Fuel Cell connected to Grid through Inverter

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Abstract— **Fuel cell systems are enhancing due to interest to supply electricity in remote areas as well as distributed power generation especially during the peak loads. Fuel cell generation becomes popular due to cleanliness, portability and suitability for electricity and heat generation. This paper presents the modeling of a fuel cell power plant (FCPP) in terms of fuel cell, dc-dc converter, dc-ac inverter and power system parameters, to interface with loads or grid. The control strategy of this model is hysteresis current controller (HCC). HCC is used to generate inverter switch pulse for the ac grid voltage. MATLAB/SIMULINK is used to validate the modeling and simulation of fuel cell generation and power conditioning unit. The proposed control strategy makes the distribution generation system work properly when the voltage disturbance occurs in the distribution system.**

Keywords- FCPP, Fuel cell(FC), HCC and Distribution System.

I. INTRODUCTION

Energy is one of the major requirements for the development of a country. The ever-demanding energy requirement needs huge investments to meet the demands. As the need for energy is briskly escalating, the energy resources which are limited may not be sufficient to sustain the process of economic development. The energy requirement must be met through safe, clean and convenient forms of energy, at least cost in a technically efficient, economically viable and environmentally sustainable manner [1].

Fuel cells are electrochemical devices which converts the chemical energy to dc electrical energy via electrochemical reactions. There are five kinds of fuel cells currently being investigated for the use in industry: 1) proton exchange membrane fuel cell (PEMFC), 2) solid oxide fuel cell (SOFC), 3) molten carbonate fuel cell (MCFC), 4) phosphoric acid fuel cell (PAFC), 5) aqueous alkaline fuel cell (AAFC). Among these, PEMFC is being considered and developed as the primary source in the movable power supplies and distribution generation, because of its high energy density, low working temperature and firm yet simple structure. The main characteristics of PEMFC stacks are: a) they produce water as residue, b)they have high efficiency when compared to thermal generations; c) they operate at low temperature (up to 90^0 C), which allows a fast start-up; and d) they use a solid polymer as the electrolyte which reduces concerns related to construction, transportation and safety.

An FC based power system mainly consists of a fuel processing unit (reformer), fuel cell stack and power conditioning unit (PCU).The PEMFCs are being rapidly developed as the primary source for both stand-alone as well as grid connected applications. The PEMFCs use hydrogen and oxygen as input fuel and produce dc power at the output of the stack. The characteristics of the stack are presented through polarization curve; this curve depicts relation between stack terminal voltage and load current drawn from that stack. The cell voltage decreases almost linearly as the load current increases. Therefore, the output voltage should be regulated at a desired value. To keep the polarization characteristics at constant level, additional parameters such as cell temperature, air pressure, oxygen partial pressure and membrane humidity also needs to be controlled [1], [2].

Power electronic interfacing circuit is called power conditioning unit. It is necessary for FC based systems to condition its output dc voltage. It converts the dc voltage to ac voltage. The FC source is connected to the load or grid through inverter which must be synchronized with the grid in terms of voltage and frequency. In this paper, a two-level pulse width modulation (PWM) voltage source inverter (VSI) is used because this is the state-of-the–art technology used today by all manufactures worldwide [3].

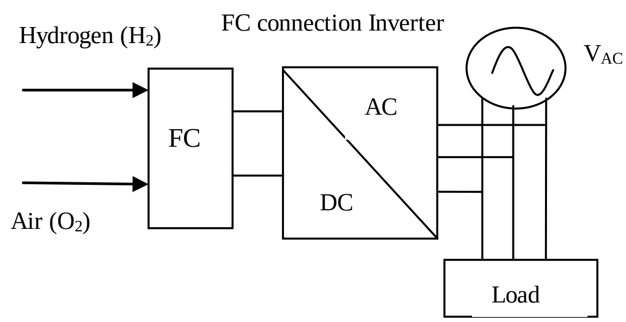

Fig. (1) FC System Connected to Grid

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II. The Fuel Cell

A. Description of Fuel Cell

The type of FC used in our research is the high temperature proton-exchange membrane (HTPEM) fuel cell. This kind of FC is quite developed and seems to be the first hydrogen technology to be used for massive integration into Electric Power system (EPS). Apart from that, the range of power they produce is from several watts to some tens of kilowatts. This range fits perfectly with the low voltage distribution network; future trends indicate that these will be probably used locally in many places by individual consumers.

The electrochemical model of fuel cell is described in this paper. The assumptions for the fuel cell model are as follows:

- The gases are ideal.
- The fuel cell is fed with hydrogen and air.
- The electrode channels are small enough that the pressure drop across them is negligible.
- The ratio of pressures between the inside and outside of the electrode channels is large enough to assume choked flow.
- The fuel cell temperature is stable.
- The Nerst equation is applied.

The behavior of these FCs can be described as follows: at the anode of the fuel cell, the hydrogen gas oxidizes releasing electrons and creating H^+ ions (or protons).

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

During this reaction, energy is released. On the other hand at the cathode, oxygen reacts with electrons taken from the electrodes (reduction), and H^+ ions from the electrolyte form water which is waste product.

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad (2)$$

To achieve optimal working conditions, proper air flow as well as humidification of the gases must be ensured. The overall reaction taking place at the fuel cell can be summarized as:

$$O_2 + 2H_2 \rightarrow 2H_2O + heat + electricity \quad (3)$$

Four major irreversibilities are highlighted in FC [4].

- Activation losses: These are caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost driving the chemical reaction that transfers the electrodes from one electrode to other.
- Fuel crossover and internal current losses: This energy loss results from the waste of the fuel cell passing through the electrolyte. The fuel loss and its effect are usually not very important.
- Ohmic losses: This voltage drop is the straightforward resistance to the flow of electrons through the materials of the electrodes and the various interconnections.
- Mass transport or Concentration losses: These result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. Because the reduction in concentration is the result of a failure to transport sufficient reactant to the electrode surface, this type of loss is also called "Mass transport" loss.

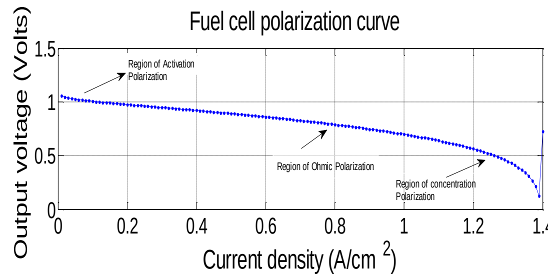

Fig. 2 FC V-I Characteristic

The most important among these are activation and ohmic losses [4]-[5]; at high temperatures activation losses become less significant than ohmic ones. The PEM FC voltage-current characteristics resulting from all of this can be observed in Fig. (2).

B. Equivalent model of a Fuel Cell

Taking into account the parameters and characteristics presented in the previous section, the steady state FC voltage, V_{FC}, is calculated using the following equations:

$$V_{FC} = E_{rev} - \eta_{act} - \eta_{ohmic} - \eta_l \quad (4)$$

Where E_{rev} is the reversible voltage or internal potential of the FC, and the other variables are the irreversible loss voltages, or over potentials:

η_{act} = the voltage loss produced by the activation polarisation (activation over potential).

η_{ohmic} = the voltage drop related to the ohmic polarization (ohmic over potential).

η_l = the drop introduced by the concentration polarization (concentration over potential).

Many attempts have been undertaken to develop and simplify mathematical model defining the behavior of a PEMFC [6], [7]. An accurate model can be obtained modifying equation (4) and substituting the values of the different losses. This results in equation (5):

$$V_{FC} = E_{rev} - \frac{2.3RT}{\alpha nF}\ln\left(\frac{I_{FC}}{I_0}\right) - R^{int} I_{FC} - \frac{RT}{nF}\ln\left(1 - \frac{I_{FC}}{I_l}\right) \quad (5)$$

where the different parameters are:

R = Universal gas constant (8.31451 J/(mol. K)),

F = Faraday's constant (96485 Coulomb/mol),

T = Stack temperature,

α = Transfer coefficient,
n = Number of electrons involved in the reaction,
R^{int} =Sum of electrical and photonic resistances,
I_{FC} =Fuel cell current,
I_0 =Exchange current,
I_l =Limiting current of the fuel cell.

This mathematical equation can be represented by the equivalent electric circuit shown in Fig (3), which fits quite precisely with Dicks-Larminie's model .

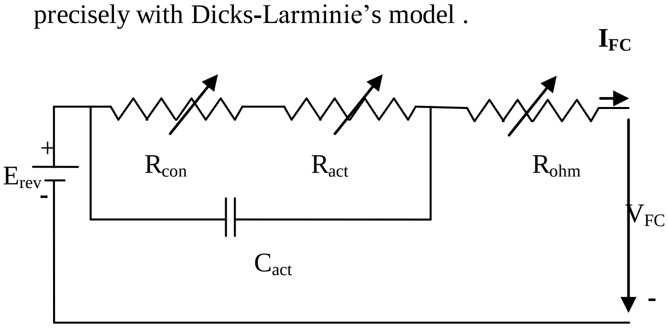

Fig. (3) FC Equivalent Electric Circuit

The circuit depicted in Fig. 3 is the one implemented in Matlab/Simulink in order to perform distributed generation (DG) integration simulation analysis in this paper.

III. POWER CONDITIONING UNITS

Fig. no (4) shows the block diagram of Fuel cell based Distributed Generation (FCDG) system with power converter interface and its control. The fuel cell is connected to the utility load/grid through power converters. The utility grid is modeled as a three phase ac source with equivalent internal impedance. Pulse Width Modulation (PWM) voltage source inverters (VSI) with low loss and high frequency IGBT switches is used to connect the FC system to the utility load/grid for real and reactive power control purposes. A dc-link capacitor on the dc side of the voltage source inverter acts as an energy buffer and maintains a stable dc voltage for the converter in the steady state condition. A low pass filter is connected at the output of the inverter to provide a sinusoidal output voltage. The high current rating of the filter inductor is compensated by capacitors rated at a reduced voltage. The cut-off frequency of the LC filter can be given as

$$f_c = \frac{1}{2\Pi\sqrt{LC}} \qquad (6)$$

A low pass LC filter is used at the PWM inverter output to achieve better harmonic reduction in the phase currents and inverter output voltages. This filter is of higher current rating as dictated by the load circuit. In order to meet the requirements for connecting the FCDG system to a utility grid and control the real and reactive power flow between them, it is necessary to shape and control the inverter output voltage in amplitude, angle and frequency.

The fuel cell stack output current and the fuel flow rate q_{H_2} are related as:

$$I_{fc} = \frac{2Fq_{H_2}}{N} \qquad (7)$$

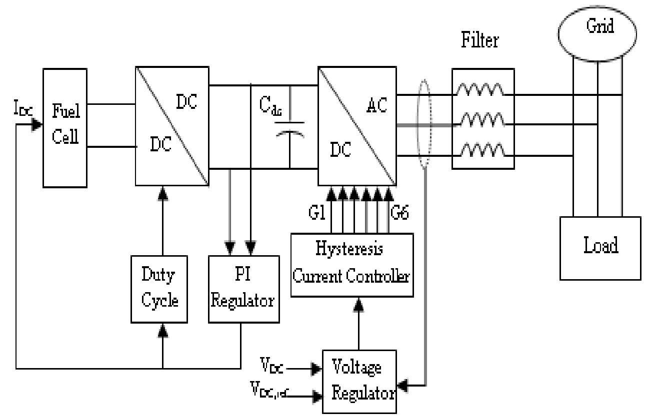

Fig. (4) FC Based Distributed Generation System

As the power demand increases, load current increases, the inverter are constrained to supply this higher current; furthermore this would force the FC to supply additional current, hence FC output voltage falls. For efficient working of FC based system, the hydrogen flow rate needs to be adjusted with change in power demand. Hence a fuel flow controller is required to control the fuel flow rate to meet the desired output power.

A. Control Strategy

i) DC-DC Converter

The capacitor voltage (on the dc side of the inverter) is sensed and compared with reference voltage. This error e = V_{dcref} - V_{dc} is used as input for PI controller. The PI controller is used to regulate the output of the dc-dc converter voltage (by varying duty cycle) to meet the required dc current (I_{DC}). Its transfer function is H(s) = K_p+K_I/S. where, [K_p=0.005] is the proportional constant that determines the dynamic response and [K_I= 0.15] is the integration constant that determines it's settling time. The PI controller is eliminating steady-state error in the dc-side voltage.

ii) DC-AC Inverter

It comprises regulated dc voltage at the input and hysteresis current controller for current control within the inverter (inner loop control) besides a voltage regulator circuit. The dc-side capacitor voltage is regulated and hence facilitates obtaining required inverter output voltage. The output of voltage regulator feeds to 'Hysteresis Current Controller' (HCC) as an input.

HCC is utilized independently for each phase and directly generates the switching signals for three phase voltage source inverter. An error signal e (t) is the difference between the desired current $i_{ref}(t)$ and the actual current $i_{actual}(t)$. If the error current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned OFF and the lower switch is turned ON and vice-versa. As a result, the current gets back into the hysteresis band. The switching performance is as follows:

$$S = \begin{cases} 0 \text{ if } i_{actual}(t) > i_{ref}(t) + h \\ 1 \text{ if } i_{actual}(t) < i_{ref}(t) + h \end{cases}$$

Here, hysteresis band limit h=0.5.

IV. SIMULATION RESULTS

We have developed a fuel cell which has 450 numbers of fuel cells in series connection. The FC is designed for 480 DC output voltages as shown in Fig. (5). The DC-DC converter output voltage is shown in Fig. (6) that provides approximately 500 V DC controllable voltage. The DC current of the FC is shown in Fig. (7). It has a value typically 50 A .The output of the FC is fed to the ac system via dc-dc and dc-ac power converters and controlled in a closed loop. Fig. 8 shows current magnitude of dc-dc converter at the output. This is mentioned in the initial model system. The grid voltages and phase currents (V_{abc} and I_{abc}) are shown in Fig. 9(a) and Fig.9 (b) respectively. The currents are dictated by the load (as per the requirement in the grid) and are supplied from the inverter. This investigation is undertaken for a balanced load condition. The chattering is observed in the current waves as we are adopting HCC. However; these are high frequency ripples and would normally be suppressed by the line inductances.

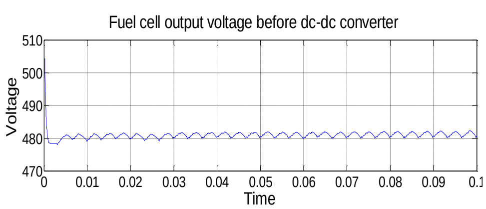

Fig. (5)

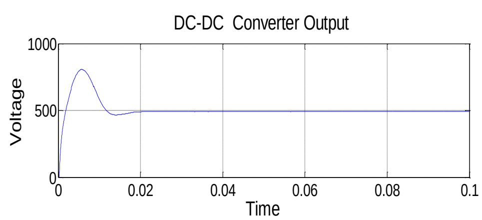

Fig.(6)

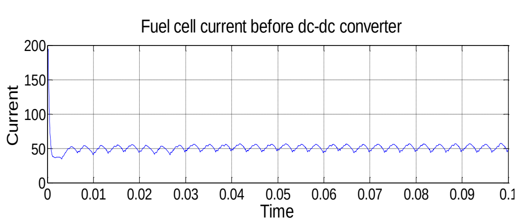

Fig.(7)

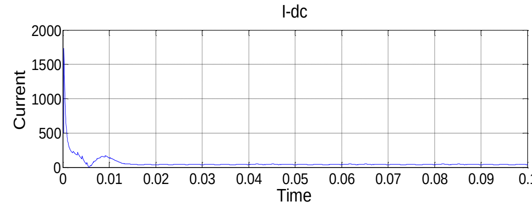

Fig.(8)

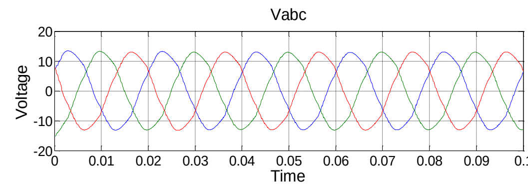

Fig.9(a)

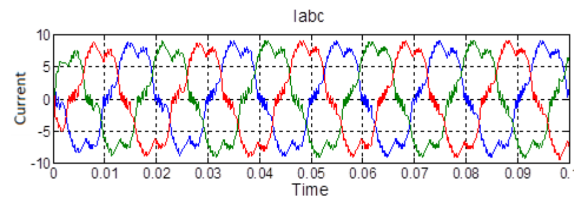

Fig.9(b)

V. CONCLUSIONS

A simulation model of the fuel cell power plant (FCPP) is developed using dc-dc power converters, inverter, fuel cell stack and power system parameters. This model would be useful to define the flow limits for a stand-alone as well as distributed grid connected environment. The PI controller is used for controlling the duty cycle in order to get the desired DC voltage that would feed the grid through inverter after conversion. The hysteresis Current Controller (HCC) is adopted to generate the switching pulses of the dc-ac inverter. These controllers facilitate developing a fuel cell based power conditioning system so that FC system can be connected to any grid for meeting power requirements.

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APPENDIX: Operating Data of the Systems

Systems Parameters	Values
System Frequency	50 Hz
Load (R_L & L_L)	20 ohms & 0.01 mH
Filter (LC)	2.3 mH & 0.1 µF
DC-DC Capacitor	2100 µF