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Control of Fuel Cell Based Distribution Generation System

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Abstract: In the distribution generation system the use of power electronics technology together with renewable energy sources plays an important role for satisfying the increasing demand of electric power all over the world. Among the various distribution generation technologies, fuel cell based distribution system appears to be a promising technology. In this paper, a Solid Oxide Fuel Cell for distribution generation application is introduced. The mathematical modeling of the fuel cell is studied and simulation study of the interfacing power electronics converters is done in this paper. The physical model of fuel cell stack and power conditioning units are described in this paper. The control design methodology for each component of the proposed system is also described. 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 the real and reactive power compensation capability of the distribution system.

Keywords: Distribution Generation, Fuel cell, Power electronics converters, Power conditioning units.

I. INTRODUCTION

Today, new advances in power generation technologies and new environmental regulations encourage a significant increase in the use of distributed generation resources around the world [1, 2]. Distributed generation systems (DGS) have mainly been used as a standby power source for improving the power quality issues. For example, diesel generators are used as an emergency power source in the case of power failure and also for improving voltage disturbances. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust. On the other hand, environmental-friendly distributed generation systems such as fuel cells, micro turbines, biomass, wind turbines, hydro turbines or photovoltaic arrays can be a solution to meet both the increasing demand of electric power and environmental regulations due to green house gas emission.

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. DG units such as fuel cell, photo voltaic, micro turbine, and storage devices are always linked via a nonlinear interface. Usually, this interface consists of a current controlled Voltage Source Inverter (VSI). With the new age 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)

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systems can be strategically placed at any site in a power system (normally at the distribution level) for grid reinforcement, thereby 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 modeling 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. But, 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. 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.

II. FUEL CELL DISTRIBUTED GENERATION SYSTEM

The dynamic modeling of a Fuel Cell Distributed Generation (FCDG) system is an important problem that needs a careful study. To study the performance characteristics of FCDG systems, accurate models of fuel cells are needed. Moreover, models for interfacing the power electronic circuits in a FCDG system are also needed for designing controllers, which are required 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 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 explained in detail in the following section.

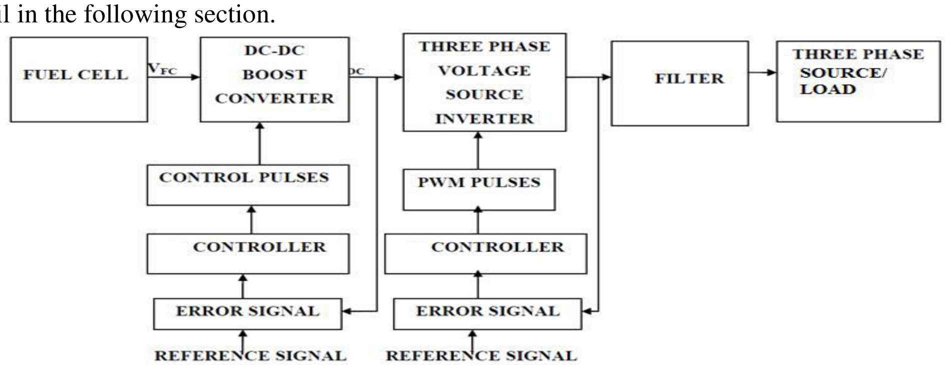

Fig. 1: Block diagram of the FCDG system

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III. FUEL CELL MODEL

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy. They can be considered 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, U_f, 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_{H_2} 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:

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

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_{H_2}, P_{H_2O} and P_{O_2} are the partial pressure of the flow of hydrogen, oxygen and water, and are determined by the following differential equations:

$$P_{H_2}^{*} = -\frac{1}{t_{H_2}}\left(P_{H_2} + \frac{1}{K_{H_2}}(q_{H_2}^{in} - 2K_r I_{fc})\right) \tag{3}$$

$$P_{H_2O}^{*} = -\frac{1}{t_{H_2O}}\left(P_{H_2O} + \frac{2}{K_{H_2O}}K_r I_{fc}\right) \tag{4}$$

$$P_{O_2}^{*} = -\frac{1}{t_{O_2}}\left(P_{O_2} + \frac{1}{K_{O_2}}(q_{O_2}^{in} - K_r I_{fc})\right) \tag{5}$$

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

$$q_{H_2}^{r} = -\frac{N_0 I}{2F} = 2K_r I \tag{6}$$

IV. 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.

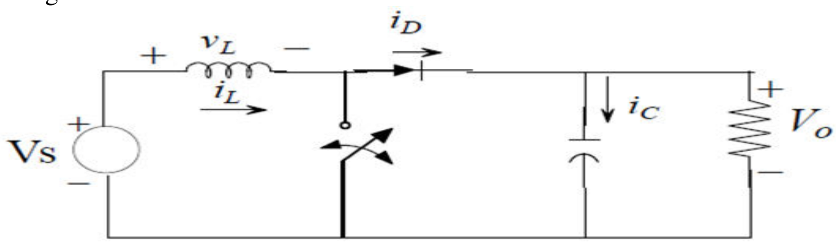

Fig. 2: DC – DC Converter Model

This boost converter is described by the following two non-linear state space averaged equations [14]:

$$\rho X_1 = \frac{(1-d)}{L} X_2 + \frac{d}{L} U \tag{7}$$

$$\rho X_2 = \frac{-(1-d)}{C} X_1 - \frac{X_2}{RC} \tag{8}$$

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.

V. 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 Ls and Rs 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 Ia, Ib, Ic 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].

$$\frac{di_k}{dt} = \frac{-R_S}{L_S} i_k + \frac{1}{L_S}\left(V_{ik} - V_{sk}\right) \tag{9}$$

Where k= {a, b, c}.
To develop the dynamic model, the state equations (9) are transformed to the system synchronous reference frame as:

$$\frac{di_q}{dt} = \frac{-R_S \omega_S}{L_S} i_q - \omega_S i_d + \frac{\omega_S}{L_S} m \sin(\delta + \theta_S) V_{dc} - \frac{\omega_S}{L_S} \sin(\theta_S) V_S \tag{10}$$

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$$\frac{di_d}{dt} = \frac{-R_S\omega_S}{L_S} i_d - \omega_S i_q + \frac{\omega_S}{L_S} m\cos(\delta+\theta_S)V_{dc} - \frac{\omega_S}{L_S}\cos(\theta_S)V_S \quad (11)$$

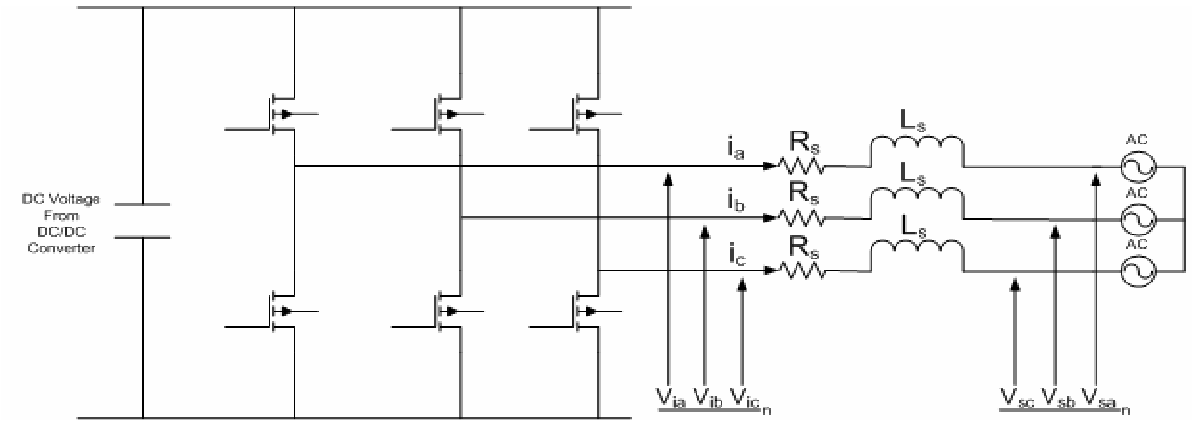

Fig 3: Three-phase dc/ac voltage source inverter

VI. DC – DC CONVERTER CONTROLLER

The DC - DC converter is an integral part of fuel cell power conditioning unit and hence PI controller based boost converter has been used in SOFC based DG to maintain a constant voltage. 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 PI controller. The duty ratio is set at a particular value for the converter to provide desired average value of voltage at the output, for any fluctuation in the FC voltage due to variation in the output load. 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 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 error signal is fed as inputs to the PI Controller. The PI controller generates control signal based upon the inputs. 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 PI control scheme for boost converter is shown in Fig. 4.

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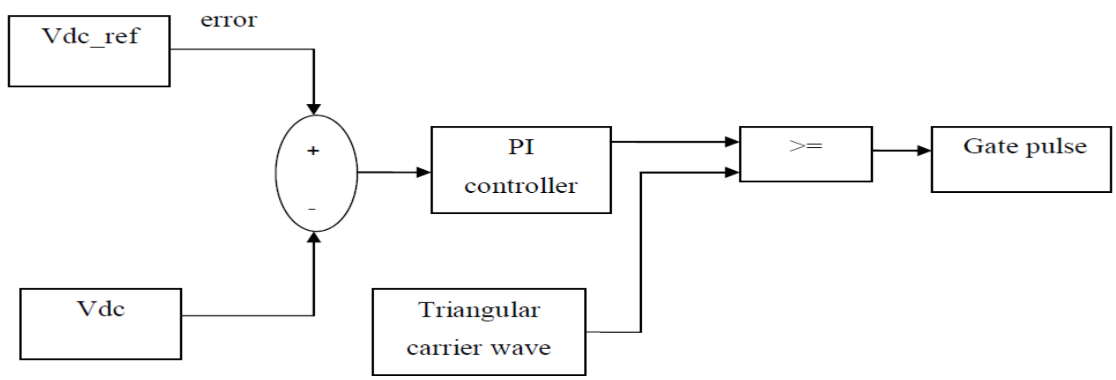

Fig. 4: PI control scheme for DC – DC Boost Converter

VII. 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. These disturbances cause problems, such as overheating, motor failures, in accurate metering, and disoperation 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. In order to connect the fuel cell to the main grid, the injection of output current of inverter has to be regulated.

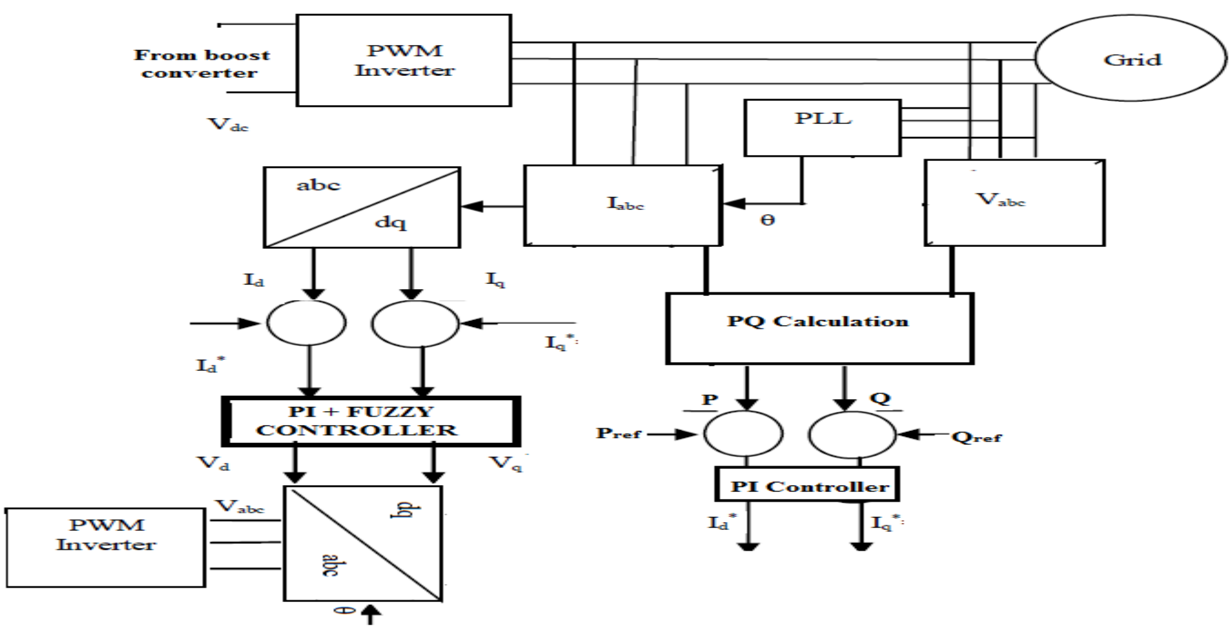

Fig. 5: Control scheme for DC – AC Converter

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The main part of the three phase ac voltage controller for grid connected application is the current injection unit. A PI controller and a fuzzy logic controller is used to inject the current of the three phase ac voltage controller to the grid thereby enabling the control of both active and reactive power injection to the grid. The output current of the ac voltage converter is converted to dq reference frame and compared with reference current to generate the error signal which is fed as an input to the PI / Fuzzy controller. The PI controller generates control signal based upon the inputs. The control signal is converted back to abc frame and fed to the PWM generator. The PWM generator based upon the control signal adjusts the pulses of the switches of the ac voltage converter. The ac voltage converter injects the output current based upon the duty ratio provided by the PWM generator. The general schematic of a PI controller plus fuzzy logic controller for grid connected application is shown in Fig. 5.

VIII. SIMULATION RESULTS

The topology used in this study for the fuel cell system, power condition unit, and load is shown in Fig. 6. 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 1. The simulation result obtained is the variation of output voltage of fuel cell with respect to time. The maximum power obtained from the fuel cell model is 200V which can be increased or decreased by connecting or disconnecting the number of cells in series. The simulation result of the output voltage of fuel cell is shown in Fig. 7. For fuel cell based generation system, boost chopper circuit is always used as the DC-DC converter. Since the output voltage of fuel cell is low, the use of boost circuit will enable low-voltage fuel cell to be used in distribution generation system. As a result, the total cost will be reduced. The Fig.8 and Fig.9 shows the simulation result of the fuel cell fed boost converter and output voltage, current, real and reactive power output of the proposed system. The parameters used to model a boost converter are shown in Table 1.

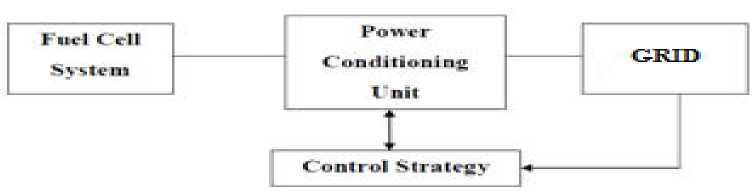

Fig. 6: Block diagram of power conditioning system

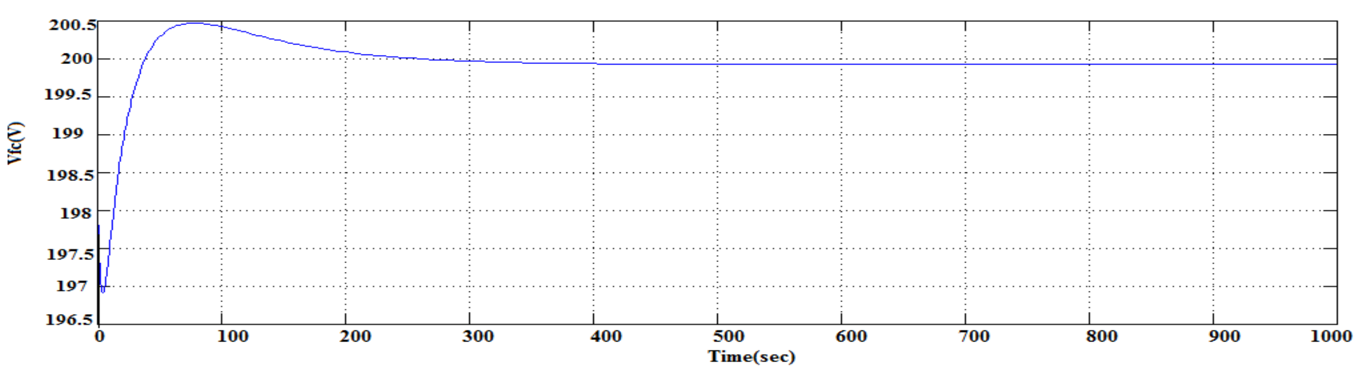

Fig. 7: Output voltage of fuel cell module

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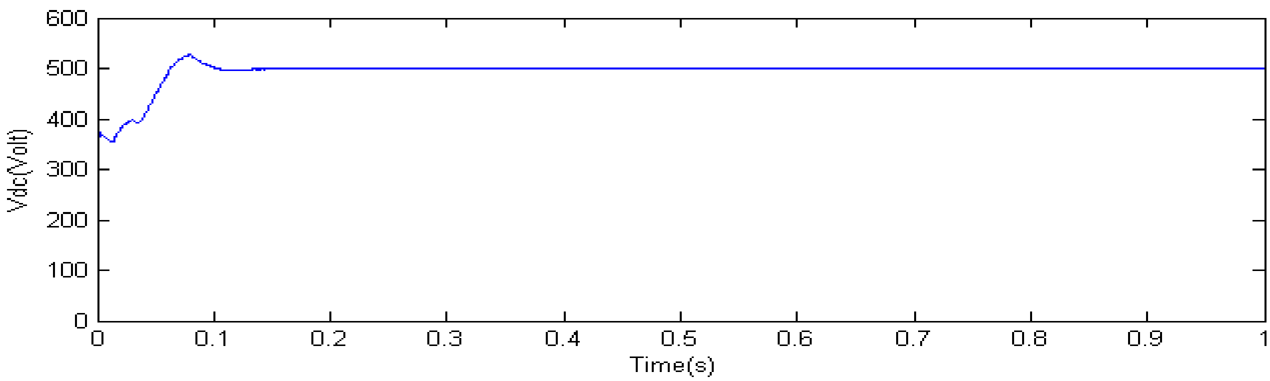

Fig. 8: Output voltage of fuel cell fed boost converter

TABLE 1
Experimental system parameters

FUEL CELL PARAMETRERS	
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 = No/4F	$9.9497*10^{-7}$
No load voltage (Eo)	0.6[V]
Number of cells (No)	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]
Universal gas constant (R)	8314.47[J(KmolK)]
FC absolute temperature (T)	343[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/500V
Resistance (R)	2.3[Ω]
Capacitance(C)	1.5[mf]
Inductance (L)	415[μH]
DC/AC CONVERTER PARAMETERS	
Rated voltage (V)	500V dc/220V ac
Rated power (W)	50KW
Ls (H)	0.053[H]
Fs (Hz)	50[Hz]

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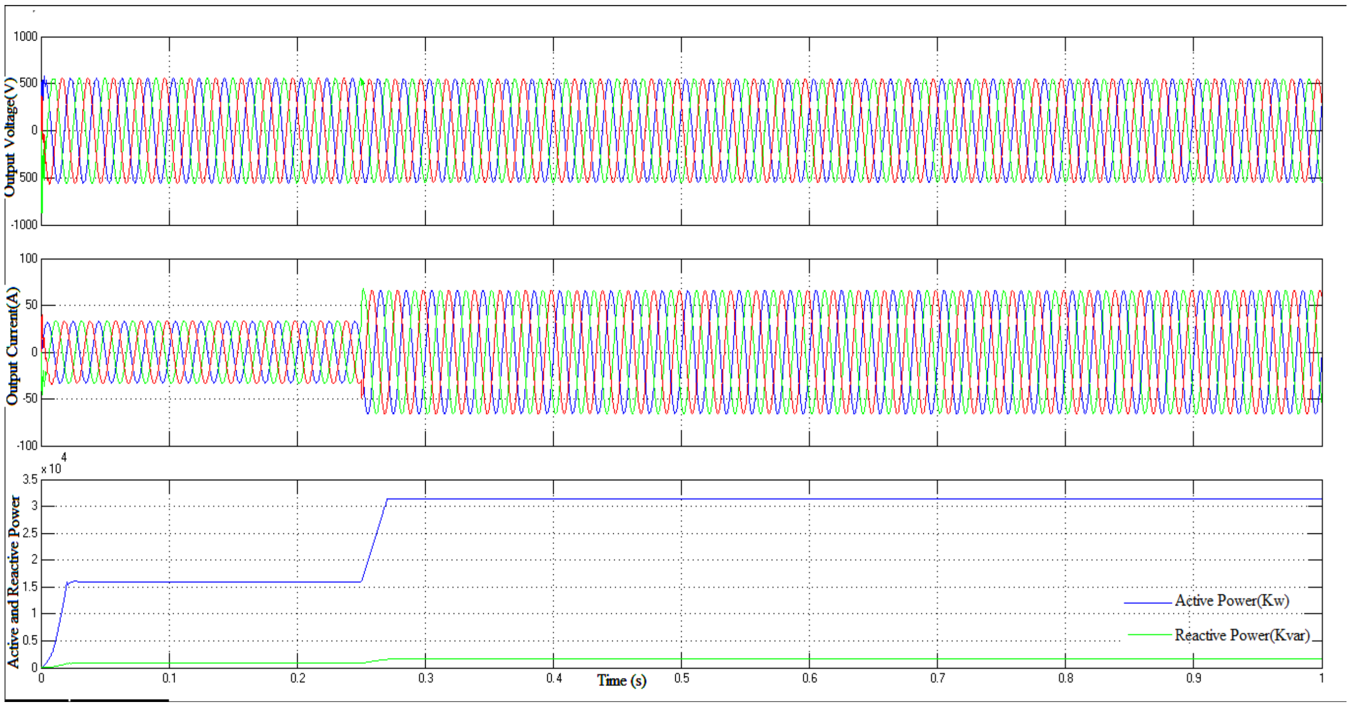

Fig. 9: Simulation results of grid connected inverter

IX. CONCLUSION

Modeling, control and simulation study of a fuel cell based distribution generation system is proposed in this project. In this project, a PI/fuzzy control strategy is proposed for the fuel cell based distributed generation system to evaluate the performance of this system during power quality disturbances, which occurs in the distribution system. Also based on the dynamic modeling of power electronic converters, fuel cell etc; the PI/fuzzy controller is investigated to guarantee the safe operation of each component. The proposed control strategy for this kind of distribution system helps in delivering the maximum power of fuel cell power source and makes the proper operation of each power source under power quality disturbances. Also the proposed control strategy is insensitive to the parameter variation in the distribution system network. The effectiveness of the proposed system can be verified by using the MATLAB/SIMULINK environment.

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