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Modeling and Analysis of Solid Oxide Fuel Cell Based H_2 Generator for Distribution Generation

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Abstract: The main aim of this paper is development of renewable energy sources in distributed generation (DG) systems. A fuel cell (FC) is considered as a promising power generating sources for DG system. In this paper, a mathematical analysis of Solid Oxide Fuel Cell is carried out for extensive MATLAB/Simulink modeling. For the transient analysis of SOFC distributed generation system, a AC/DC load is taken. A detailed study on solid oxide fuel cell modeling has been done. Furthermore, a novel research work is required to enhance the performance and its cost. The performance of designed system is investigated for predicting the fuel cell operating behaviour with more accurately and it is found satisfactory.

Keywords: Fuel cell, Green energy, Renewable energy, Distribution generation, Solid oxide fuel cell

I. INTRODUCTION

The energy consumption is increasing exponentially day-by-day. The supply of electrical energy is totally dependent on fossil fuels e.g. diesel, petrol, coal and gas etc. In near future, the storage capacity of fossil fuels is going to decay. So, it is forced to researchers to explore more sustainable energy resources. In this context, the renewable energy is best suitable option to fulfill the demand of human being. Furthermore, many researchers as well as manufacturers are currently working to develop a variety of fuel cells and planning to develop self sustained energy environment with renewable energy technology [1].

Among the various types of FCs, SOFC is most attractive because of its high efficiency and fuel availability. FC was first used by NASA in the 1960's in their space program. Those fuel cells used pure oxygen and hydrogen as the reactant gases and were small-scale, expensive and not commercially viable. NASA's interest pushed further development, as did the energy crisis in 1973. Since then, the researchers are focusing on the development of FC performance and its cost continuously[3]. The Fuel cells are categorized on the basis of their operating parameters specially: operating temperature, membrane resistance, catalyst, start-up time, efficiency etc. The FC technologies have replaced battery system due to their high power density in comparison other storage device also.

On the basis of choice of fuel cell and electrolyte, they are categorized into six types. Their technical characteristics are compared. Different types of a fuel cell are used for various purposes. SOFC is a type of fuel cells identified as the likely fuel cell technologies that will capture the most significant market in the future [4]. A large amount of literature has been published about SOFCs as well as other fuel cells. Most of the work is focused on investigating static electrochemical characteristics, such as reaction mechanisms, state-of-the-art cell components, new materials, etc. [5]. For the purpose of dynamic simulation and control, the dynamic characteristics of fuel cell must be understood. The authors in [6], proposed an interest toward fuel cell studies as they are clean and efficient sources of electricity. The electrical characteristics of a SOFC are analysed.

The research addition of this paper is to present detailed modeling of SOFC and perform transient analysis of the system under variable AC/DC loads.

II. SYSTEM DESCRIPTION

The system consists of (a) Renewable energy power generating source (i) SOFC (b) Power electronics interface (i) DC/DC Boost converter (ii) Inverter (c) Variable AC/DC loads. The schematic diagram of complete system is shown in Fig. 1 as,

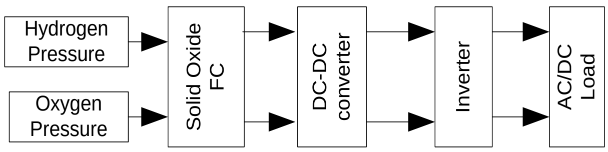

Fig.1. Schematic diagram of Fuel cell base energy system.

III. MATHEMATICAL MODELING OF SOFC

The FC is an electrochemical device which produces electricity by supplying hydrogen reactant. The static nature of fuel cell makes it a low noise device, however it can be used for both stationary and mobile applications, can offer significant advantages [7]. It has a power density of 200-300Wh/L which is almost ten times of a battery system. Because of this it is recommended to be used in distributed generation system.

The modeling of SOFC is based on the assumptions that the fuel cell temperature is made to be constant; the fuel cell gasses are ideal and the Nernst's equation applicable to the cell. By Nernst's equation output fuel cell dc voltage, V_{fc} across stack of the fuel cell at current I_{fc} is given by the Eq. (1) as [8-10],

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$$E = E_o + \left(\frac{RT}{nF}\right)\log\left(\frac{P_{H_2}P_{O_2}^{\ 0.5}}{P_{H_2O}}\right) \quad (1)$$

Hydrogen, Oxygen and water flow pressure can be expressed in Eq. (2) & (3) as,

$$P_{H_2} = \left(\frac{m_{H_2}R_{H_2}}{V_{anode}}T\right) \text{and } P_{O_2} = \left(\frac{m_{O_2}R_{O_2}}{V_{cathode}}T\right) \quad (2)$$

$$P_{H_2O} = \left(\frac{\left(m_{H_2O}\right)^{\frac{1}{2}}Q_{H_2O}}{k_{cathode}}\right) \quad (3)$$

For industrial purpose there are five types of commonly used fuel cells. Comparisons of various FCs with their operating features, chemical reactions, benefits and drawbacks are shown in Table 1 & 2 as [11-14],

Table 1. COMPARISON OF FCS WITH THEIR SPECIFICATIONS [11-12]

Fuel cell	**Fuel Utilized**	**Catalyst**	**Start up time**	**Power density kW/m^2**	**Efficiency**	**Operating temp. (°C)**
SOFC	CO	Perovskites	Few minutes	0-1.5	55-65%	700-1000
PEMFC	H_2, CH_3OH	Platinum	Seconds	3.8-6.5	35-45%	60-100
AFC	H_2	Platinum	Seconds	~ 1.0	40-50%	100-250
PAFC	H_2	Platinum	Few minutes	0.8-1.9	55%	150-250
MCFC	CO	Nickel	Few minutes	1.5-2.6	55-65%	500-700

Table 2. **COMPARISON OF FCS WITH THEIR UTILIZATIONS, BENEFITS AND DIFFICULTIES [13-14]**

Fuel cell	**Utilizations**	**Benefits**	**Drawbacks**
SOFC	• Electrical utility • Stand alone DG	• Fuel flexibility • Increased tolerance to fuel cell impurities	• High temperature enhances corrosion and breakdown of FC components
PEMFC	• Portable power backup • Distribution generation • Electric vehicles	• Electrolyte reduces corrosion • Operating temp. low • Fast startup time	• Requires expansive catalysts • Pure fuel requirement
AFC	• Space craft power backup • Distribution generation	• Reaction rate is much faster at cathode • High performance	• Expansive removal of CO_2 from fuel and air steam required
PAFC	• Stand- alone power	• Impure fuel is also acceptable	• Low output current and power • Big size and heavy weight and Platinum catalyst is required
MCFC	• Electrical utility • Distribution generation	• Fuel flexibility	• High temperature enhances corrosion and harmful for FC components

The activation drop (V_{act}) can be denoted by Tafel's equation. which gives the activation drop is shown in eq. (4) as,

$$V_{act} = -\varsigma_1 + \varsigma_2 T - \varsigma_3 T\left[\ln(I)\right] + \varsigma_4\left[\ln(Conc.O_2)\right] \quad (4)$$

The oxygen concentration $(Conc.O_2)$ is given as a meaning of stack temperature shown in Eq. (5)

$$Conc.O_2 = \frac{P_{O_2}}{5.08\times10^6 \times \exp^{\left(\frac{-498}{T}\right)}} \quad (5)$$

$$V_{act} = -V'_{act} \quad (6)$$

The effect of double layer capacitance charging at the electrolyte interface can be expressed in Eq. (7) as,

$$\frac{dV_{act}}{dt} = \frac{1}{C_{dl}} - \frac{V_{act}}{R_{act}C_{dl}} \quad (7)$$

Where, C_{dl} is the double layer capacitance and R_{act} is the activation resistance,

$$R_{act} = \frac{V_{act}}{I} \quad (8)$$

The concentration voltage drop (V_{conc}) is defined in Eq. (9)

$$V_{conc} = \ell_1 - \ell_2\left(T-273\right)e^{\ell_3 I} \quad (9)$$

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The ohmic voltage drop (V_{ohm}) is almost linear in nature and become using Eq. (10) as,

$$V_{ohm} = IR_{mem} \text{ and } R_{mem} = \frac{t_m}{\sigma} \qquad (10)$$

Where, R_{mem} is membrane resistance, t_m is membrane viscosity and σ is conductivity. An empirical different equation is used to determine the proton (C_H^+), Eq. (11) and (12) can be used to estimate the membrane conductivity (σ) as,

$$\frac{dC_{H^+}}{dt} + \frac{C_{H^+}}{\tau_{H^+}} = \frac{1+\alpha_H + I^3}{\tau_{H^+}} \qquad (11)$$

$$\sigma = \frac{F^2}{RT} D_{H^+} C_{H^+} \qquad (12)$$

The I-V characteristics of FC are shown in Fig. 2 as,

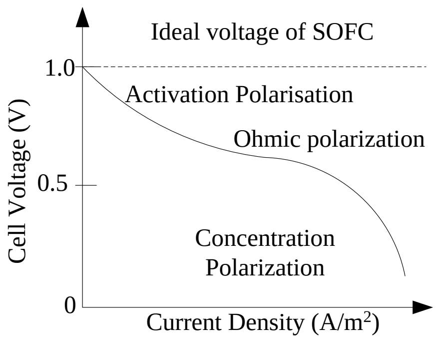

Fig. 2 Typical I-V characteristic of SOFC.

IV. Power Electronics Interface

(a) DC- DC boost converter

A DC-DC boost converter is used to boost the DC voltage and supplied suitable DC power to the load [15-16]. The duty ratio of DC-DC boost converter is expressed by Eq. (13) as,

$$Duty \ ratio = 1 - \frac{V_{in}}{V_{out}} \qquad (13)$$

The main applications of this circuit are in regulated dc power supplies, where a negative polarity output may be desired with respect to the common terminals of the input voltage and the average output is either higher dc input voltage. A boost converter circuit is a combination of the Boost converter topology in cascade. The output to input conversion ratio is also a product of ratios in the boost converter. The output voltage is controlled by controlling the switch duty cycle.

Schematic diagram of DC/DC boost converter is shown in Fig. 3 as,

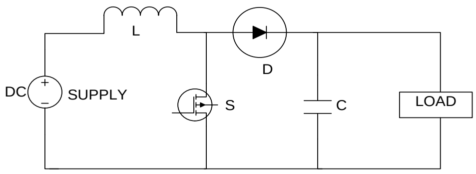

Fig. 3. Schematic diagram of a boost converter.

(b) Inverter

Inverter is an electronic device that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source [17-18]. A power inverter can be entirely electronic or may be a combination of mechanical effects (such as a rotary apparatus) and electronic circuitry. Static inverters do not use moving parts in the conversion process.

V. Results and Discussion

The performance of designed model of SOFC system for distributed generation is investigated under variable resistive load application. Following results have been obtained to validate the model as,

- Voltage, current and power of SOFC
- System performance analysis with DC load
- System performance analysis with AC load
- Harmonic analysis of load current of the system

The SOFC stacks generated output voltage, current and power are shown in Fig. 5 as,

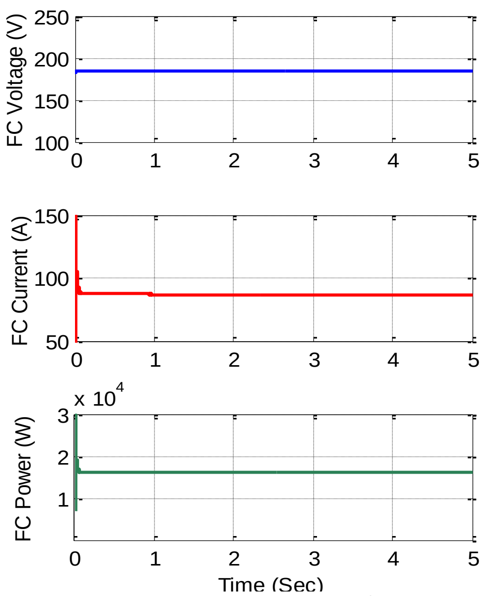

Fig. 5. Output voltage, current and power of SOFC stack.

DC-DC boost converter output voltage of SOFC stacks are shown in Fig 6 as,

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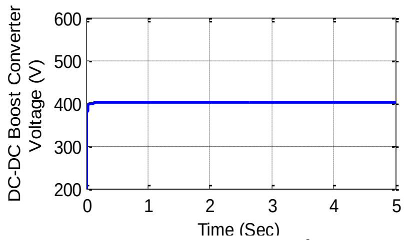

Fig. 6 DC-DC Boost converter performances.

Voltage, current and power of DC load is shown in Fig. 7 as,

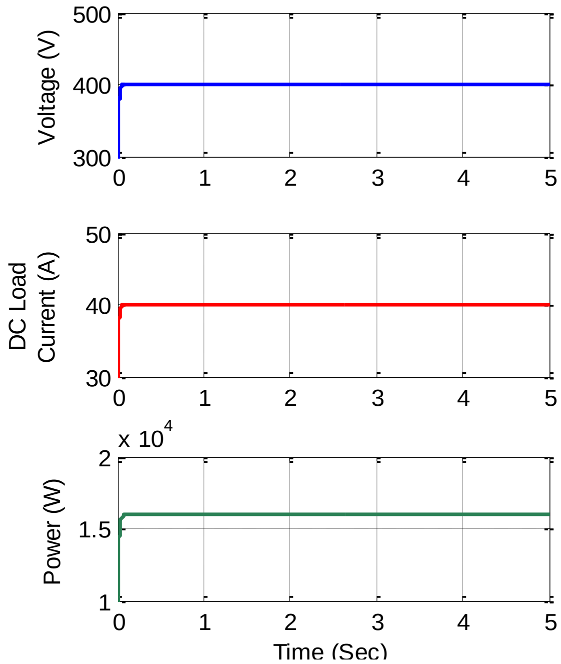

Fig. 7 Voltage, current and power across DC load.

The PWM converter output voltage, voltage and current at the load side are shown in Fig. 8. The THD analysis of load current is shown in Fig 9.

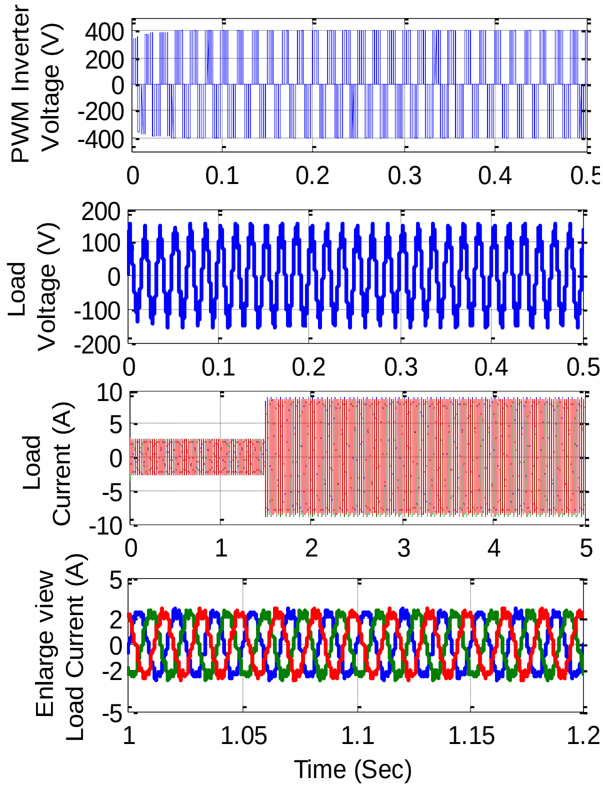

Fig. 8. PWM converter output voltage, load voltage and current.

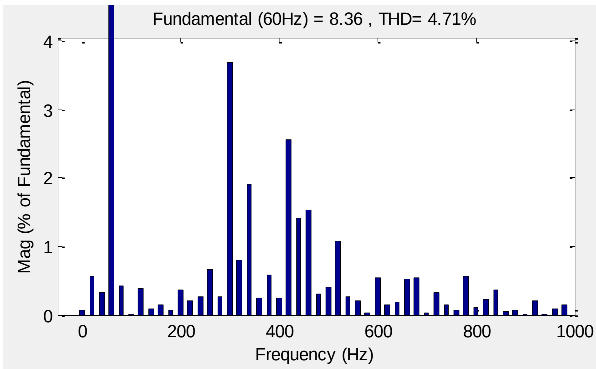

Fig. 9 THD analysis of load current (A)

The parameters of the analyzed system are summarized in Table 3 as,

Table 3. Summary of system parameters.

Parameters		Voltage (V)	Current (A)	Power (W)
SOFC		183.85	87.1	1600
DC/DC converter		400	-	-
Inverter		400	-	-
DC load		400	40	1600
AC load	20 kW	147	2.4	-
	50 kW	147	8.55	-

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VI. CONCLUSION

In this paper a SOFC system has been proposed for distribution power generation system. Furthermore, a study and comparison of various FCs and their operating parameters, advantages, drawbacks as well as applications are presented in detail. A mathematical study of SOFC has been done. The polarization curve (I-V characteristics) with voltage drops are discussed. The SOFC based DG system under consideration is modeled and simulated in MATLAB/Simulink environment and the performance has been investigated with both AC and DC loads. The harmonic analysis and THD of the load current have been shown for power quality point of view.

Appendix I

Reference potential,(E_0)	1.229 V
Universal gas const., (R)	8.314 Jmol^{-1}K^{-1}
Faraday constant, (F)	9.6485 C mol^{-1}
Stack temperature, (T)	353 K
Fuel cell pressure, (P)	1.2 atm
Ambient pressure, (P_{amb})	1 atm
Anode volume, (V_{anode})	0.0159 m^3
Cathode volume, ($V_{cathode}$)	0.0025 m^3
Anode flow const. (k_{anode})	0.004 mols^{-1} atm^{-1}
O_2 Gas Constant, (R_{O_2})	1.185×10^{-3} J kg^{-1} K^{-1}
H_2O pressure, (P_{H_2O})	2.032 atm
H_2 Gas Constant, (R_{H_2})	0.00125 J kg^{-1}K^{-1}
Membrane resistance (R_{mem})	0.0056 Ω
Mass of H_2O at Cath., (m_{H_2O})	18.0×10^{-3} kg mol^{-1}
H_2O Molar flow rate, (Q_{H2O})	0.0298 mol sec^{-1}
ς_1 , ς_2	0.951, 3.12×10^{-3}
ς_3 , ς_4	1.8×10^{-4}, 7.4×10^{-5}
Membrane Cond., (σ)	45.31 kΩ^{-1} cm^{-1}
Membrane thickness, (t_m)	0.0026 cm
ℓ_1	1.1×10^{-4}
ℓ_2	1.2×10^{-6}
ℓ_3	8×10^{-3}
Mass of H_2, (m_{H_2})	0.004 kg mol^{-1}
Mass of O_2, (m_{O_2})	0.0002 kg mol^{-1}

Appendix II

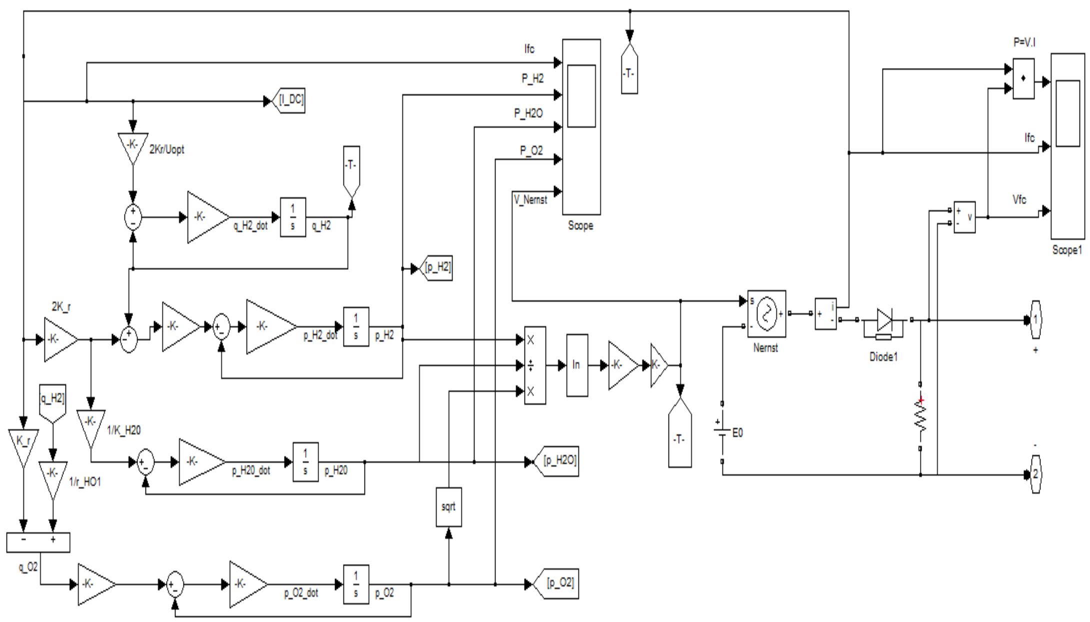

Fig. II (a). MATLAB/Simulink model of SOFC.

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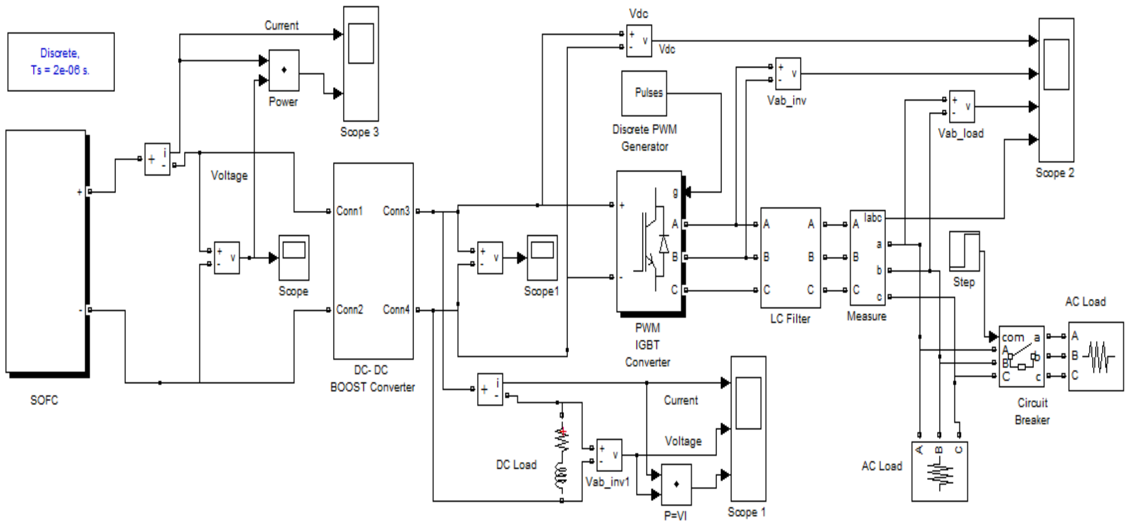

Fig. II (b). MATLAB/Simulink model of complete system.

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