Operation and Control of a Hybrid Photovoltaic-Diesel-Fuel Cell System Connected to Micro-Grid

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***Abstract*-This paper presents modeling and control of a hybrid Photovoltaic (PV), Diesel-Engine Generator (DEG) - Fuel Cell (FC) system connected to electric grid. A case study on impact of FC operation on the frequency stability of electric grid has been carried out. The model of fuel cell system includes a fuel cell generator, electrolyzer and a hydrogen storage facility. The limits on hydrogen volume due to limited storage capacity have also been incorporated. The modeling of photovoltaic is also presented and analyzed for a time period of 24-hours with varying solar radiation and temperature. Results of simulation indicate that FC system can contribute to frequency stability in both cases when the load increases and also when the load drops. This feature of FC system will be helpful if it is operated along with a hybrid Wind-PV System.**

Keywords- Distributed generation (DG); fuel cells(FC); electrolyzer; diesel engine generator(DEG); Photovoltiac (PV); hydrogen storage.

I. INTRODUCTION

Non-renewable sources of energy and fossil fuels are continuously consumed. Combustion of these fuels gives excessive heat and cause environmental pollution. Consumption of these fuels at continual rapid rate may result in shortage of electrical energy in the near future. Thus, it becomes extremely important to think for alternative renewable resources such as wind, photovoltaic (PV), fuel cells (FC), small hydro, bio-fuels etc. These technologies have many benefits, such as high fuel efficiency, short construction lead-time, modular installation, and low capital expense [1]. Their demand is further enhanced due to encouragement of the generation sector by the ongoing deregulation in the generation sector [2]. The distributed generation was integrated into the distribution system which emphasizes over optimal operating strategy [3], [4], [5], [6]. Small generators supply with bulk power which is one of the most commonly used strategy. The distribution system which comprises of the energy and the ancillary service market is also of great importance to both market and research [7]. For example, the case of power failure, local DG can maintain the power supply capacity to customers. DG also maintains frequency within the local distribution system in case of instability by fluctuation in connected load. Frequency stability is a newer topic of concern related to the distributed generation [8]. Earlier a single substation supplied power to the distribution system, but now the distribution system may have numerous generators feeding various customers. Addition of multiple generators in the distribution system can result in instability in frequency. Thus, such a distribution system is under a threat of frequency drift (as on the transmission grid when there is no tertiary control), or even of losing synchronism.

Distributed generators, typically ranging between 250 kW to 5 kW output, include small wind turbines, PV solar, diesel and gas-powered generators, and two types of fossil fuel units: fuel cells and micro-gas turbines. In this paper, the impact of fuel cell operation on the frequency stability under grid-connected conditions is considered. The complete fuel cell system comprises of fuel cell, electrolyzer and a hydrogen storage facility. Fuel cells are essentially fossil-fueled batteries. As long as they are provided with a flow of fuel and air, they never run out of energy. They offer a completely different way of making electrical power from fossil fuels, i.e., natural gas or gasified coal. Modern fuel cells produce electricity without noise causing little pollution and provide fuel efficiency upto 50%, i.e., they are half as good as the best steam turbine units [9]. Each fuel cell works as an independent module. Any number of fuels cells can be installed depending upon power requirement. Easy manufacture in assembly-line in various sizes is yet another benefit of fuel cell.

II. FUEL CELL SYSTEM

Fuel cell is an electrochemical device that converts chemical energy into electrical energy. Fuel cell has an electrolyte and a pair of electrodes. Unlike battery which needs repeated recharge, fuel cell regenerates species utilized during the electrochemical reactions avoiding a need to recharge. The basic requirement of a fuel cell is anode channel, cathode channel, electrolyte, fuel oxidant. Usually air is used as oxidant and hydrogen as a fuel. Fuel is supplied to anode where it is oxidized resulting in production of electrons and positively charged ions. The electrons travel through external circuit to cathode. Positively charged ions move through electrolyte towards cathode where they recombine with electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

A. Fuel Cell System Application

Fuel cell system can be used for portable power as well as for on-site generation. In stationary applications, natural gas is

978-1-4673-0766-6/12/$31.00 ©2016 IEEE

mainly used as fuel source which is primarily methane. On-site back up power system based on diesel engines is generally operated only in case of emergency. Fuel cells have high efficiency, low noise and small emissions, so they can be operated continuously. Fuel cell does require any back up power. Fuel cell systems based on PEMFC technology are low in. Fuel cells can be used as both centralized and distributed generation. Distributed generation is more favorable in remote areas or where electrical demand has grown beyond the limit of the utility grid. Fuel cell systems also can supply the power a grid- connected systems.

B. Electrolyzer

Water is decomposed into H_2 and O_2 by supply of direct current through electrodes of the fuel cell. A small fraction of H_2 production comes from the electrolysis. Now a day, it is significantly cheaper to produce H_2 from hydrocarbons. Net reaction for splitting of water is:

$$H_2O \rightarrow H_2 + 1/2O_2 \qquad (1)$$

Electrolysis plants, which are, use alkaline electrodes known as alkaline electrolyzer. Traditionally alkaline electrolyzers have been designed for constant H_2 production rates. For variable rate of H_2 production Proton Exchange Membrane (PEM) electrolyzer is used. PEM electrolyzer have simpler process layout. There is no circulating liquid electrolyte. Thus, the PEM electrolyzer is easier to operate and provides fast start up. Its power density is also high. The efficiency of PEM electrolyzers is lower than alkaline electrolyzers. Main drawback with PEM fuel cell is their low operating lifetime systems.

C. Hydrogen Storage System

Hydrogen produced by electrolyzer can be stored in compressed form, as cryogenic liquid, in solids (metal hydrides, carbon materials) and in liquid H_2 carriers (methanol, ammonia). Compressed gas storage is most suitable for large-scale stationary storage. Compression of H_2 is normally done by the use of piston compressors or centrifugal compressors. Depending on the pressure difference, several stages of compression may be required because of the low density of H_2.

III. PHOTOVOLTAIC MODEL

Photovoltaic is the assembly of solar cells, connections, protective parts and supports.

A. Solar Cell

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor. When light falls on a solar cell, photons with energy greater than the band gap energy of the semiconductor are absorbed and a large number of electron-hole pairs are created. Generated holes tend to flow from n-side to p-side, resulting in the separation of the charge carriers which can flow in the external circuit. Thus, this p-n junction makes it possible to convert light energy into electrical energy. Magnitude of the generated current is proportional to the incident radiation. When the cell is short circuited, this current flows in the external circuit; when open circuited, this current is shunted internally by the p-n junction diode. The characteristic of this diode therefore sets the open circuit voltage characteristics of the cell.

B. Modelling of Solar Cell

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell. The diode determines the I-V characteristics of the cell. Equation of ideal solar cell [10] which represents the ideal solar cell model is:

$$I = I_L - I_R\left[\exp\left(\frac{V}{AV_i}\right) - 1\right] \qquad (2)$$

where:
"I_L " is photocurrent (A); "I_R " is reverse saturation current(A); "V " is diode voltage (V); " V_i " is thermal voltage, "A" is diode ideality factor.
The photocurrent (I_L) in (2) depends on solar irradiance intensity and temperature which is described as:

$$I_L = \frac{\lambda}{\lambda_{ref}}\left[I_{sc,ref} + \mu_{Isc}\left(T - T_{ref}\right)\right] \qquad (3)$$

where: "$I_{sc,ref}$" is solar cell short –circuit current at reference condition."μ_{Isc}" is the solar cell short-circuit temperature coefficient.
On the other hand, the cell's reverse saturation current is described as:

$$I_R = I_{R,ref}\left(\frac{T}{T_{ref}}\right)^{\frac{3}{A}} \exp\left[qE_g\left({}^{1}/_{T_{ref}} - {}^{1}/_{T}\right)/kA\right] \qquad (4)$$

$$I_{R,ref} = I_{sc,ref} \Bigg/ \left[exp\left({}^{V_{oc,ref}}/_{AV_i}\right) - 1\right] \qquad (5)$$

Where: "$V_{oc,\,ref}$" is solar cell open circuit voltage at reference condition; " E_g " is band-gap energy in the solar cell, (1.12-1.15eV). Modified voltage-current characteristic equation of solar cell is given as:

$$I = I_L - I_R\left[\exp\left(\frac{V+IR_{Se}}{AV_i}\right) - 1\right] - \frac{V+IR_{Se}}{R_{Sh}} \qquad (6)$$

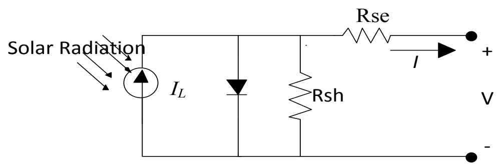

Fig. 1. Equivalent Circuit diagram of PV Model

C. Module

A solar PV module can be considered as a big solar cell i.e.- array of several solar cells connected in series and parallel with large voltage and current output than a single solar cell[10]. Single solar cell's voltage is too minor to be in real operation, so module is shape of a group of solar cells in series and parallel, with their protection device. Current-voltage characteristic equation of equivalent circuit for a PV module arranged in series N_s and parallel N_p can be described as:

$$I^M = N_p I_L - N_p I_R \left[\exp\left(\frac{V^M/N_s + I^M/N_s}{AV_i}\right)\right] - \frac{(N_p/N_s)V^M + I^M R_{Se}}{R_{Sh}} \quad (7)$$

" N_p " is cells parallel number; " N_s " is cells series number.

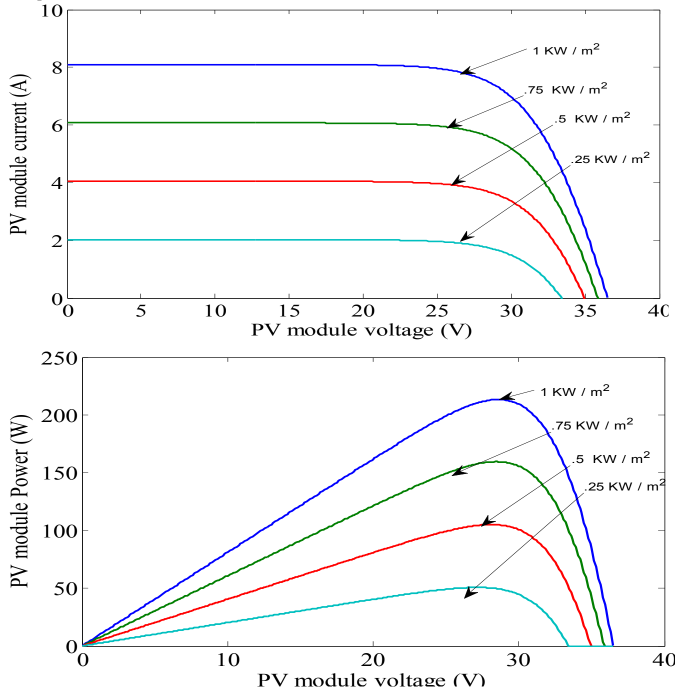

Fig. 2. PV characteristics of solar module

IV. SYSTEM MODEL

Consider a plant connected to a local grid as shown in Fig. 2. Plant having diesel generator, PV power, fuel cell system, electrolyzer and a hydrogen storage facility is connected to power system or grid. PV, diesel generator and fuel cell system are supplying power to grid. Grid is connected to a variable loads. Plant output is mainly energy source for electricity and heat, as well as for spitting water into hydrogen and oxygen in the electrolyzer. H_2 stored in hydrogen storage system, which consists of all equipment, which converts the hydrogen in volume format to, stored in storage tank. H_2 has used as input to fuel cell system. In electrolyzer dc supply is required as input which supplied by grid or power system by using ac-dc converter. There is another by-product produced by electrolyzer that is oxygen, which stored in oxygen storage system. Fuel cell system, which consist of fuel cell and dc-ac

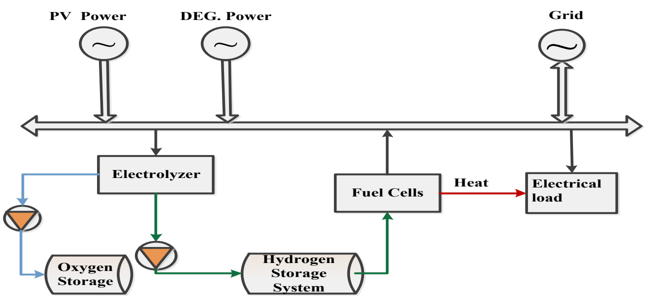

Fig. 3. Schematic diagram of a hybrid wind power, DEG- fuel cell system connected to a Micro-Grid.

converter .Converter, converts fuel cell dc output to ac power, which has supplied to grid. Fuel cell is producing heat energy, This has supplied to heat load. This plant model is also applicable for standalone and distributed power generation. If the electricity consumers are connected to the utility grid, the grid can be used for both power export and import.

A. *Mathematical Model*

In this section, a mathematical model of proposed hybrid power generation system has been presented. A block diagram shown in Fig. 3 describes the modeling of the hybrid power system containing P_V, DEG, FC, AE and hydrogen storage system. Power converters are properly operated at their appropriate locations. Presenting the mathematical analysis of each block separately and parameter used in the analysis has given in Table II. To maintain a stable operation of a hybrid system, the total power generation must be effectively controlled and properly dispatched to meet the total power demand of the connected loads.

Control strategy has determined by the difference between power demand ΔP_D and change in total generation ΔP_T.

$$\Delta P_T = \Delta P_V + \Delta P_{FC} + \Delta P_{DEG} - \Delta P_E \quad (8)$$

whereas ΔP_V, ΔP_{FC}, ΔP_{DEG}, ΔP_E are the change in- PV generation, diesel power generation, fuel cell power and power consumption by the electrolyzer in per units

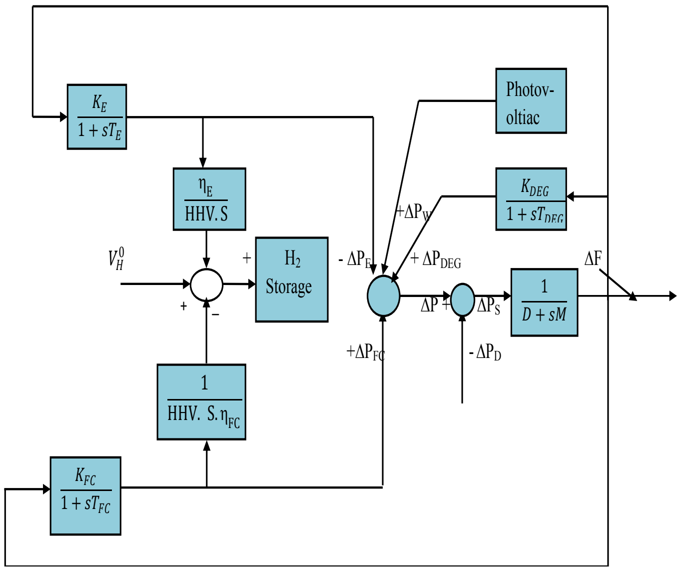

Fig. 4. Block diagram of hybrid PV, DEG-FC system

$$\Delta P_S = \Delta P_T - \Delta P_D \quad (9)$$

where ΔP_S is net power deviation.

The system frequency variation ΔF is calculated by-

$$\Delta F = \frac{K_{PS}}{1+T_{PS}} \Delta P_S \quad (10)$$

Since an inherent time delay exists between system frequencies so the transfer function for system frequency variation to per unit power deviation can be expressed by:

$$\Delta F = \frac{1}{D+sM} \cdot \Delta P_S \quad (11)$$

$$D = \frac{1}{K_{PS}}, \quad M = \frac{T_{PS}}{K_{PS}}$$

Where M and D are, respectively, the equivalent inertia constant a damping constant in per unit of the hybrid power system. Consider 2 MW power generations as base value of the complete system.

a) *Transfer Function Equation of Fuel Cells-*

The transfer function for system frequency variation to per unit fuel cell power is expressed by

$$\Delta P_{FC} = \frac{K_{FC}}{1+sT_{FC}} \cdot \Delta F \quad (12)$$

b) *Transfer Function Equation of Electrolyzer-*

A part of the generated power is sent to the electrolyzer to produce available hydrogen for the fuel cell. The transfer function of the electrolyzer is expressed by-

$$\Delta P_{E} = \frac{K_{E}}{1+sT_{E}} \cdot \Delta F \quad (13)$$

c) *Transfer Function Equation of Diesel Engine Generator -*

The transfer function equation of diesel power generation expressed by

$$\Delta P_{DEG} = \frac{K_{DEG}}{1+T_{DEG}} \cdot \frac{\Delta F}{R} \quad (14)$$

R is speed regulation. DEG automatically starts up with proper control.

d) *Transfer Function of hydrogen Storage-*

Hydrogen is produced in the electrolysis process with the following transfer function equation:

$$\Delta V_{E} = \frac{\eta_E}{HHV} \cdot \frac{\Delta P_E}{s} \quad (15)$$

Where ΔV_E is net change H_2 volume due to processing of electrolyzer and η_E is the electrical efficiency of electrolyzer, taking into account the stack losses and power conversion losses. HHV is the higher heating value. Similarly, change in hydrogen volume due to working of fuel cell is defined by following transfer function equation:

$$\Delta V_{FC} = \frac{1}{HHV \cdot \eta_{FC}} \cdot \frac{\Delta P_{FC}}{s} \quad (16)$$

Where ΔV_{FC} change in H_2 volume due to FC and η_{FC} is the electrical efficiency of the fuel cell including power conversion losses. The equation also determine the fuel cell power if ΔV_{FC} is known. From above equations net H_2 volume stored in tank is determine by following equation:

$$V_H = V_H^0 + \Delta V_E - \Delta V_{FC} \quad (17)$$

where V_H is net H_2 volume stored in tank and V_H^0 is initial H_2 volume of the tank.

V. OPERATION STRATEGY

Figure 5 shows a flow chart, which describes the operation of plant model discussed in previous section. Plant can be connected to a grid or isolated power system with variable loads. Frequency of power system is inversely proportional to load demand. From the point of view of system stability, frequency of system must remain constant. In order to obtain constant grid frequency, power supply should be adjusted such that whenever load demand increases, power supply should increase and when load demand is decreased, power supply should be reduced. The operation of plant is based on this principle. When change in frequency becomes negative, fuel cell system supplies power to grid. Before start operating, a fuel cell compares its hydrogen volume of tank is less than its maximum volume, then electrolyzer run and producing H_2 and O_2 that is stored in their tanks and this H_2 is used in fuel cell, otherwise electrolyzer hydrogen content to minimum volume limit. It produces power only of volume of hydrogen present in it exceds minimum volume limit. In case when change in frequency is positive, fuel cell does not supply the power and thereby the total generated power reduces. Some of excess power supply to the electrolyzer, before running the electrolyzer hydrogen volume of tank has compared to its maximum hydrogen volume. It will stop.

TABLE I
PARAMETER AND RATING OF THE HYBRID POWER SYSTEM

K_{FC} = 0.1, and T_{FC} = 0.03s	System power rating – 2 MW
K_{DEG} = 1 , and T_{DEG} = 0.05s, R =.5	Fuel cells power = 80 KW, DEG.Power = 250KW,Peak PV Power = 200 KW, Electrolyzer Power = 80KW
K_E = 0.1,andT_E = 0.05s	H_2 max. volume = 500Nm^3, H_2 min. volume = 60 Nm^3, Intial H_2 vol.= 250Nm^3
M = 0.12, and D = 0.1	η_E = 85%, η_{FC} = 50% , HHV =3.509 Kwh/Nm^3, Frequency 50 Hz

(10)

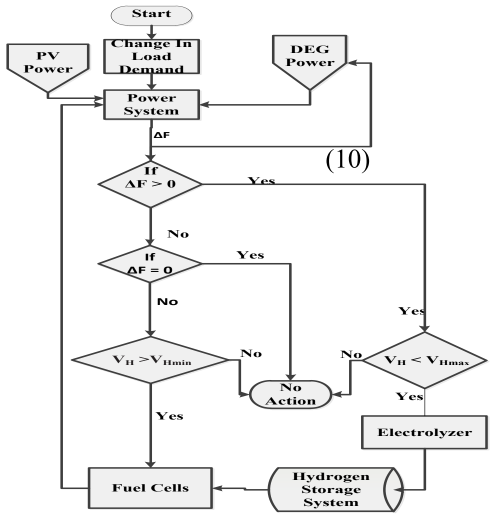

Fig. 5. Illustration of the operation strategy

VI. SIMULATION RESULTS & ANALYSIS

In this section, time domain simulation has been done and results are analyzed. For the purpose of calculation, all input and output quantities in the plots are considered in per unit (p.u.). Responses of the hybrid system shown by time simulation are in per unit value. Simulation time for the model is taken to be 24 hours. Real-time simulation results of PV model are also analyzed. Figure 6 and 7 show the variation in solar irradiation and PV power variation throughout a day. The SESG-ND-216u1F PV module [11] is taken for example, which provides 216 watt of nominal maximum power, and has 60 series connected polycrystalline silicon cells. Variation of solar irradiation is taken from Ref.[12]. Real-time demand load is taken from a substation 11kV DS feeder Kaniana Urban Haryana Bijli Vitran Nigam Haryana India [13]. Change in load demand with respect to real-time load demand has been shown in figure 8. Time domain simulated responses of the system under various operating points have been observed. Consider mainly two cases disturbances in demand load.

A. Case-I

Increase in load demand-

As change in load demand increases, change in frequency decreases, so production of power supply should increase to balance the frequency variation. PV power is supplying power to the grid. Due to decrease in system frequency, DEG power is increased to supply power to the grid, up to its rated capacity and increase the production power .To compensate the load fuel cell system also supplying the power to the hybrid power system as shown in Fig. 9. Due to operation of fuel cell hydrogen volume is consumed as shown in Fig. 12. Net variation in frequency with increase of input load demand is shown in Fig. 13.

B. Case- II

Decrease in load Demand-

As change in load demand decreases, change in frequency increases, so production of supply power should decrease to maintain the frequency variation. Due to increase in frequency DEG, power can be decreased, to reduce the production power Due to variation in frequency, net change in DEG power shown in Fig 8. As in Fig. 8 when load demand is decreasing power supplied should be decreasing by shutting down fuel cell and its response reached to zero as shown in Fig. 9 but power supply is still more than load demand so for balancing power is fed to electrolyzer and its response shown in Fig. 11. Due to operation of electrolyzer, hydrogen volume of tank will also increase, so its response is shown in Fig. 12

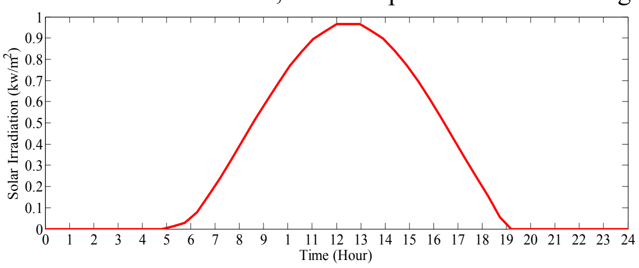

Fig. 6. Variation of Solar Irradiation throughout a day

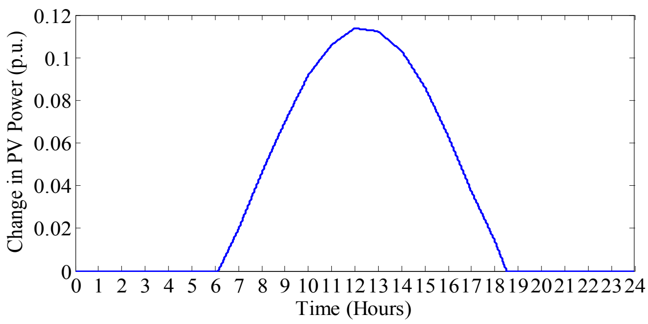

Fig. 7. Variation of PV Power

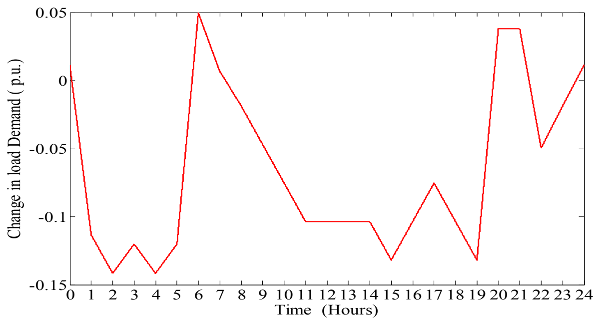

Fig. 8. Variation in load demand

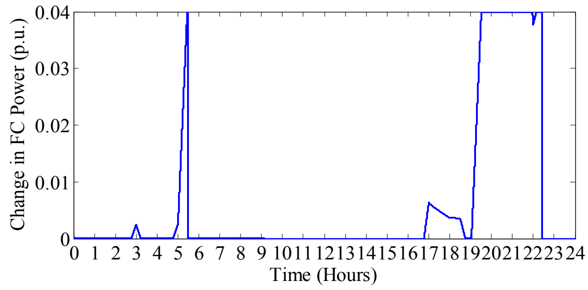

Fig. 9. Change in Fuel cells Power output

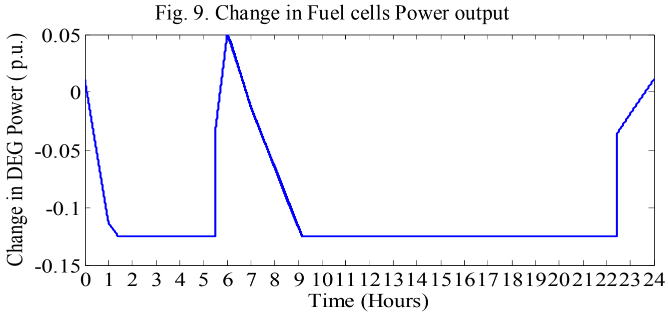

Fig. 10. Variation in DEG. Power output.

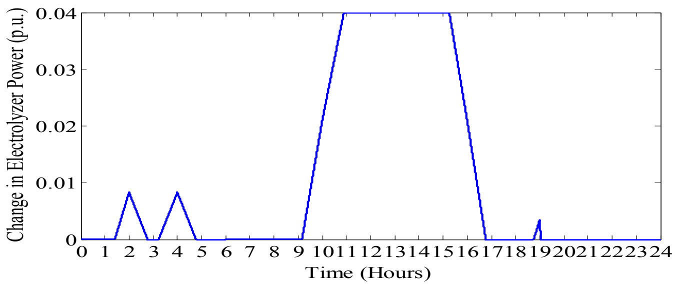

Fig. 11. Power consumed by electrolyzer.

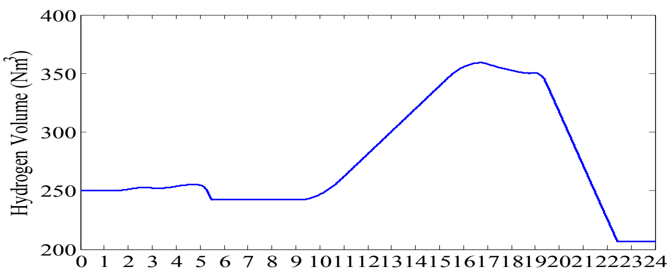

Fig. 12. Variation of hydrogen volume in storage tank.

So from above cases, resulting variation in frequency is shown in Fig. 13. Variation of frequency for a hybrid system with fuel cell and without fuel cell are shown in Fig.13. It can be concluded that fluctuation in frequency decrease by adding the fuel cell sytem with hybrid power system.

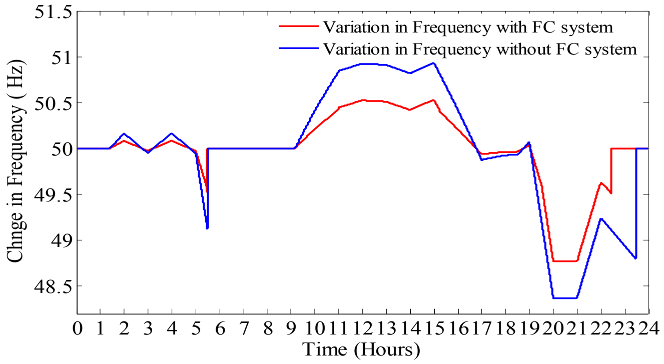

Fig. 13. Variation in frequency of the system.

VII. CONCLUSION

This paper emphasizes on the role of DG sources in controlling grid frequency. A model of fuel cell generator for response to grid frequency fluctiations has been developed. Result of simulation indicates that fuel cells combined with diesel generator gives better response in controlling frequency deviation in comparison to only diesel generator. Additionally, the operation of electrolyzer results in the considerable saving of fuel hydrogen as the volume of hydrogen is replenished in the storage tank. At the same time, rise in frequency due to fall in demand is also controlled by the operation of electrolyzer. This flexible model of operation of fuel cell alongwith electrolyzer would be extremely useful for hybrid DG systems having solar component. Futher research is required to drive operating strategies of fuel cells in presence of wind power systems.

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