DESIGN AND MODELLING OF FUEL CELL POWERED QUADRATIC BOOST CONVERTER BASED MULTI LEVEL INVERTER

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Abstract — The paper will discuss an Air Breathing Fuel Cell (ABFC), as an alternate power source for industry Drive applications. An empirical model has been developed with MATLAB/SLMULINK in order to investigate the polarisation characteristics of the ABFC. This model includes phenomena like activation loss, ohmic loss, and concentration loss. The paper will also throw light on the DC to DC converter and multilevel inverter, as ABFC stack power conditioning unit (PCU). The DC to DC converter is a Quadratic Boost Converter (QBC), implemented with fixed frequency Pulse Width Modulation (PWM) based sliding-Mode Control technique which enables a tight voltage regulation besides offering a good dynamic performance. The cascaded H-bridge inverter converts DC to AC and carrier type sinusoidal pulse width modulation (SPWM) technique is used to improve THD as well as to control output voltage

Keywords— Air Breathing Fuel Cell (ABFC), Power Conditioning Unit (PCU), Quadratic Boost Converter (QBC), Sinusoidal Pulse Width Modulation (SPWM) and Sliding-mode controller

1. Introduction

Fuel Cell is an electro chemical device which converts fuel and oxidant into DC electricity [1]. Fuel cell is characterised by high electrical efficiency and zero/low pollutant emission. Only water, heat and electricity are the products of electrochemical -reaction in the fuel cell. Cells that take up oxygen, for the cathode reaction, from ambient air by passive means are known as “air-breathing” fuel cells (ABFC) [2-5]. In the ABFC, hydrogen and oxygen are fed at anode and cathode respectively as reactants.

The electrons will move to the cathode through external load and protons travel through the electrolyte membrane as shown in Fig. 1.

Anode side reaction:

$H_2 \rightarrow 4H^+ + 4e^-$

Cathode side reaction:

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

Overall reaction:

$2H_2 + O_2 \rightarrow 2H_2O$ + Electricity + Heat

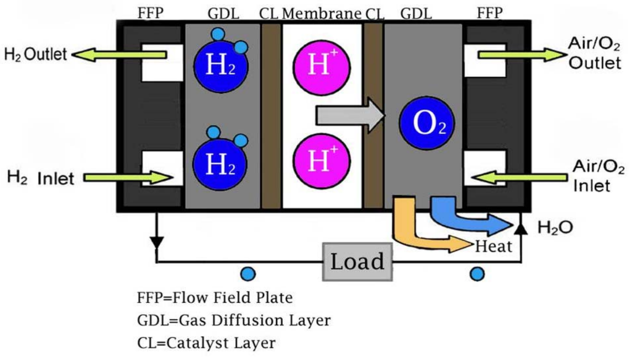

Fig. 1.Work process and reaction principle of an ABFC

The overall ABFC power system includes fuel cell stack, power conditioning units, and control units. The power conditioning circuits(PCU)includes DC to DC converter , a boost converter and the Multi level inverter. The boost converter produces output voltage more than the input voltage and controls the unregulated voltage output of the fuel cell stack(60V) and maintains the desired value (230V) using sliding -mode control The boost converter in closed loop mode can achieve good dynamic performance, in addition to load as well as line regulation. The other part of the PCU includes Multi level inverter for converting DC to AC. The Multilevel power conversion is a sophisticated technology with excellent potential for further growth. The applications of this technology include motor drives, power quality and power conditioning which uses medium to high voltages ranging from 2 to13 kV. The DC source for Multi Level

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Inverter is a Fuel Cell and it can be directly connected or through a DC-DC converter.

The organization of this paper, in Section 2 block diagram of the Proposed ABFC stack PCU and section 3 describes modeling of the ABFC fuel cell. In section 4 designing procedure and simulation results for power conditioning unit is given. Finally in Section 5 conclusion is stated.

2. Modelling of ABFC Power system

The overall system consists of:

- MATLAB model of the ABFC Stack.
- MATLAB model of DC–DC converter and Multi Level Inverter.

The block diagram of the proposed scheme is shown in Fig. 2. The design and modelling and Simulation results of each system are presented in the paper.

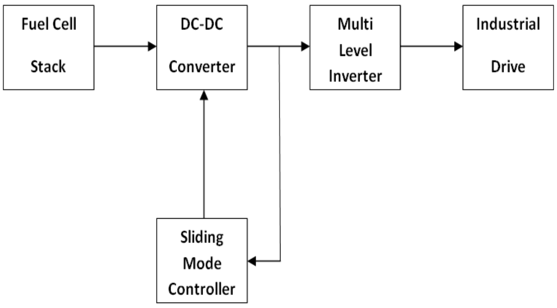

Fig. 2. Block diagram of the proposed scheme.

3. Mathematical Modelling of the ABFC

The analytical model of the ABFC can be represented by a set of mathematical equations. Gibbs free energy (Δg) is the net electrical work done by the system and is represented by Eq. (1).

$$\Delta g = \Delta h - T\Delta s \tag{1}$$

The change in the enthalpy of formation and entropy are modelled by the mathematical Eqs. (2) and (3).

$$\Delta h = h_{H_2O} - h_{H_2} - \frac{1}{2}h_{O_2} \tag{2}$$

$$\Delta s = s_{H_2O} - s_{H_2} - \frac{1}{2}s_{O_2} \tag{3}$$

However, h and s are expressed as functions of temperature as represented in Eqs. (4) and (5).

$$h_T = h_{298.15} + \int_{298.15}^{T} C_P dT \tag{4}$$

$$s_T = s_{298.15} + \int_{298.15}^{T} \frac{C_P}{T} dT \tag{5}$$

The molar specific heat of for steam, oxygen and hydrogen at constant pressure (C_p), are given by the mathematical Eqs. (6) - (8).

$$C_{P.Steam} = 143.05 - 58.04T^{0.25} + 8.2751T^{0.5} - 0.036989T \tag{6}$$

$$C_{P.Oxygen} = 37.432 - 2.0102X10^{-5}T^{1.5} + 17850T^{-1.5} - 2368800T^{-2} \tag{7}$$

$$C_{P.Hydrogen} = 56.505 - 22222.6T^{-0.75} + 116650T^{-1} - 560700T^{-1.5} \tag{8}$$

The standard potential of a fuel cell at STP (25°C and 1 atm) is 1.229V. The activation, ohmic and concentration losses are the three types of losses present in the ABFC, due to which the actual voltage of the cell drops from the equilibrium potential. The output potential of the ABFC single cell is expressed by the Eqs. (9) and (10).

$$V_{Cell} = E_{nernst} - \Delta V_{act+crossover} - \Delta V_{Ohmic} - \Delta V_{Conc} \tag{9}$$

$$E_{nernst} = \frac{-\Delta g}{2F} + \frac{RT}{2F}\ln\left(\frac{\gamma\beta^{\frac{1}{z}}}{\delta}P^{\frac{1}{z}}\right) \tag{10}$$

It is assumed that the reactants oxygen and hydrogen are pure (i.e. $\gamma = \beta = 1$). The adopted Eqs. (11) - (13) represents the activation, ohmic and Concentration losses.

$$\Delta V_{act+crossover} = \frac{RT}{2\alpha F}\ln\left(\frac{i+i_n}{i_o}\right) \tag{11}$$

$$\Delta V_{Ohmic} = ir \tag{12}$$

$$\Delta V_{Conc} = m\exp(ni) \tag{13}$$

The model built in MATLAB using the Eqs. (1) – (13) is shown in Fig. 3. The values of simulation parameters taken from the literature [6-14] and are tabulated in Table 1. The polarisation curve is plotted over a range of current densities at an operating temperature of 30°C, as shown in Fig. 5.

The fuel cell operating voltage ranges between 0.5 and 0.6 V [15]. The current density exists in between 40– 60 mA/cm^2 for the operating voltage range as shown in Fig.4. Thus, an operating current density of 50 mA/cm^2 was choosen for the implemented model. It was found that the operational voltage is 0.5656 V for a current density of 50mA/cm^2, and an exchange current density of 1 mA/cm^2 from Fig.4. The cell performance for different cell temperatures viz. 30°C, 50°C, and 60°C is depicted in Fig.5 to ensure the correctness of results. It is observed form results that as the cell temperature increases, the cell voltage drops with increase in current density.

Table 1. Parameters of ABFC model

Parameter	Value
m	0.00003 V
n	0.008 $cm^2\,mA^{-1}$
r	0.0002 $K\Omega\,cm^2$
i_n	3 $mAcm^{-2}$
i_o	1 $mAcm^{-2}$
α	0.25

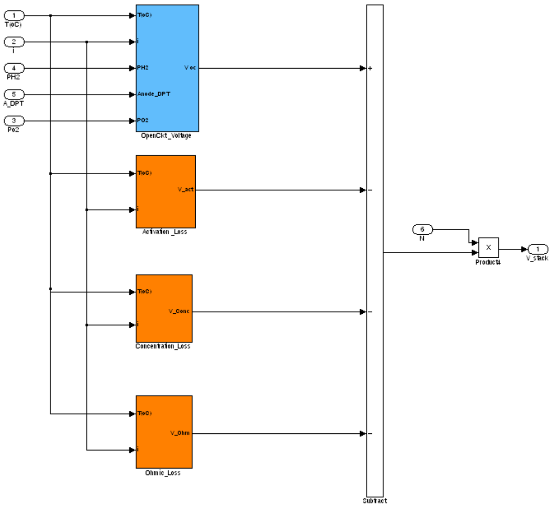

Fig. 3. Scheme of the model developed in MATLAB in order to simulate stack behaviour under steady state conditions

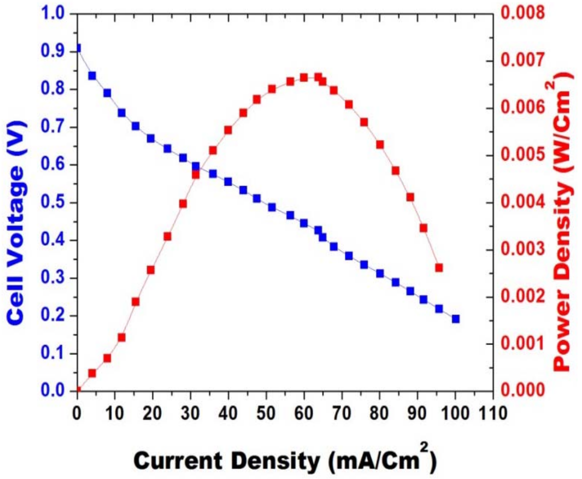

Fig. 4. Polarization curve for an ABFC operating at 30°C.

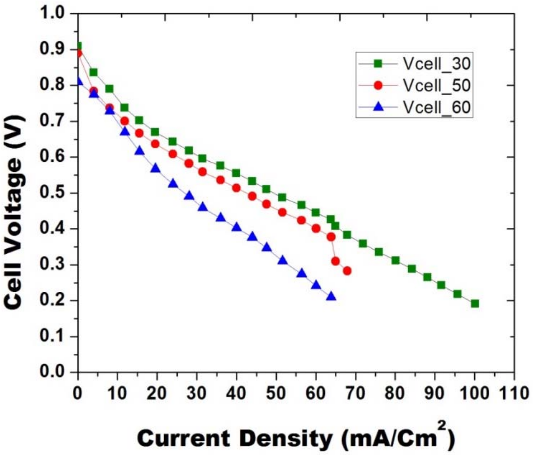

Fig.5 Cell voltage of an ABFC for different cell temperatures

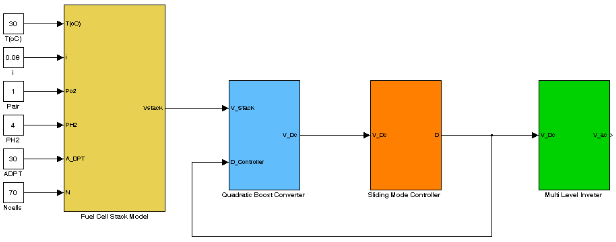

Fig.6 The integrated MATLAB/Simulink model of the proposed system

4. Design of Power Conditioning Unit (PCU)

4.1 Boost converter

The integrated MATLAB/Simulink model of the proposed system is shown in Fig. 6 and the Schematic of Boost converter with sliding mode controller is shown in Fig. 7.

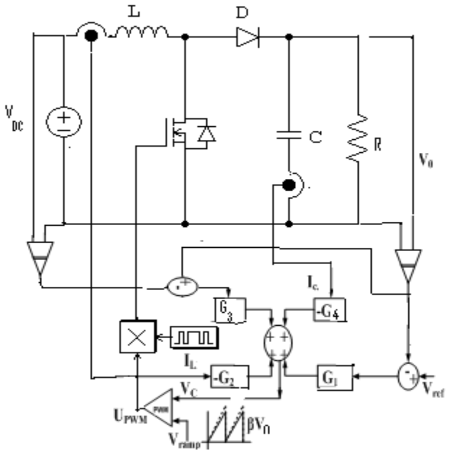

Fig. 7 - Schematic of Boost converter with sliding mode controller

The equivalent-control law for [16-17] sliding-mode control is represented as:

$$u_{eq} = 1 - (\frac{K_2}{V_O}) i_c + K_1 \frac{(V_{ref} - \beta V_0)}{V_O} - (\frac{V_{in}}{V_o}) - K_3 (\frac{i_L}{V_{in}}) \quad (14)$$

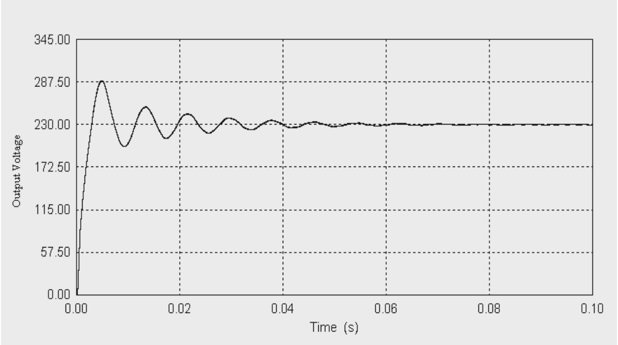

Fig. 8 - Output voltage wave form of the Boost converter

The Boost converter produces Output voltage with a steady-state ripple of ±1V (±0.434%) as shown in Fig. 8.The converter parameters are Inductance (L_1) = 0.887mH, Capacitance (C_1) = 128µF and Switching frequency f_{sw} = 50kHz.

4.2 Multi level inverter

The series H-bridge design was the first multi level topology [18-20]. Later a diode clamped converter with series capacitors bank was introduced followed by flying capacitor design in which floating capacitors were used instead of series connected capacitors. Cascading of different fundamental topologies provides high power quality due to the multiplying effect of the number of levels than the fundamental topologies alone.

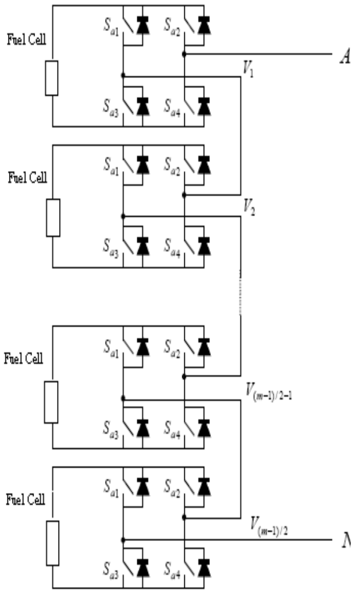

Fig. 9 Single Phase cascaded multi-level full-bridge inverter.

Fig. 9 shows the single phase cascaded multi-level full-bridge inverter with fuel cell as the power source .In multilevel case, the SPWM techniques with three different disposed triangular carriers were proposed as follows: Alternate phase disposition (APOD) , Phase opposition disposition (POD) and Phase disposition (PD). The APOD carrier base technique is shown in Fig. 10.

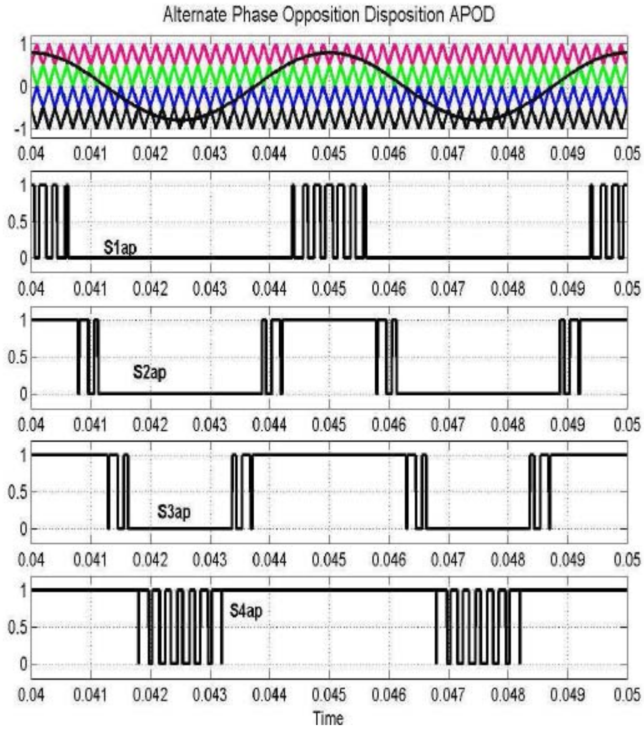

Fig. 10. Switching pattern produced using the APOD carrier based PWM scheme for a five-level inverter.

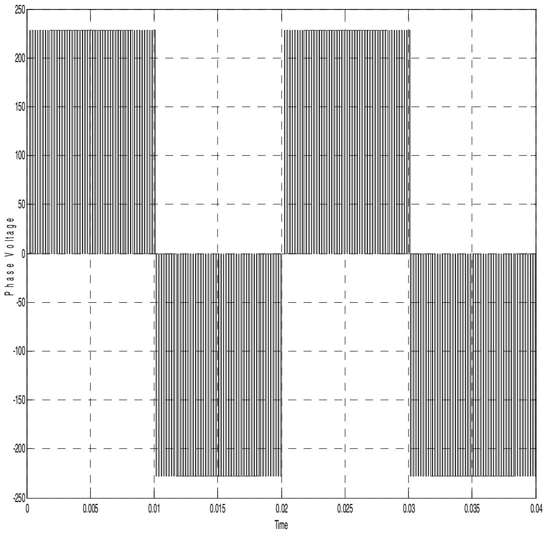

Fig. 11 Phase Voltage waveform of 3-Level Inverter

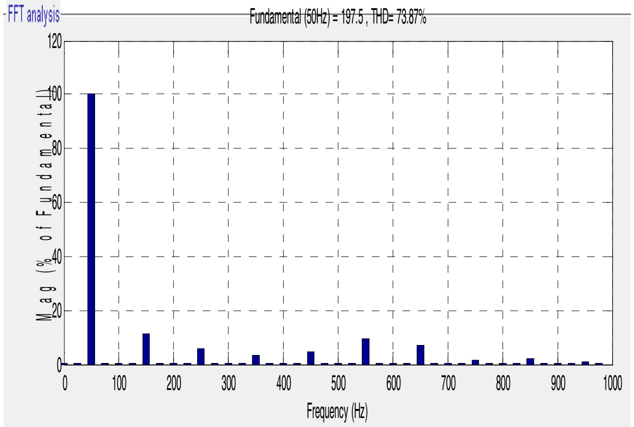

Fig. 12. FFT analysis for Phase Voltage waveform of 3-Level Inverter

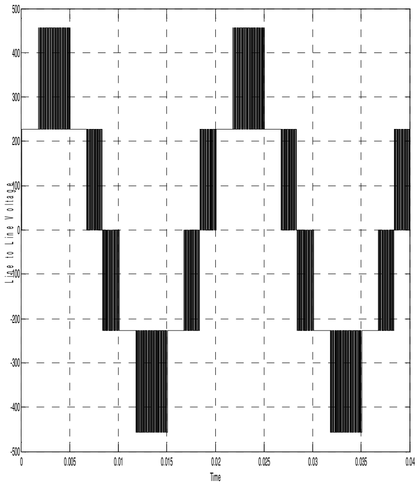

Fig. 13. Line to line Voltage waveform of 3-Level Inverter

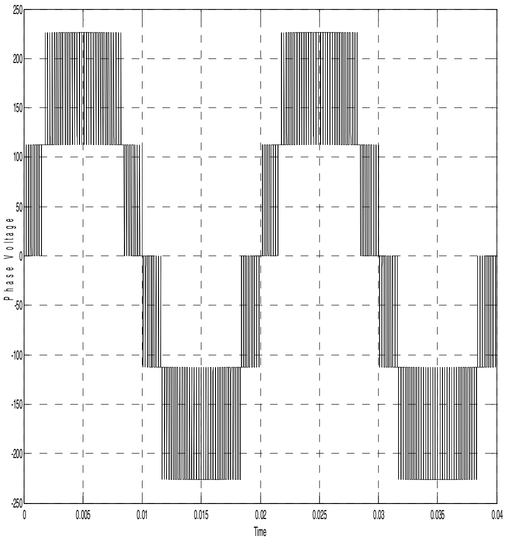

Fig.14 Phase Voltage waveform of 5-Level Inverter

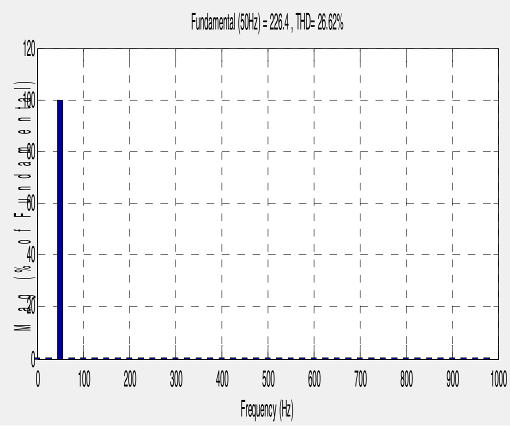

Fig.15 FFT analysis of Phase Voltage waveform of 5-Level Inverter

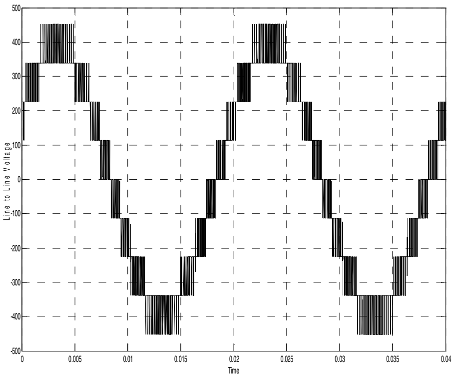

Fig.17. Line to line Voltage waveform of 5-Level Inverter.

Fig. 11, Fig. 12 and Fig. 13 show the Phase Voltage waveform, FFT analysis for phase voltage and Line to line Voltage waveform of 3-Level Inverter at modulation index ,m=0.8. The Total Harmonic Distortion is found to be 73.81%.Similarly Fig. 14, Fig. 15 and Fig. 16 show the Phase Voltage waveform, FFT analysis for phase voltage and Line to line Voltage waveform of 5-Level Inverter. The Total Harmonic Distortion is found to be 26.62%.In case of 7-level inverter the THD is found to be 18.00% and in 5-level inverter it is 13.64%. Table 2 shows THD comparison for different levels.

Table.2 Comparison of H-Bridge Inverter Levels

Type of cascaded H-Bridge Inverter	Total Harmonic Distortion (**THD**) for Phase voltage
3-Level	73.81%
5-Level	26.62%
7-Level	18.00%
9-Level	13.64%

6. conclusion

In this paper an Air breathing proton exchange membrane fuel cell power system model is developed, which includes an ABFC stack, a DC–DC converter and a cascaded H-bridge Multi level inverter. The polarisation characteristic of an ABFC is obtained with the development of empirical model using MATLAB/SIMULINK.The DC to DC converter will boost the voltage obtained from the Fuel cell stack and maintains constant output voltage by controlling the unregulated output of the fuel cell stack with sliding-Mode Control technique for achieving good line and load regulation. The Multi Level inverter converts DC to AC to meet the industry drlve with abridgening the power Quality problems.

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