Control Strategies of a Fuzzy Controlled Solid Oxide Fuel Cell/Battery Distributed Generation System for Power Quality Enhancement

T.Praveen Kumar
Electrical Engineering Department
National Institute of Technology,
Warangal, Andhra Pradesh, India
praveen3564@gmail.com

N. Subrahmanyam
Electrical Engineering Department
National Institute of Technology,
Warangal, Andhra Pradesh, India
s_manyam2001@yahoo.co.in,

M. Sydulu
Electrical Engineering Department
National Institute of Technology,
Warangal, Andhra Pradesh, India,
sydulumaheswarapu@yahoo.co.in

***Abstract*— The proposed work deals with the control strategies of a fuzzy controlled solid oxide fuel cell/battery hybrid distributed generation system. The grid connected hybrid system consists of a solid oxide fuel cell as its primary source of energy and battery as the complimentary source of energy. The battery energy storage compensates the slow transient response of the fuel cell (FC) stack and supports the FC to meet the grid power demand. A Matlab/Simulink model is built for the fuel cell power plant, DC-DC converter & DC-AC converter using fuzzy logic control to regulate the fuel flow to meet the output power demand. The fuel cell/ battery hybrid distributed generation system is studied for voltage sag and voltage swell under unbalanced conditions. Simulation results illustrates the system performance for enhancement of power quality for voltage sag and swell, battery state of charge (SOC), active and reactive power , fuel cell voltage, voltage at point of common coupling and molar flow rate of the fuel cell.**

***Index Terms*— Solid Oxide Fuel cell, Battery, State of charge Distributed Generation, Fuzzy controller, Voltage Sag & Swell.**

I. INTRODUCTION

The probability of rundown of the conventional fuel like coal for the generation of electrical power generation has increased the demand for green and non conventional renewable energy sources such as Fuel cells, Wind, Solar and etc. These energy sources have many benefits[1]like environmental friendliness, reduces transmission and distribution losses, peak load shaving, higher operating efficiencies, improved reliabilities, lower emission levels and can be used as backup sources but the drawback is they are intermittent in nature. Due to the intermittent nature of these renewable energy sources it is worthy of being recommending the distributed generation system to reduce the intermittency of non-conventional energy sources. Distributed Generation[2] systems are defined as installation and operation of small modular power generating technologies that can be combined with energy management and storage systems, powered by micro sources such as fuel cells, photovoltaic cells, and micro turbines. Because of the wide spread technological advancement in power electronic devices it is capable of integrating the distributed generation in grid-connected mode or islanding mode.

From the various distributed generation systems fuel cell is one of the promising device for improving system efficiency. The fuel cell is a device which converts chemical energy into electrical energy i.e. fuel cells produce electricity by the electrochemical reaction of Hydrogen and Oxygen. Fuel cells are of various types such as Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cells (AFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC) etc. Among these fuel cell types Proton Exchange Membrane Fuel Cells and Solid Oxide Fuel Cells have great potential for distributed generation applications.

Fuel cell is an important distributed generation source because of their advantages such as no pollutant gases, high efficiency and modular structure flexibility but limited by long start up-time and poor transient response/ instantaneous power demand[3]. Because of this drawback the fuel cell distributed generation is combined with a battery energy storage which has fast transient response and enhances the dynamics of the system. This paper deals with the design of suitable control strategies for a hybrid fuel cell/battery distributed generation systems to keep the system stable under unbalanced voltage sag and swell conditions. A Matlab/Simulink model is built in the proposed work using fuzzy logic control for power quality enhancement of the hybrid fuel cell/battery distributed generation system

II. SYSTEM MODELING

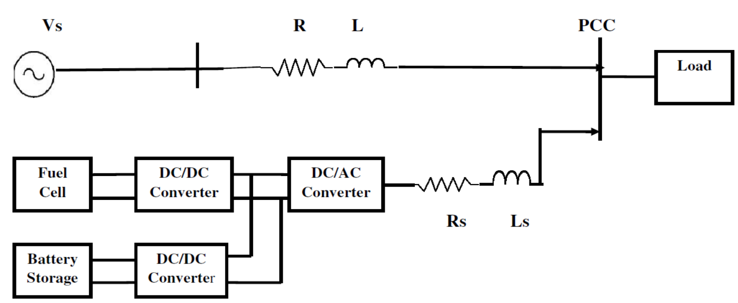


Fig.1. Grid Connected Fuel Cell/Battery DG System

The grid connected hybrid system shown in Fig.1. comprises of a fuel cell, battery, DC/ DC converter and DC/AC converter which are connected to the main grid and load at point of common coupling (PCC). To connect the fuel cell to the external power system it is necessary to boost the voltage. The DC/DC converter role is to boost the voltage, control the fuel cell power and regulate the voltage. The grid connected hybrid system consists of a solid oxide fuel cell[4] as its primary source of energy and battery as the complimentary source of energy. The battery energy storage compensates the slow transient response of the fuel cell The fuel cell/ battery hybrid distributed generation system is studied for voltage sag and voltage swell[5] under unbalanced conditions.

A. Solid Oxide Fuel Cell Model

Fuel cell is a static device which produces electrical energy by the electrochemical reaction of hydrogen and oxygen. Fuel cells are important distributed generation source because of their advantages such as no pollutant gases, high efficiency and modular structure flexibility.

The fuel cell voltage is described by a relationship given below [4]

$$E = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \tag{1}$$

Where E_{Nernst} is the "thermodynamic potential" of Nernst, which represents the reversible (or open-circuit) voltage of the fuel cell.

The performance of the SOFC is affected by many parameters and one important parameter is reactant utilization, U_f [6] and is given by equation (2)

$$U_f = 1 - \frac{q_{H2}^{out}}{q_{H2}^{in}} = \frac{q_{H2}^{r}}{q_{H2}^{in}} = 2K_r I \tag{2}$$

The Nernst's equation[6] and ohm's law determine the average voltage magnitude of the fuel cell stack and is given by equation (3)

$$V_{fc} = N_0\left(E_0 + \frac{RT}{2F}\left(\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right)\right) - rI_{fo}\right) \tag{3}$$

where

N_0 is the number of fuel cells connected in series
E_0 is the reaction free energy voltage
R is the universal gas constant
T is the temperature
I_{f0} is the fuel cell stack current
q represents the molar flow
K_r is the Constant
P_{H2}, P_{H2O}, and P_{O2} are the partial pressures of hydrogen, water and oxygen respectively.

$$P_{H_2} = -\frac{1}{t_{H_2}}\left(P_{H_2} + \frac{1}{K_{H_2}}\left(q_{H_2}^{in} - 2K_r I_{fc}\right)\right) \tag{4}$$

$$P_{H_2O} = -\frac{1}{t_{H_2O}}\left(P_{H_2O} + \frac{2}{K_{H_2O}} K_r I_{fc}\right) \tag{5}$$

$$P_{O_2} = -\frac{1}{t_{O_2}}\left(P_{O_2} + \frac{1}{K_{O_2}}\left(q_{O_2}^{in} - K_r I_{fc}\right)\right) \tag{6}$$

B. Battery Model

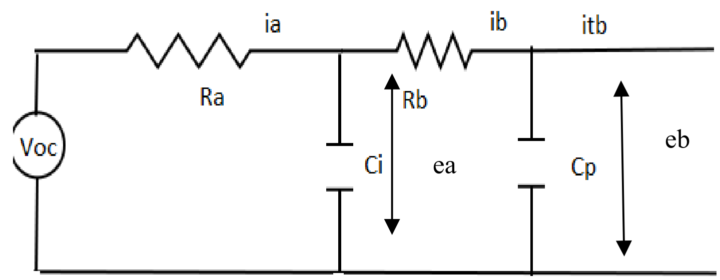


Fig. 2. Battery Model

The battery is a device which stores energy in electrochemical form. Battery is used as energy storage device in wide range of applications like hybrid electric vehicles and hybrid power systems. In this paper, the battery energy storage is combined with fuel cell distributed generation system to enhance the power quality and transient response of the hybrid FC/Battery distributed generation system. The battery model considered in this paper is shown in fig. 2. [7] is essentially a series connected two RC circuits. The battery model consists of a internal resistance R_a and open circuit voltage V_{OC} which are the functions of the state of charge (SOC) of the battery. The capacitances C_i & C_P are the incipient capacitance and polarization capacitance respectively, R_b is the terminal ohmic resistance and are assumed to be constant. The equations of the battery model shown in fig.2 . are

$$V_{OC} = 338.8\times[0.94246 + 0.05754.Soc] \tag{7}$$

$$R_a.C_p.\frac{de_a}{dt} + \left(\frac{R_a + R_b}{R_b}\right).e_a = V_{oc} + \frac{R_a}{R_b}.e_b \tag{8}$$

$$R_b.C_i.\frac{de_b}{dt} + e_b = e_a - R_b.i_{tb} \tag{9}$$

C. DC/DC Boost Converter Model

While connecting a fuel cell to the grid it is necessary to boost the voltage from the fuel cell. The dc/dc boost converter[8] is used for this purpose . Fig.3 shows the DC/DC converter model. This boost converter is described by the following two non-linear state space averaged equations.

$$\rho X_1 = \frac{(1-d)}{L} X_2 + \frac{d}{L}.U \qquad (10)$$

$$\rho X_2 = \frac{-(1-d)}{C}.X_1 - \frac{X_2}{RC} \qquad (11)$$

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.

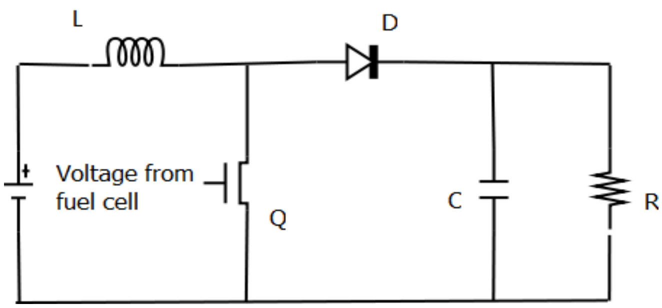


Fig.3. DC/DC Boost Converter

D. DC/AC Inverter Model

The dynamic model of the voltage source inverter (VSI) is used. The DC/AC inverter is shown in fig.4. To eliminate the harmonics filters are used in between grid and the inverter. The dynamic model of the VSC inverter is represented in [9]

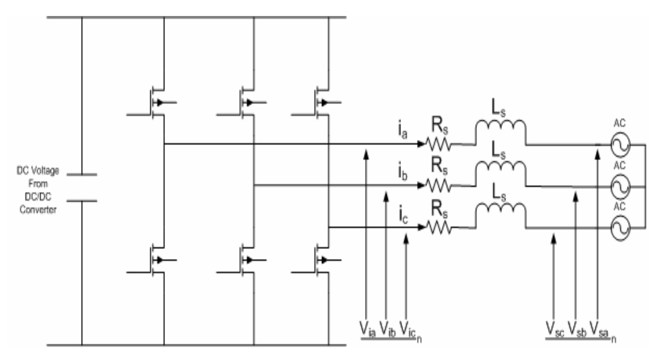


Fig.4. DC/ AC Three Phase Inverter

III CONTROL STRATEGY FOR FC/BATTERY DG SYSTEM DURING VOLTAGE SAG & SWELL

In this part of the paper the control strategy for FC/Battery distributed generation system is discussed during voltage sag and swell under unbalanced conditions.

A. Control Strategy using Intelligent Fuzzy Logic Controller

Fuzzy logic controllers is the alternate to many challenging applications. The fuzzy controllers used in this paper consists of membership function, rule base, fuzzification and defuzzification. The rule base is formed from the expert knowledge and experience in the fuzzy set. The fuzzification process involves conversion of numbers into linguistic variables and then from the fuzzy values and rule base control values are generated. The control values must be converted into numerical values by defuzzification. the centre of gravity method is used for defuzzification.

(i) DC/DC Converter Controller using Fuzzy Logic

The unregulated dc output voltage of the fuel cell is fed to the dc/dc boost converter. The voltage is boosted depending on the duty ratio. The duty ratio is controlled by the logic controller. The input to the fuzzy logic controller is the voltage error (reference-generated) and the change in the voltage error. The fuzzy controller then generates a control signal which is fed to the PWM signal generator. The boost converter generates the output voltage[8]. The membership functions for the duty ratio control of DC/DC converter is shown in fig.5. with seven linguistic variables such as, negative big, negative medium, negative small, zero, positive small, positive medium & positive big.

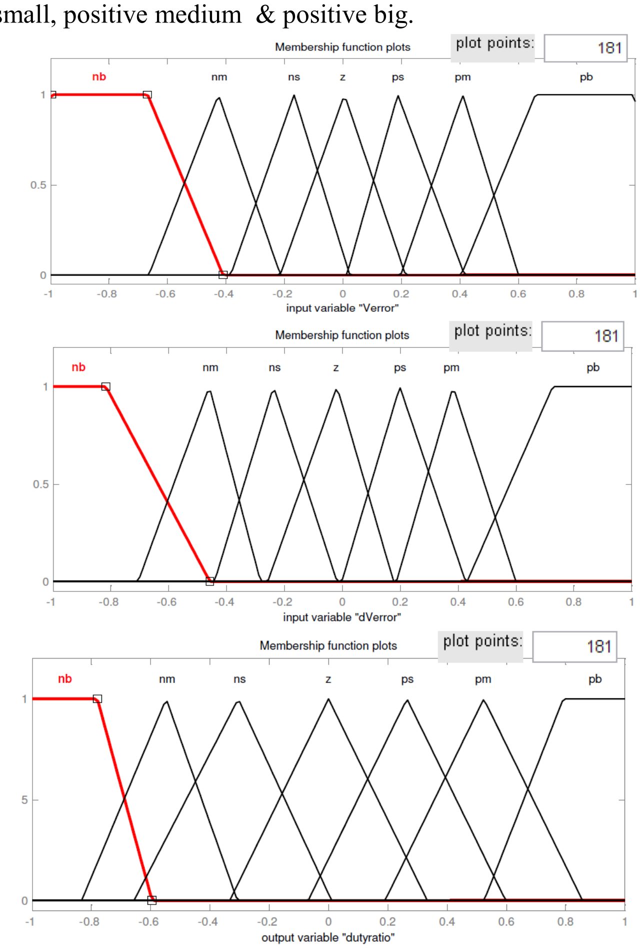


Fig.5. I/O Membership functions for DC/DC Converter

(ii) Fuel Cell Converter Controller using Fuzzy Logic

To overcome the transient conditions in fuel cell, a fuzzy controller is designed for molar flow control. The inputs to the to the fuzzy controllers are fuel cell current error and its derivative and the output is the molar flow control of hydrogen $q_{H2ref.}$ The membership functions for molar flow control of fuel cell is shown in fig.6. with linguistic variables namely, negative, medium, small, zero, positive, & large.

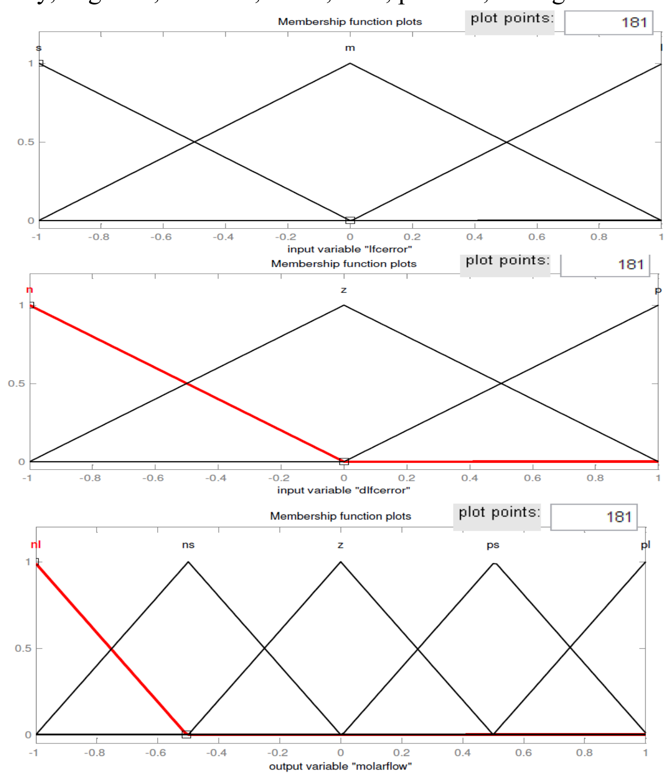
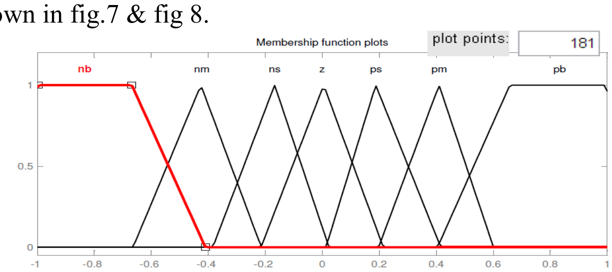


Fig.6. I/O Membership functions for fuel cell controller

(iii) DC/AC Converter Controller using Fuzzy Logic

The DC/AC converter shown in fig.4. has two controller units namely, voltage regulation control and active power control unit[11]. The inputs to the voltage regulation unit are rms voltage and its derivative and the output of the fuzzy controller is the current i_{qref}. Similarly the inputs to the active power control unit is the active power error and its derivative and the current i_{dref} is the output of the fuzzy controller. For both the active power control and voltage regulation unit seven linguistic variables such as negative big, negative medium, negative small, zero, positive small, positive medium & positive big. The I/O membership functions are shown in fig.7 & fig 8.



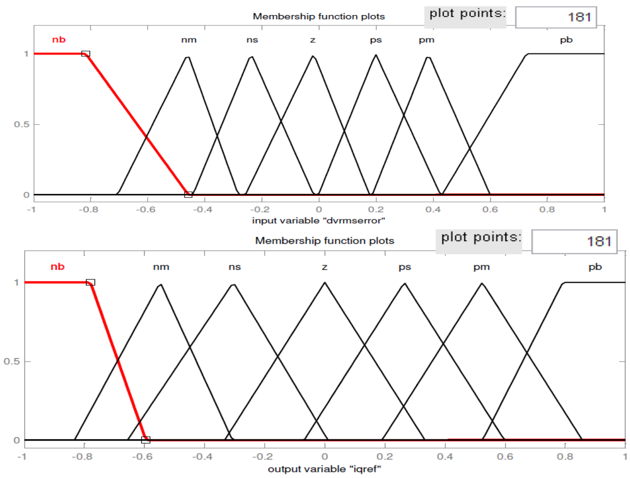


Fig.7. I/O Membership functions for voltage regulation unit

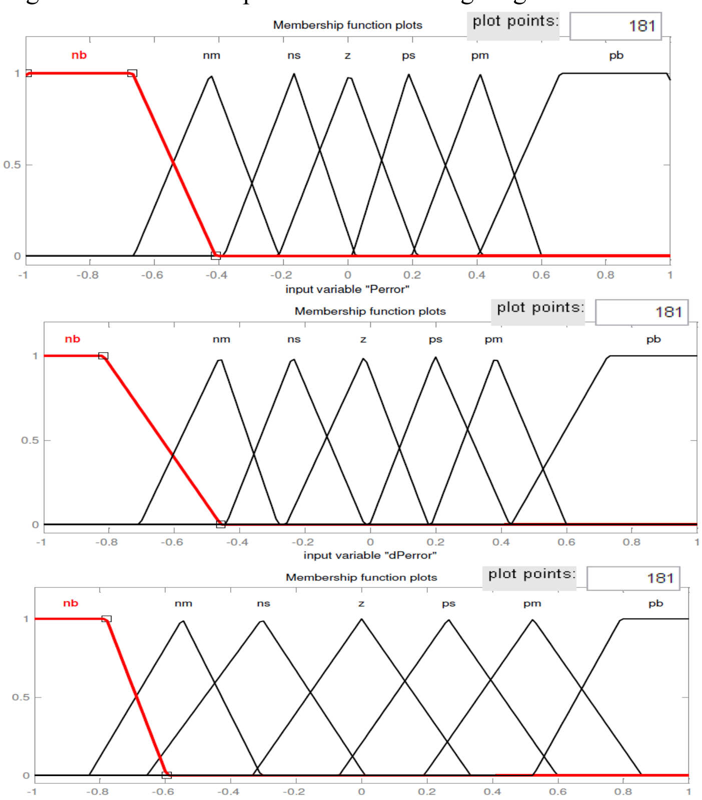


Fig.8. I/O Membership function for active power control

IV SIMULATION RESULTS & DISCUSSIONS OF FC/BATTERY DG SYSTEM

The performance of the proposed structure is simulated by using MATLAB/SIMULINK Software. The parameters of the system under study are given in Table 1. The study case is dedicated to test the dynamic performance of the proposed structure. Voltage sag and swell 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 0.1 second. The disturbance causes a voltage sag in the three phases, as shown in Fig. 9(a). 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 0.1 second, the voltage sag is initiated and the proposed algorithm succeeds to detect the disturbance in less than half of a cycle. At 0.4 second, the voltage swell is initiated and the proposed algorithm succeeds to detect the disturbance in less than half of a cycle Fig. 9(b) 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 0.1s and 0.3s (sag) 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 9(c). Fig. 9(e) 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. 9(f) shows the injected reactive power from the distributed energy sources to compensate for the voltage. It is clear from Fig. 9(e) and 9(f) that the control of the active and reactive power is independent of the other. Fig. 9(g) shows the output voltage changes of fuel cell. As depicted in this Figure, the voltage decreases when the active power increases. The fuel cell voltage has not been affected during the voltage sag. The hydrogen flow rate varies according to the system power requirements as illustrated in Fig. 9(h) The proposed control structure based Fuzzy Logic Control succeeds in regulating the PCC voltage at 1.0 pu and load voltage in 1 .0 pu even when the load disturbance occurs at 0.4s to 0.6s (swell) with fast dynamics and minimum overshoot. This result examines the disturbance rejection capabilities of the proposed Battery. This is done by removing the excess voltage from the distributed energy source and stores it in the battery.

Fig.9.Simulation Results of FC/Battery DG System

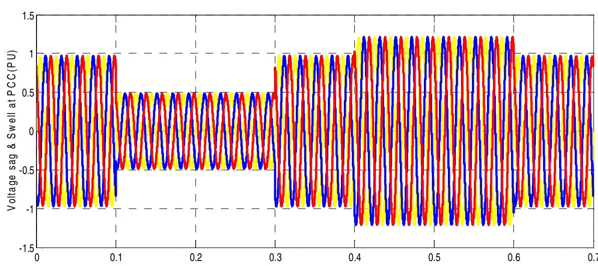


Fig.9(a) Supply voltage during sag & Swell

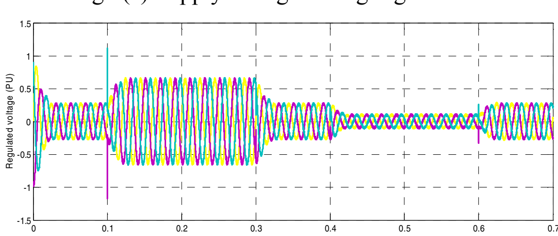


Fig.9(b) Regulated voltage with fuzzy logic controller

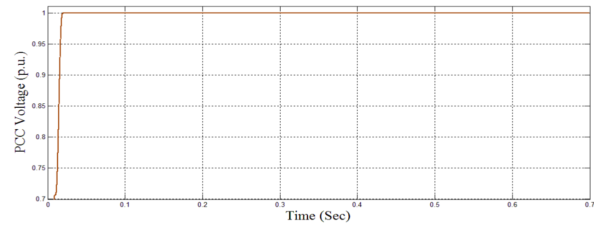


Fig.9(c) Voltage at PCC in Per Unit

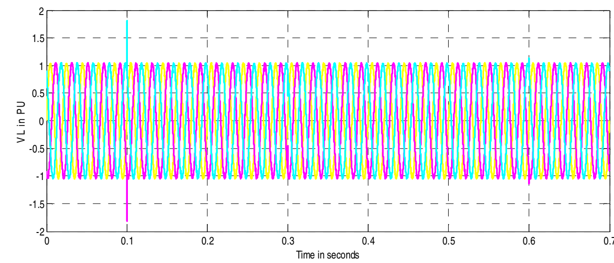


Fig.9(d) Load Voltage in Per Unit

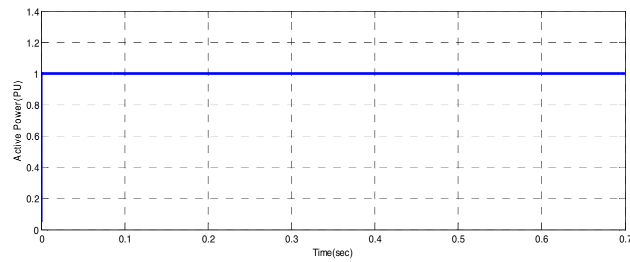


Fig.9(e) Active Power FC/Battery with Fuzzy Logic Controller

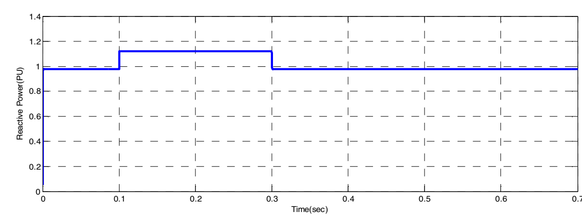


Fig.9(f) Reactive Power FC/Battery with Fuzzy Logic Controller

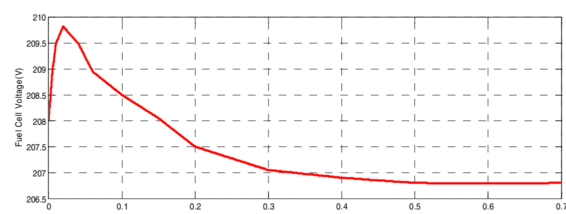


Fig.9(g) Fuel Cell Voltage variation with Fuzzy logic controller

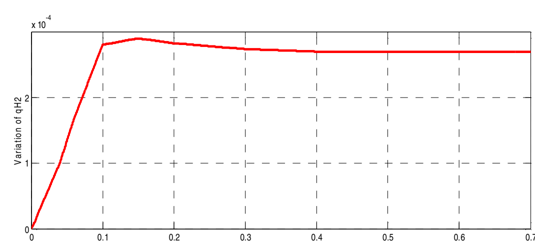


Fig.9(h) Hydrogen Molar flow variation with Fuzzy Logic Controller

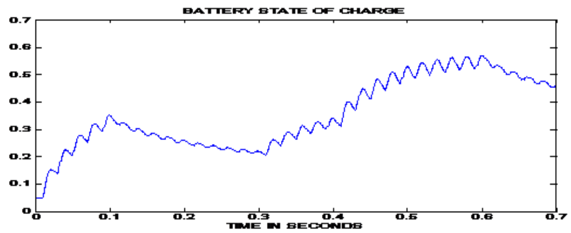


Fig.9(i) Battery State of Charge

Table 1 SOFC distributed generation system parameters.

SOFC Parameters	
Faraday's Constant	96487000 C/kmol
Hydrogen time constant(t_{H2})	26.1 sec
Hydrogen valve molar constant(K_{H2})	8.43×10^{-4}
K_r Constant=N0/4F	9.9497×10^{-7}
No load voltage (E_0)	0.6V
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 ohms
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}
Battery Model parameters	
Capacity Q_m .A.h	50
Number of modules	25
Rated voltage ,V	308
Internal resistance R_a ,Ω	0.015 ±25%
Terminal resistance R_b ,Ω	0.015± 25%
Incipient capacitance C_i ,F	3
Polarization capacitance C_p ,F	3
Minimum soc,%	70
Maximum soc,%	80
DC/AC Converter Parameters	
Rated Voltage	540v dc/ 220v ac
Rated Power	100KW
R_s	0.9 mΩ
L_s	0.01mH
F_s (Hz)	50 Hz
DC/DC Converter Parameters	
Rated Voltage (V)	220/540V
Resistance (R)	2.3Ω
Capacitance (C)	1.5 mf
Inductor (L)	415 µH

V. CONCLUSIONS

The proposed work deals with the control strategies of a fuzzy controlled FC/Battery distributed generation with fuzzy control to mitigate the voltage sag and swell under unbalanced conditions. The simulation results shown and discussed indicates that the proposed fuzzy control is adaptive in nature and mitigates voltage sag & swell, controls fuel cell voltage, active power, regulates the voltage at Point of Common Coupling and enhances the power quality of the hybrid solid oxide fuel cell/battery distributed generation system.

REFERENCES

[1] Edward J. Coster, Johanna M. A. Myrzik, Bas Kruimer, Wil L. Kling, " Integration issues of distributed generation in distribution grids" proceedinds of IEEE, January 2011

[2] Honghai Kang, Shengqing Li, Zhengqiu Wu, "Discussion on advantages and disadvantages of distributed generation connected to the grid" ICECE 2011

[3] Caisheng Wang & M.H. Nehrir "Distributed generation Applications of Fuel Cells"Power Systems Conference 2006

[4] Jaroslaw Milewski, Konrad Swirski, "Advanced methods of solid oxide fuel cell modeling" Springer 2011

[5] Bollen M. H. J., Understanding Power Quality Problems: Voltage Sags and Interruptions. New York IEEE Press, 2000

[6] J. Padulle´s, G.W. Ault, J.R. McDonald, " An integrated SOFC plant dynamic model for power systems simulation", Jounal of Power Sources.

[7] Kwi-Seong Jeong, Won-Yong Lee, Chang-Soo Kim, "Energy management strategies of a fuel cell/battery hybrid system using fuzzy logics", Journal of power sources, June 2005

[8] Golkar M. A. and Hajizadeh A., “Intelligent power management strategy of hybriddistributed generation system,”.Journal of Electrical Power and Energy Systems, June 2007

[9] Golkar M. A. and Hajizadeh A., “Fuzzy-Based Mitigation of Voltage Sag and Active Power Control in Distribution System Using Fuel Cell Distributed Generation,” International Power System Conference (PSC2006), 13-15 Nov. 2006, Tehran-Iran.

[10] Amin Ghazanfari, Mohsen Hamzeh, Hossein Mokhtari, *a*nd Houshang Karimi, "Active Power Management of Multihybrid Fuel Cell/Supercapacitor Power Conversion System in a Medium Voltage Microgrid" IEEE Transactions on Smart Grid, December 2010

[11] JIANG Z., GAO L., DOUGAL R.A.: ‘Flexible multiobjective control of power converter in active hybrid fuel cell/ battery power sources’, IEEE Trans. Power Electron., 2005,

[12] El-Samadhi I. and El-Satiny E., “The Effect of DG on Power Quality in a Deregulated Environment,” in Proc. IEEE PES General Meeting, Jun. 2005.

[13] Tanrioven M, Alam MS. "Modeling, control and power quality evaluation of a PEM fuel cell based power supply system for residential use". In: Proceedings of the 39th IAS annual meeting, vol. 4; 2004. p. 2808–14.

[14] Bathaee SMT, Emami SR, Hajizadeh A. "Dynamic modeling and intelligent control of hybrid electric vehicles". In: The nineth world multi-conference on systemics. Orlando, FL, USA: Cybernetics and Informatics; July 10–13, 2005

[15] El-Shater TF, Eskander M, El-Hagry M. Hybrid pv/fuel cell system design and simulation. In: 36th Intersociety energy conversion engineering conference, Savannah, GA; July 29–August 2, 2001