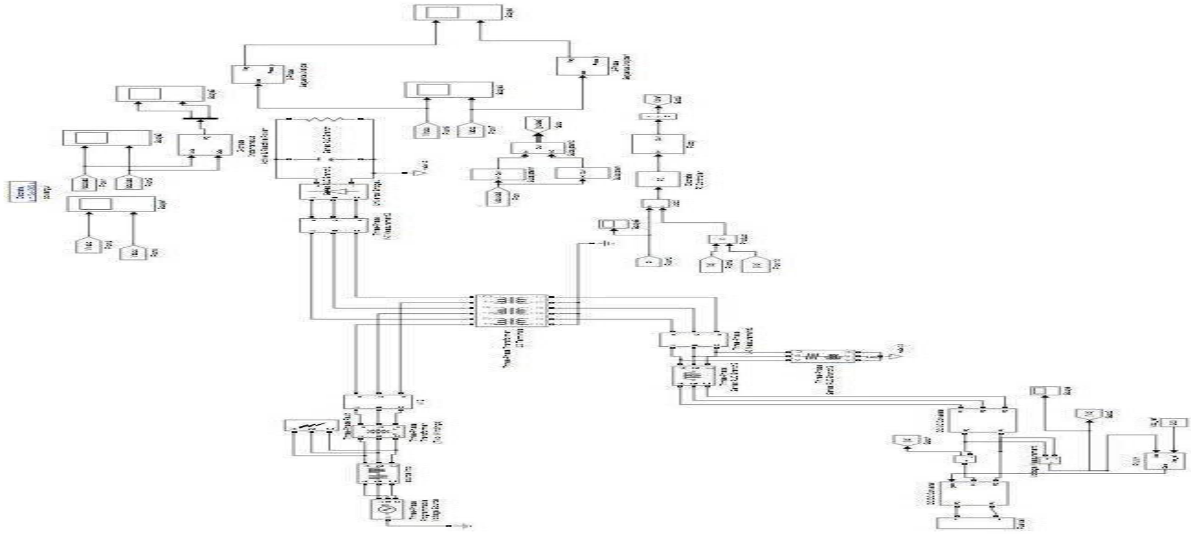

Fig 4.6 Complete MATLAB/SIMULINK Model of Proposed System

V. SIMULATION RESULTS

The fig 5.1(a) represents the rated source voltage wave form and fig 5.1(b) represents the control voltage wave form as shown in below fig 5.1(a&b) respectively.

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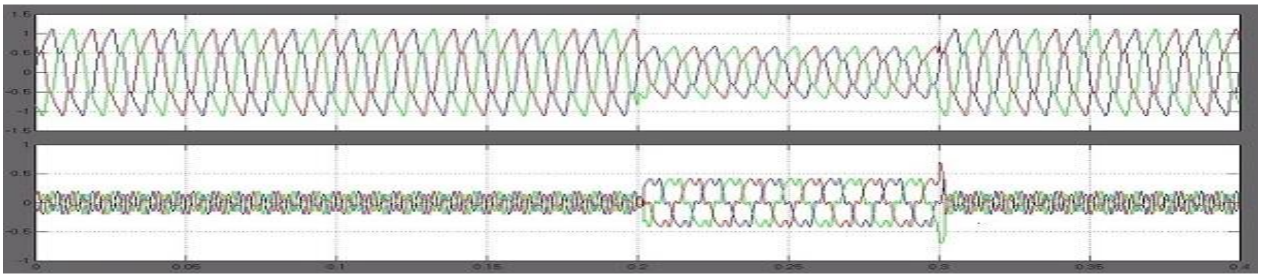

Fig 5.1 a) Rated Source Voltage b) Control Voltage

Below fig 5.2 (a&b) indicates the wave forms for load voltage and load current.

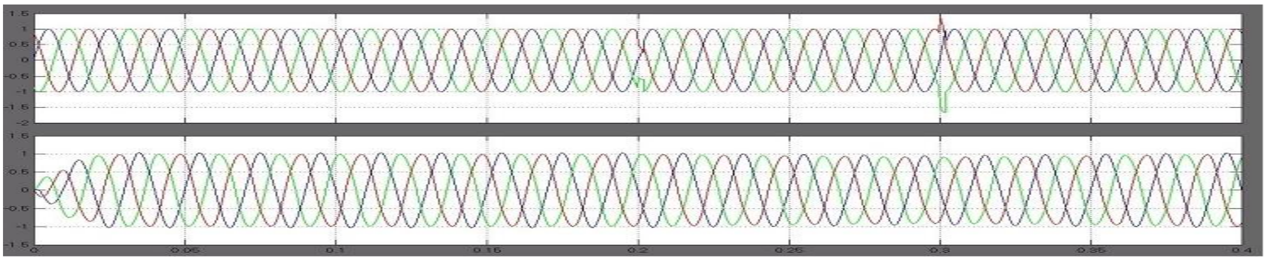

Fig 5.2 a) Load Voltage b) Load Current

Wave form for RMS value of source voltage as shown in fig 5.3(a) and DC/AC output wave form as shown in fig 5.3(b).

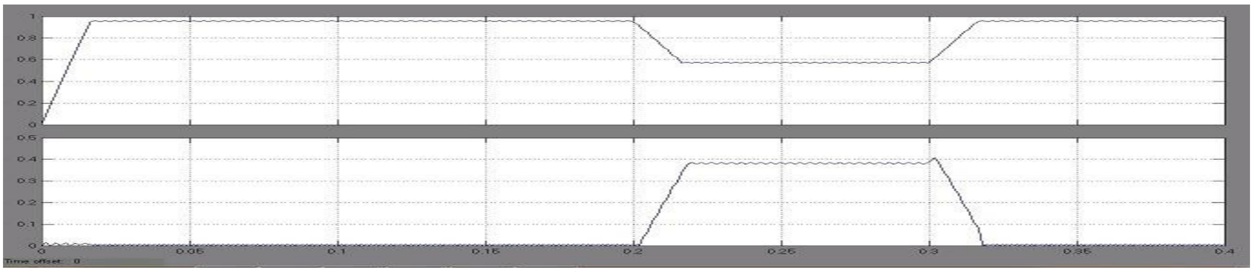

Fig 5.3 a) RMS Value of Source Voltage b) DC/AC Output

The fig 5.4(a) represents the Active power wave form and fig 5.4(b) represents the Reactive power wave form as shown in below fig 5.4(a&b) respectively.

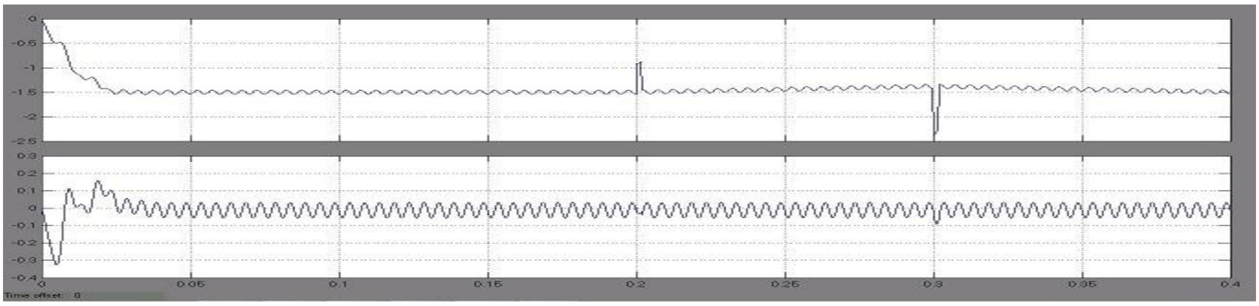

Fig 5.4 a) Active Power b) Reactive Power

DC output voltage wave form as shown in below fig 5.5.

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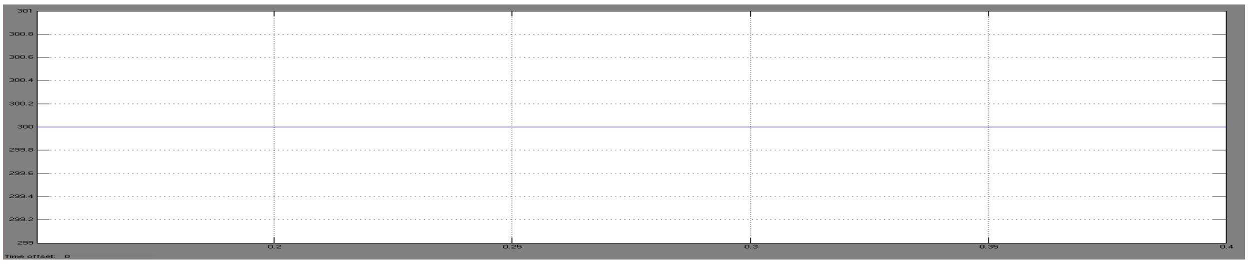

Fig 5.5 DC Output Voltage

Fig 5.6 represents the AC output power wave form as shown in below.

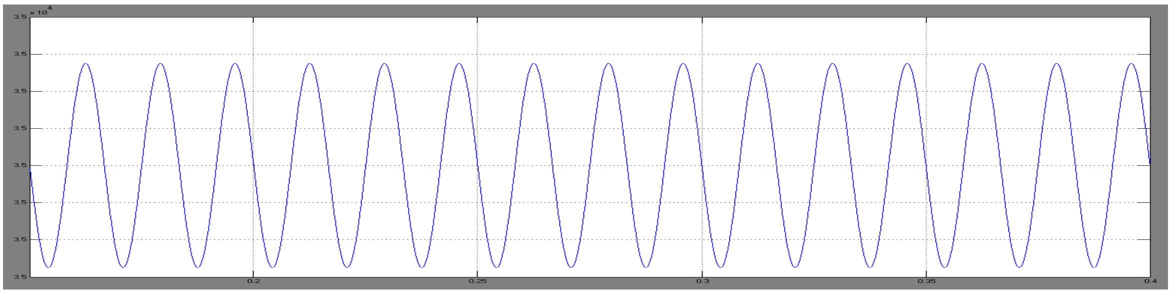

Fig 5.6 AC Output Power

VI. CONCLUSION

Modelling, 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.

VII. FUTURE SCOPE

The developed SOFC based DG system can be considered along with the other DG sources in the micro grid such as wind, photovoltaic to study the operational interaction among the Dg source in utility interactive/islanded operation. The developed dynamic model of SOFC based DG system can be used along with micro turbine based DG system for combined operation to increase the efficiency of the complete system, the heat generated in fuel cell can be utilized for micro turbine operation in this case. New control scheme for power electronic interface of SOFC based DG system using artificial intelligence can be developed for utility interactive operation. The dynamic variation of stack voltage of fuel cell can be included in the sofc model to improve the performance of the developed SOFC model in this work.

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