Implementation of fuel cell distributed generation system with conventional and fuzzy based PI controllers

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ABSTRACT

This paper presented modeling of fuel cell (FC) and shows the operation strategies of grid connected FC. In this system, proposed controllers based on fuzzy. However performance of proposed system is compared with PI controllers. It compares the results of the system and highlights the benefits of using fuzzy based PI controllers in the system. An inverter is required for connecting fuel cell to grid. In this system, controller of inverter is designed to operate FC at maximum power in all the cases as well as acts as DSTATCOM to the grid. Hence extra DSTATCOM is not required for distribution system supplied by grid and FC. The purpose of DSTATCOM is to mitigate the voltage sag and to make proper power flow control in the system. A DSTATCOM control for this inverter is proposed here, so this controller mitigates sag, compensate reactive power and improve voltage stability, so by using proposed control, system maintains good power quality at load. Voltage sags will occur at source side only and sometimes it may occur due to large variations in load. In this paper, the modeling of FC, design guidelines and operation principle of both PI and fuzzy based DSTATCOM are presented along with the simulation results. Based on extensive simulation results using MATLAB/SIMULINK, it is found that the performance of the controllers both in transient as well as in steady state is quite satisfactory.

Keywords : Fuel cell, DSTATCOM, Distributed generation, Reactive power compensation, PI controller, Fuzzy based PI controllers.

1. INTRODUCTION

The distributed generation system plays a key role in power supply to all over the world by utilizing various energy resources. Power production should be made available at all the seasons and hence even during the period of non-availability of renewable energy sources like wind, hydro, etc. and non - renewable energy sources like thermal, etc. we opt the possibility of using fuel cell as the source of constant power supply and this can also be made as alternate source i.e. it can be used as an integrated source with wind power plant or hydro power plant too. The Fuel Cell (FC) is one of the most promising sources of renewable energy. They can be considered as green power because they are automatically clean. The advantages of using fuel cells are as follows: (a) Fuel cells convert hydrogen and oxygen directly into electricity and water, with no combustion in the process. The resulting efficiency is between 50 and 60%, about double that of an internal combustion engine. (b) Fuel cells are clean. If hydrogen is the fuel, there are no pollutant emissions from a fuel cell itself, only the production of pure water. (c) Fuel cells are quiet. A fuel cell itself has no moving parts, although a fuel cell system may have pumps and fans. As a result, electrical power is produced relatively silently. (d) Fuel cells are modular. That is, fuel cells of varying sizes can be stacked together to meet a required power demand. As mentioned earlier, fuel cell systems can provide power over a large range, from a few watts to megawatts. (e) Fuel cells are environmentally safe. They produce no hazardous waste products, and their only by-product is water (or water and carbon dioxide in the case of methanol cells).Fuel cells may give us the opportunity to provide the world with sustainable electrical power. However, the power thus produced by fuel cell can be used effectively by DSTATCOM which helps in proper power flow control and mitigation of voltage sags and maintains power quality at load (i.e., Point of Common Coupling (PCC)).

2. SYSTEM OVERVIEW

The distributed generation system comprises of the fuel cell as source of power supply in this paper. The fuel cell operates at a voltage level of 410V and which gets boosted up to 710 V by DC-DC boost converter and then fed into IGBT based inverter. The DC link voltage controller controls the pulse fed to DC –DC converter as shown in Fig 1.From the inverter , the output voltage obtained as 444 V AC is checked at the PCC for any voltage disturbances or if there is any need for power flow control by using the current regulator and power regulators. Based upon the requirements of proper control in power and voltage, the regulator operates and and provides better voltage and power supply.

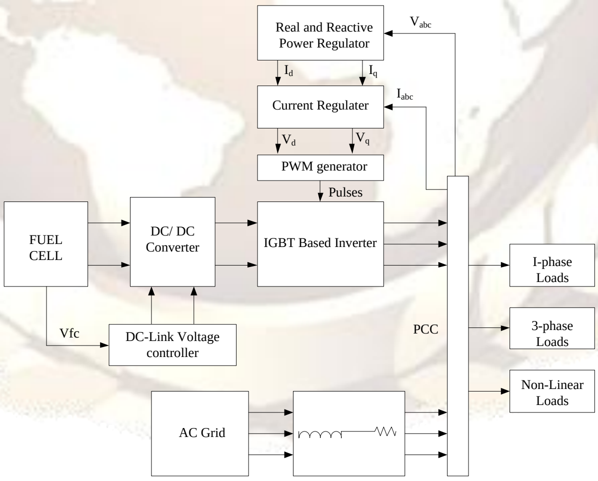

Fig 1:Block diagram of the system with DSTATCOM

3. DSTATCOM

The D-STATCOM is a three-phase and shunt connected power electronics based device. It is connected near the load at the distribution systems. The major components of a D-STATCOM are shown in Fig. 2. It consists of a dc capacitor (or sometimes DC source, i.e. battery), three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control strategy. The basic electronic block of the DSTATCOM is the voltage-sourced inverter that converts an input dc voltage into a three-phase output voltage at fundamental frequency.

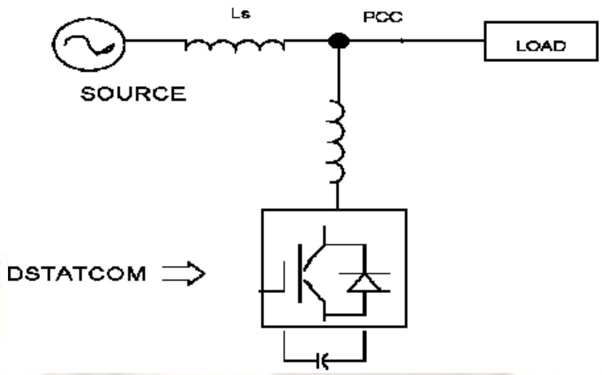

Fig.2.block diagram of DSTATCOM

The performance of the DSTATCOM depends on the control algorithm i.e. the extraction of the current components. For this purpose there are many control schemes which are reported in the literature and some of these are instantaneous reactive power (IRP) theory, instantaneous compensation, instantaneous symmetrical components, synchronous reference frame (SRF) theory, computation based on per phase basis, and scheme based on neural network. Among these control schemes instantaneous reactive power theory and synchronous rotating reference frame are most widely used. This paper focuses on the compensating the voltage sag, swells and momentary interruptions. The dynamic performance is analyzed and verified through simulation. It is a custom power device which is gaining a fast publicity during these days due to its exceptional features like it provides fast response, suitable for dynamic load response or voltage regulation and automation needs, Both leading and lagging VARS can be provided, to correct voltage surges or sags caused by reactive power demands DSTATCOM can be applied on wide range of distribution and transmission voltage, overload capability of this provides reserve energy for transients.

Basic operating principle of a DSATCOM is similar to that of synchronous machine. The synchronous machine will provide lagging current when under excited and leading current when over excited.

DSTATCOM can generate and absorb reactive power similar to that of synchronous machine and it can also exchange real power if provided with an external device DC source.

1) Exchange of reactive power:- if the output voltage of the voltage source converter is greater than the system voltage then the DSATCOM will act as capacitor and generate reactive power(i.e.. provide lagging current to the system)
2) Exchange of real power: as the switching devices are not loss less there is a need for the DC capacitor to provide the required real power to the switches. Hence there is a need for real power exchange with an AC system to make the capacitor voltage constant in case of direct voltage control. There is also a real power exchange with the AC system if DSTATCOM id provided with an external DC source to

regulate the voltage incase of very low voltage in the distribution system or in case of faults. And if the VSC output voltage leads the system voltage then the real power from the capacitor or the DC source will be supplied to the AC system to regulate the system voltage to the =1p.u or to make the capacitor voltage constant.

Hence the exchange of real power and reactive power of the voltage source converter with AC system is the major required phenomenon for the regulation in the transmission as well as in the distribution system. For reactive power compensation, DSTATCOM provides reactive power as needed by the load and therefore the source current remains at unity power factor (UPF). Since only real power is being supplied by the source, load balancing is achieved by making the source reference current balanced. The reference source current used to decide the switching of the DSTATCOM has real fundamental frequency component of the load current which is being extracted by these techniques.

A STATCOM at the transmission level handles only fundamental reactive power and provides voltage support while as a DSTATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation. DSTATCOM can be one of the viable alternatives to SVC in a distribution network. Additionally, a DSTATCOM can also behave as a shunt active filter, to eliminate unbalance or distortions in the source current or the supply voltage as per the IEEE-519 standard limits. Since a DSTATCOM is such a multifunctional device, the main objective of any control algorithm should be to make it flexible and easy to implement in addition to exploiting its multi functionality to the maximum.

The main objective of any compensation scheme is that it should have a fast response, flexible and easy to implement. The control algorithms of a DSTATCOM are mainly implemented in the following steps:

- Measurements of system voltages and current and
- signal conditioning
- Calculation of compensating signals
- Generation of firing angles of switching devices

Generation of proper PWM firing is the most important part of DSTATCOM control and has a great impact on the compensation objectives, transient as well as steady state performance. Since a DSTATCOM shares many concepts to that of a STATCOM at transmission level, a few control algorithms have been directly implemented to a DSTATCOM, incorporating Pulse Width Modulation (PWM) switching, rather than Fundamental Frequency switching (FFS) methods. This project makes attempt to compare the following schemes of a DSTATCOM for reactive power compensation and power factor correction based on:

1. Phase Shift Control
2. Decoupled Current Control (p-q theory)
3. Regulation of ac bus and dc link voltage
4. Synchronous Reference Frame (SRF) Method

5. Adaline Based Control Algorithm (in this paper we are not discussing about this controller)

The performance of DSTATCOM with different control schemes have been tested through digital simulations with the different system parameters. The switch on time of the DSTATCOM and the load change time are also mentioned.

Phase Shift Control

In this control algorithm the voltage regulation is achieved in a DSTATCOM by the measurement of the rms voltage at the load point and no reactive power measurements are required. Fig.3 shows the block diagram of the implemented scheme.

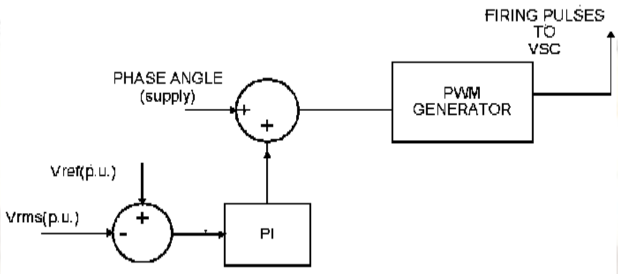

Fig.3. Block diagram of phase shift control

Sinusoidal PWM technique is used which is simple and gives a good response. The error signal obtained by comparing the measured system rms voltage and the reference voltage, is fed to a PI controller which generates the angle which decides the necessary phase shift between the output voltage of the VSC and the AC terminal voltage. This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120 degrees, to produce the desired synchronizing signal required to operate the PWM generator. In this algorithm the D.C. voltage is maintained constant using a separate dc source.

Decoupled Current Control p-q theory

This algorithm requires the measurement of instantaneous values of three phase voltage and current. Fig.4. shows the block diagram representation of the control scheme. The compensation is achieved by the control of id and iq. Using the definition of the instantaneous reactive power theory for a balanced three phase three wire system, the quadrature component of the voltage is always zero, the real (p) and the reactive power (q) injected into the system by the DSTATCOM can be expressed under the dq reference frame as:

$$p = v_d i_d + v_q i_q$$
$$q = v_q i_d - v_d i_q$$

Since vq=0, id and iq completely describe the instantaneous value of real and reactive powers produced by the DSTATCOM when the system voltage remains constant. Therefore the instantaneous three phase current measured is transformed by abc to dqo transformation. The decoupled d-axis component id and q axis component iq are regulated by two separate PI regulators. The instantaneous id reference and the instantaneous iq reference are obtained by the control of the dc voltage and the ac terminal voltage measured. Thus, instantaneous current tracking control is achieved using four PI regulators. A Phase Locked Loop (PLL) is used to synchronize the control loop to the ac supply so as to operate in the abc to dqo reference frame. The instantaneous active and reactive powers p and q can be decomposed into an average and an oscillatory component.

$$p = \bar{p} + \tilde{p} \quad \text{and} \quad q = \bar{q} + \tilde{q}$$

Where $\bar{p}$ and q are the average part and $\tilde{p}$ and $\tilde{q}$ are oscillatory part of real and reactive instantaneous powers. The compensating currents are calculated to compensate the instantaneous reactive power and the oscillatory component of the instantaneous active power. In this case the source transmits only the non-oscillating component of active power.

Therefore the reference source currents $i_{s\alpha}^*$ and $i_{s\beta}^*$ in α-β coordinate are expressed as:

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix}$$

These currents can be transformed in a-b-c quantities to find the reference currents in a-b-c coordinate.

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix}$$

Where i_o is the zero sequence components which is zero in 3-phase 3-wire system

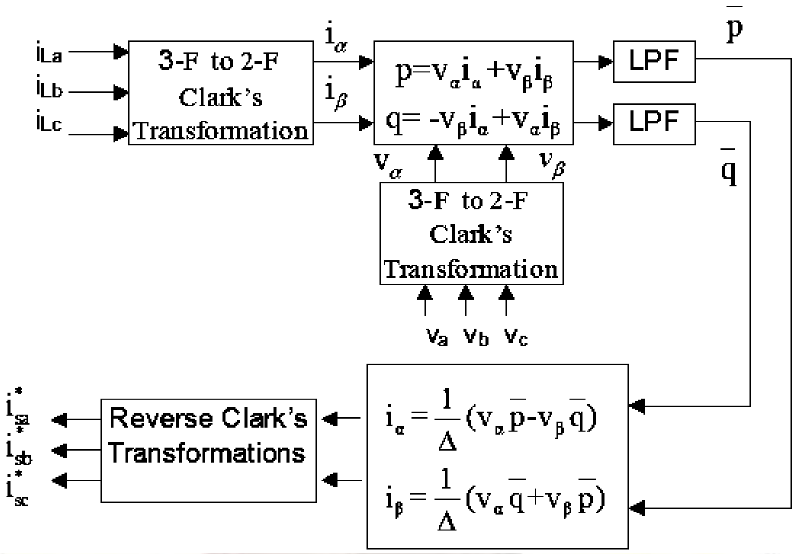

Fig.4. block diagram of decoupled theory based control of DSTATCOM

Synchronous rotating frame theory

The synchronous reference frame theory is based on the transformation of the currents in synchronously rotating d-q frame. Fig.6 explains the basic building blocks of the theory. If θ is the transformation angle, then the currents transformation from α-β to d-q frame is defined as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

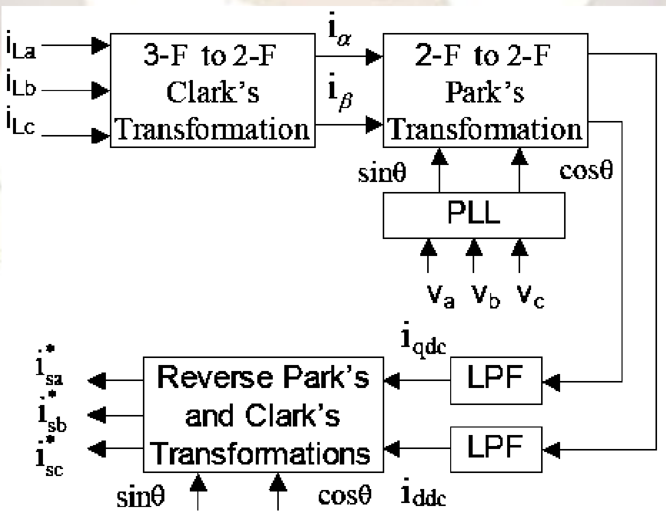

Fig.5. block diagram for synchronous frame theory

α-β frame as shown below:

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix}$$

From here the transformation can be made to obtain three phase reference currents in a-b-c coordinates using. The reactive power compensation can also be provided by keeping iq component zero for calculating reference currents.

4. MODELING OF FUEL CELL

Solid Oxide FC (SOFC) model is developed in [7] and based on Nernst's equation and Ohm's law, the fuel cell stack output voltage (V) is represented (Fig. 6). For MATLAB simulation, representation of stack output voltage (V) is then connected to controlled voltage source as shown in Fig. 6. SOFC dynamic model is interfaced to the dc-link through boost converter. In this paper operating voltage of SOFC is considered as 410 V and boost converter converts it to 700 V.

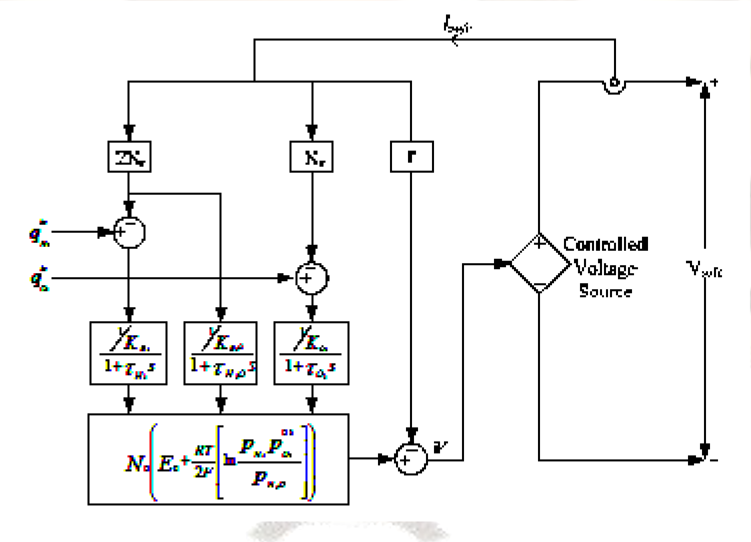

Fig. 6: Modeling of SOFC

5. SIMULATION RESULTS

The simulation model of the system is shown in the following figures below.

5.1 SYSTEM WITH PI CONTROLLER

The Fig. 7 shows the simulation model of the entire distributed generation system. The Fig 8 and 9 represent the simulation model of power regulator and the current regulator, which helps in mitigating voltage sag and reactive power compensation and also makes fuel cell to operate at maximum power level.

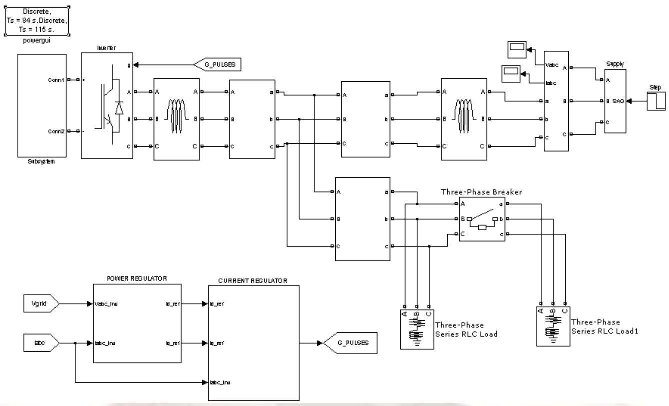

Fig 7 :Simulation model of entire system

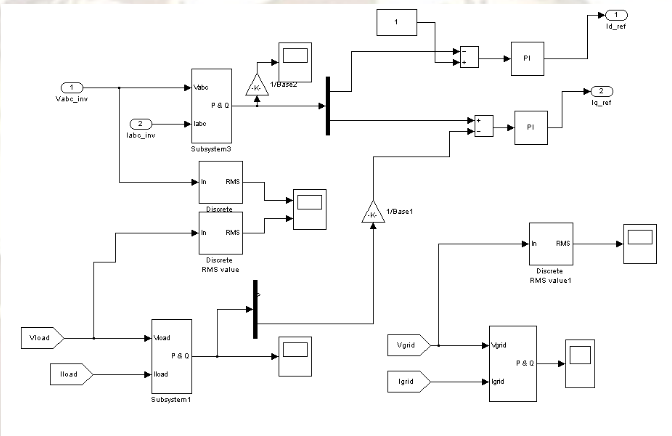

Fig 8:Simulation model of power regulator

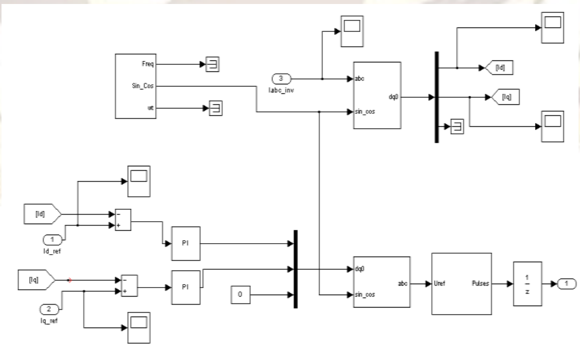

Fig 9:Simulation model of current regulator

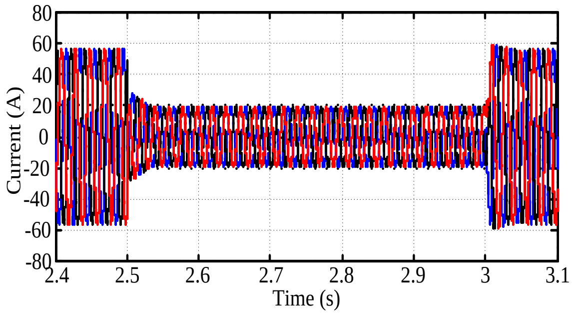

Fig10: Grid current waveform

In the Fig. 10, from 2.5 to 3sec load connected at PCC is more than the FC generation (maximum capacity) and before 2.5 and after 3 sec load is less then that of fuel cell maximum generation so during 2.5 to 3 required real power flow from grid to load, before 2.5 and after 2.3, grid is taking some power from fuel cell and the respective real and reactive powers of load is shown in Fig 11.

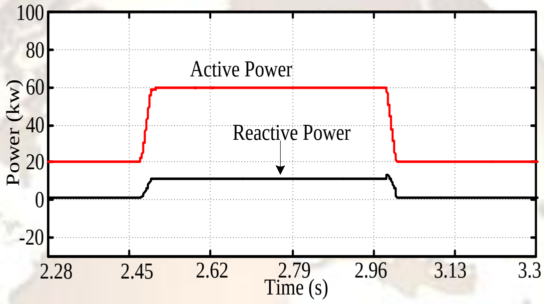

Fig 11 :Load power

In the figure shown above ,i.e, Fig 11, load power is more than that of generation of fuel cell , so grid provide only remaining real power to load but grid do not supply any reactive power to load (i.e., reactive power supplied/taking by the grid to PCC is zero). This is achieved by reactive power compensation by proper control of DSTATCOM.

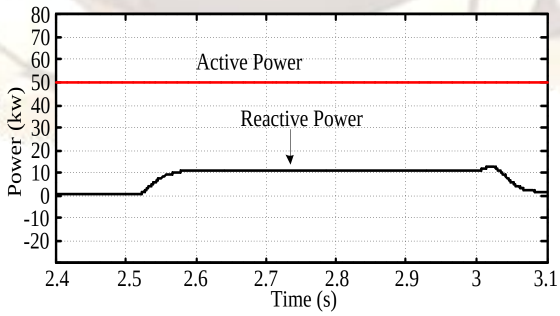

Fig 12:Inverter power

In the Fig shown above, i.e, Fig 12, inverter compensate reactive power that how much reactive power is connected to PCC and this control allows to operate fuel cell at maximum level of power generation.

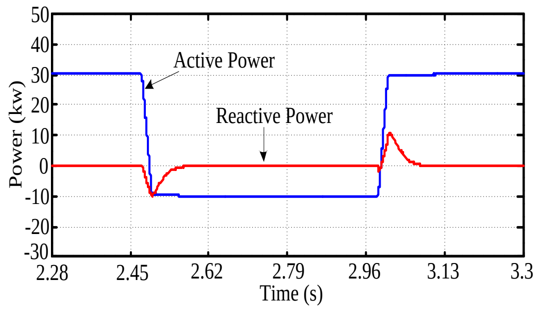

Fig 13:Grid power waveform

After compensated reactive power by inverter or DSTATCOM, reactive power supplied or consumed by grid is zero and the flow of active power is depends on both generation of FC and active load power connected to the PCC. This is shown in Fig. 13.

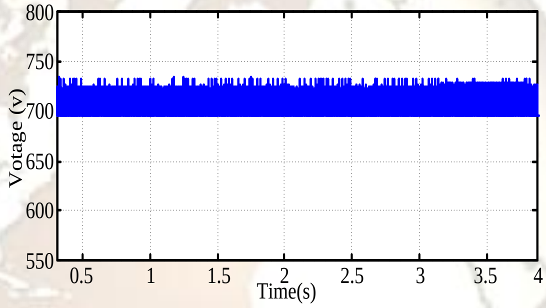

Fig 14:Voltage across DC converter

In the figure shown above ,i.e, Fig 14,the voltage produced across DC converter is 710 V dc which is boosted from 410V dc and in all the cases this dc-link voltage is maintained at its reference value (710V).

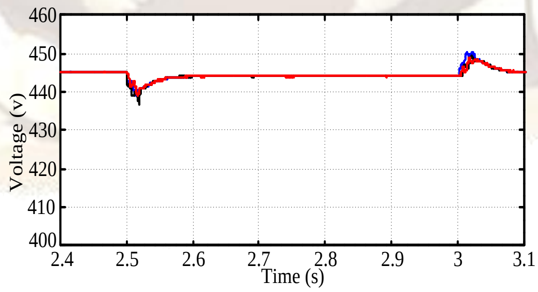

Fig 10:Rms voltage waveform at PCC

In the figure shown above ,i.e, Fig 15,the rms voltage varies from 440 V ac to 430 V and again increased to 440V and kept constant till load change is occurred in interval of 2.4 to 3 seconds and it increases to above 444 V ac.Hence the proposed control compensates reactive power and as well as improve the power quality by maintains good stability of voltage.

5.2 SYSTEM WITH FUZZY CONTROLLER

The simulation model of the system is shown in the following figures below.

The Fig. 16 shows the simulation model of the entire distributed generation system. The Fig 17 and 18 represent the simulation model of power regulator and the current regulator, which helps in mitigating voltage sag and reactive power compensation and also makes fuel cell to operate at maximum power level.

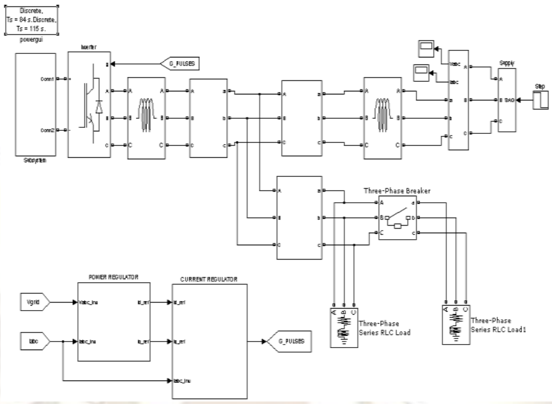

Fig 16:Simulation model of entire system

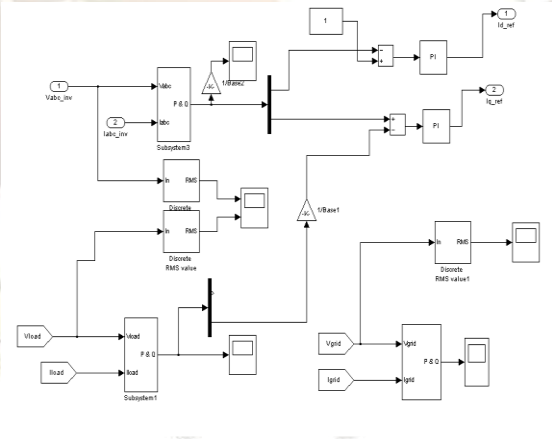

Fig 17:Simulation model of power regulator

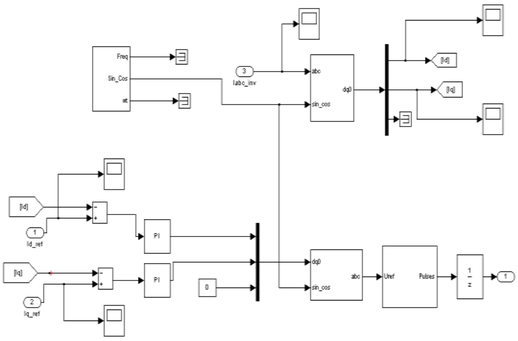

Fig 18:Simulation model of current regulator

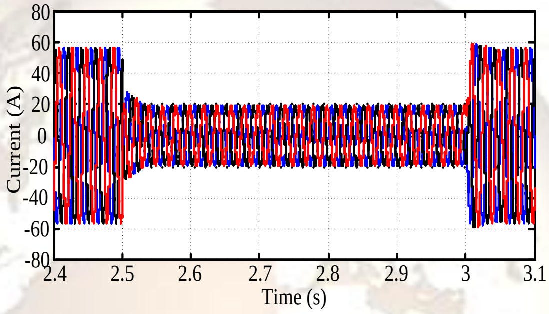

Fig 19: Grid current waveform

In the Fig. 19, from 2.5 to 3sec load connected at PCC is more than the FC generation (maximum capacity) and before 2.5 and after 3 sec load is less then that of fuel cell maximum generation so during 2.5 to 3 required real power flow from grid to load, before 2.5 and after 2.3, grid is taking some power from fuel cell and the respective real and reactive powers of load is shown in Fig 20.

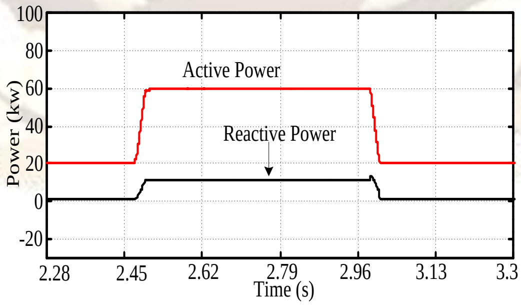

Fig 20:Load power

In the figure shown above ,i.e, Fig 20, load power is more than that of generation of fuel cell , so grid provide only remaining real power to load but grid donot supply any reactive power to load (i.e., reactive power supplied/taking by the grid to PCC is zero). This is achieved by reactive power compensation by proper control of DSTATCOM.

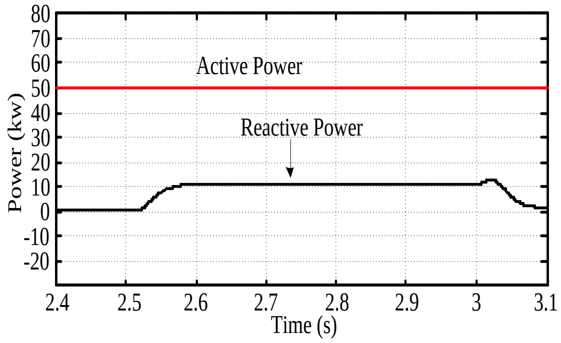

Fig 21 :Inverter power

In the Fig shown above, i.e, Fig 21, inverter compensate reactive power that how much reactive power is connected to PCC and this control allows to operate fuel cell at maximum level of power generation.

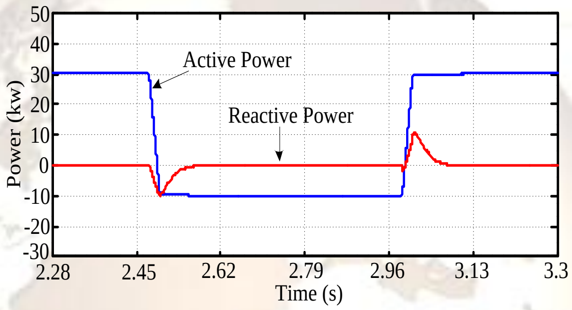

Fig 22 :Grid power waveform

After compensated reactive power by inverter or DSTATCOM, reactive power supplied or consumed by grid is zero and the flow of active power is depends on both generation of FC and active load power connected to the PCC. This is shown in Fig. 22.

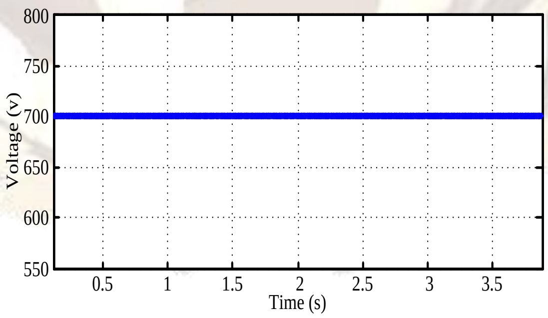

Fig 23:Voltage across DC converter

In the figure shown above ,i.e, Fig 23,the voltage produced across DC converter is 700 V dc which is boosted from 410V dc and in all the cases this dc-link voltage is maintained at its reference value (700V).Ripples in dc link is less with fuzzy controller compared to PI controller as shown in Fig 15.

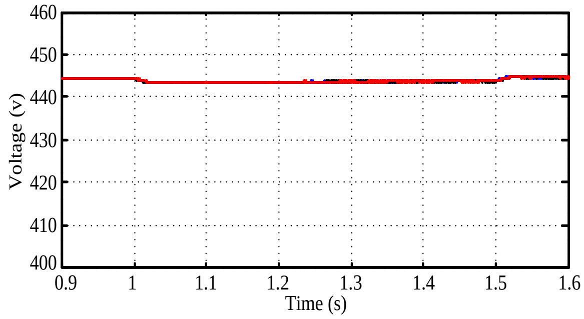

Fig 24: Rms voltage waveform at PCC

In the figure shown above ,i.e, fig 24,the rms voltage increases from 440 V ac to 450 V and reaches 444V and kept constant till load change is occurred in interval of 2.4 to 3 seconds. Comparing to Fig 15 , at the time of sag , voltage decreases much comparing to Fig 23.Hence the proposed control compensates reactive power and as well as improve the power quality by maintains good stability of voltage much better than PI based DSTATCOM control.

6. CONCLUSION

From these results, it can be inferred that the system with DSTATCOM with fuzzy based PI control can produce regulated voltage and power than compared to system with DSTATCOM with PI control. The proposed controller is also working for mitigation of sag. During sag time, the proposed controller regulates the voltage at PCC or load bus at its reference value (444 V). And the proposed controller also can compensate reactive power and it allows operating fuel cell at its maximum generation level of power. Hence no extra DSTATCOM required in distribution system. Inverter itself acts as DSTATCOM with proposed control and it can help to mitigate sag effects at load bus.

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