

Comparative Analysis of Solid Oxide Fuel Cell with Battery Energy System

Ankit Srivastava¹ Dr.Sudhir.K.Srivastava²

^{1,2}Department of Electrical Engineering

^{1,2}Madan Mohan Malviya University of Technology, Gorakhpur, India

Abstract— This Paper presents the comparative analysis of battery energy system with SOFC technology. Use of solid oxide fuel cell and lead Acid is demonstrated for supplying utility modeled as infinite bus through DC/AC conversion. MATLAB simulation for SOFC and Lead acid battery & utility interface was done to establish parameters of SOFC, Lead acid Battery and Infinite bus with respect to DC voltage and current, active and reactive power of fuel cell.

Keywords: Solid oxide fuel cell (SOFC), Lead Acid battery, Utility, Inverter, Infinite Bus

I. INTRODUCTION

Distributed generation is expected to play a vital role in the electric power production of the future. Most likely, fuel cells and battery storage system will be the dominant grid connected distributed generation system (DGs). Moreover, fuel cells are attractive because they are modular, efficient, and environmentally friendly. Fuel cells are rapidly developing generation technology. Fuel cells feature the potential for high efficiency (35_60%), low to zero emissions, quiet operation, and high reliability due to the limited number of moving parts. They produce power electrochemically by passing a hydrogen-rich gas over an anode and air over a cathode, and introducing an electrolyte in between to enable exchange of ions. The effectiveness of this process is strongly dependent upon the electrolyte to create the chemical reactivity needed for ion transport.

Cell batteries are currently the most used form of energy storage in DG. Cell batteries come in various forms and types. Important comparison criteria for different types of batteries are possible depth of discharge of the battery, cost, number of charge/discharge cycles the battery can tolerate, efficiency, self-discharge, maturity of the technology and energy density. The battery energy storage system (BESS) comprises mainly of batteries, control and power conditioning system (C-PCS) and rest of plant. The rest of the plant is designed to provide good protection for batteries and C-PCS. The battery and C-PCS technologies are the major BESS components and each of these technologies is rapidly developing.

II. MODELING OF SOFC SYSTEM

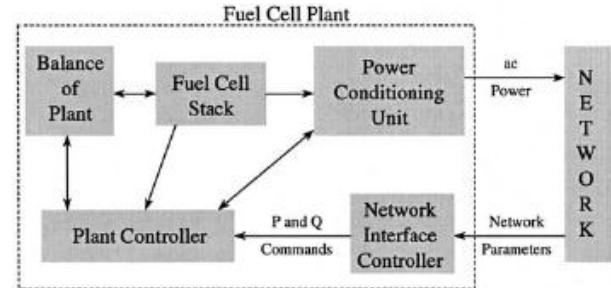


Fig. 1: Structure of Fuel Cell Plant

Figure.1 shows the structure of a generic fuel cell plant as describe in ref.[4],which is perfectly applicable SOFC technology.

A. Fuel Cell Stack Model

Fuel cells are a promising technology for producing electrical energy. The main issues that complicate the design of efficient and robust fuel cells are related to electrode heating and corrosion. However fuel cells are expected to play an important role in distributed generation.

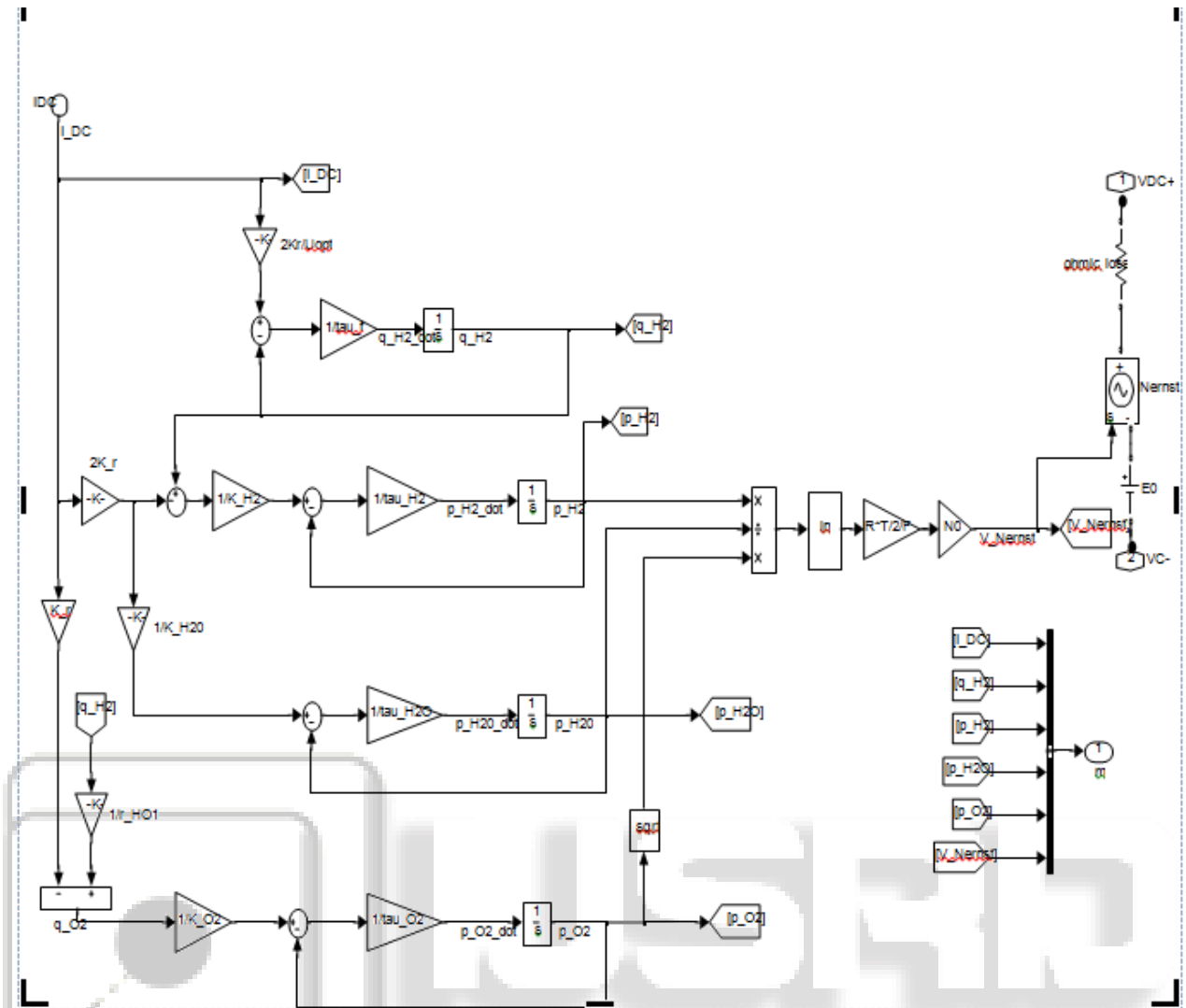
B. Model Assumption [1]

- Fuel cell gases are ideal.
- Only one pressure is defined in the interior of the electrodes.
- The only source of losses is ohmic.
- The fuel cell temperature is invariant.
- Nernst's equation applies.

C. Characterisation Of The Exhaust Of The Channels

According to Ref. [7], an orifice that can be considered choked, when fed with a mixture of gases of average molar mass M (Kg/kmol) and similar specific heat ratios, at a constant temperature, meets the following characteristic:

$$\frac{w}{P_A} = K\sqrt{M} \quad (1)$$



where W is the mass flow [kg/s]; K is the valve constant, mainly depending on the area of the orifice [$\sqrt{(\text{kmolkg}/(\text{atm s}))}$]; p_u is the pressure upstream (inside the channel) [atm]. For the particular case of the anode, the concept of fuel utilization U_f can be introduced, as the ratio between the fuel flow that reacts and the fuel flow injected to the stack. U_f is also a way to express the water molar fraction at the written as:

$$\frac{W_{an}}{P_{an}} = K_{an} \sqrt{(1 - U_f) M_{H_2}} + U_f M_{H_2O} \quad (2)$$

where W_{an} is the mass flow through the anode valve [kg/s];

K_{an} is the anode valve constant [$\sqrt{(\text{kmolkg}/(\text{atm s}))}$]; M_{H_2} , M_{H_2O} are the molecular masses of hydrogen and water, respectively [kg/kmol]; P_{an} is the pressure inside the anode channel [atm].

If it could be considered that the molar flow of any gas through the valve is proportional to its partial pressure inside the channel, according to the expressions:

$$\frac{q_{H_2}}{P_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \quad (3)$$

And

$$\frac{q_{H_2O}}{P_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} \quad (4)$$

Where q_{H_2} , q_{H_2O} are the molar flows of hydrogen and H_2 H_2O water, respectively, through the anode valve [kmol/s]; P_{H_2} , P_{H_2O} are the partial pressures of hydrogen and water respectively [atm]; K_{H_2} , K_{H_2O} are the valve molar constants for hydrogen and water, respectively [kmol/(s atm)], the following expression would be deduced:

$$\frac{W}{P_{an}} = K_{an} [(1 - U_f) \sqrt{M_{H_2}} + U_f \sqrt{M_{H_2O}}] \quad (5)$$

The comparison of Eqs.(2) and (5) shows that for $U_f > 70\%$ the error is less than 7%. It is possible to redefine slightly Eqs. (3) and (4) so that the error is even lower. This error shows that it may be reasonable to use Eqs.(3) and (4). The same study for the cathode shows that the error in that valve is even lower, because of the similar molecular masses of oxygen and nitrogen.

D. Calculation Of The Partial Prssures

Every individual gas will be considered separately, and the perfect gas equation will be applied to it. Hydrogen will be considered as an example.

$$P_{H_2} V_{an} = n_{H_2} RT \quad (6)$$

where V_{an} is the volume of the anode; n_{H_2} is the number of hydrogen moles in the anode channel; R is the universal gas constant [(1 atm) / (kmol K)]; T is the absolute temperature [K]. It is possible to isolate the pressure and to take the time derivative of the previous expression, obtaining:

$$\frac{d}{dt} P_{H_2} = \frac{RT}{V_{an}} q_{H_2} \quad (7)$$

where q_{H_2} is the time derivative of n_{H_2} , and represents the hydrogen molar flow [kmol/s]. There are three relevant contributions to the hydrogen molar flow: the input flow, the flow that takes part in the reaction and the output flow thus:

$$\frac{d}{dt} P_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^r) \quad (8)$$

Where $q_{H_2}^{in}$ is the input flow [kmol/s]; $q_{H_2}^{out}$ is the output flow [kmol/s]; $q_{H_2}^r$ is the hydrogen flow that reacts [kmol/s].

According to the basic electrochemical relationships the molar flow of hydrogen that reacts can be calculated as:

$$q_{H_2}^r = \frac{N_0}{2F} = 2K_r I \quad (9)$$

Where N_0 is the number of cells associated in series in the stack; F is the Faraday's constant [C/kmol]; I is the stack current [A]; K_r is a constant defined for modeling purposes [kmol/(s A)].

Returning to the calculation of the hydrogen partial pressure, it is possible to write:

$$P_{H_2} = \frac{1}{1 + \tau_{H_2} s} (q_{H_2}^{in} - q_{H_2}^{out} - 2K_r I_i) \quad (10)$$

Replacing the output flow by Eq.(3), taking the Laplacetransform of both sides and isolating the hydrogen partial pressure, yields the following expression:

$$P_{H_2} = \frac{1}{1 + \tau_{H_2} s} (q_{H_2}^{in} - 2K_r I_i) \quad (11)$$

Where $\tau_{H_2} = (V_{an}) / (K_{H_2} RT)$ expressed in seconds, is the value of the system pole associated with the hydrogen flow.

E. Calculation Of Stack Voltage

Applying Nernst's equation and Ohm's law (to consider ohmic losses), the stack output voltage is represented by the following expression[7]:

$$V = N_0 \left(E_0 + \frac{RT}{2F} \left[\ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2 O}} \right] \right) - rI \quad (12)$$

where E_0 is the voltage associated with the reaction free energy [V]; R is the same gas constant as previous, but care should be taken with the system unit [J/(kmol/K)]; r describes the ohmic losses of the stack[Ω].

III. MODELLING OF LEAD ACID BATTERY

The battery is modelled using a simple controlled voltage source in series with a constant resistance, as shown in Fig. 1. This model assumes the same characteristics for the charge and the discharge cycles. The open voltage source is calculated with a non-linear equation based on the actual SOC of the battery[8].

$$E = E_o - K \frac{Q}{Q-it} + A \exp(-B \cdot it) \quad (13)$$

$$V_{batt} = E - rI \quad (14)$$

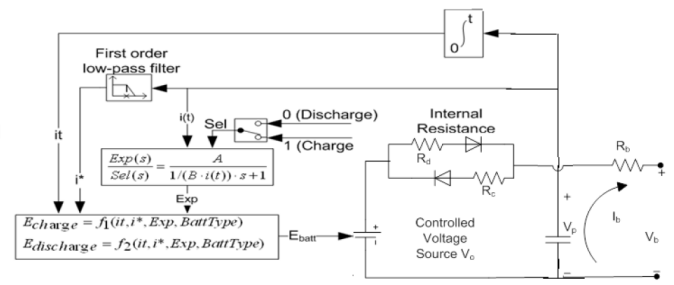


Fig. 3: Non Linear Battery Model

where

E = no-load voltage (V)

E_o = battery constant voltage (V)

K = polarisation voltage (V)

Q = battery capacity (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse

V_{batt} = battery voltage (V)

R = internal resistance (Ω)

i = battery current (A)

A. Model Assumption

- The internal resistance is supposed constant during the charge and discharge cycles and doesn't vary with the amplitude of the current.
- The model's parameters are deduced from the discharge characteristics and assumed to be the same for charging.
- The capacity of the battery doesn't change with the amplitude of the current (No Peukert effect).
- The temperature doesn't affect the model's behaviour.
- The Self-Discharge of the battery is not represented.
- The battery has no memory effect[7].

IV. POWER ELECTRONICS INTERFACE

In practical usage, SOFC is linked to ac networks through a shunt connected VSC device. AC voltage magnitude V_n is regulated by means of the VSC inverter modulating amplitude a_m .

$$a_m = (K_m (V^{ref} - V_h) - a_m) / T_m \quad (15)$$

Amplitude control has limiter set point

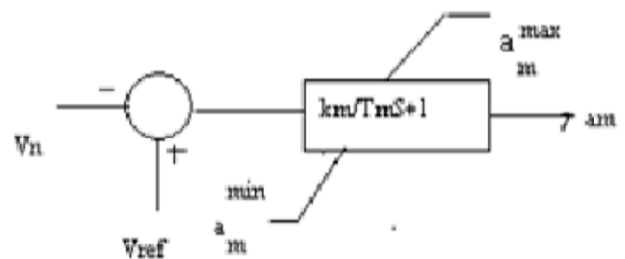


Fig. 4: A.C. Voltage Control Of Solid oxide fuel cell

Fuel cell dc current set point i_{dc}^{ref} is defined based on power reference $P^{ref} \times i_{dc}^{ref}$ set point is limited by dynamic limits proportional to the hydrogen flow:

$$U^{min} q_2^H / 2K_r \leq i_{dc}^{ref} \leq U^{max} q_2^H / 2K_r \quad (16)$$

U_{max}^{min} are hydrogen gas flow limiter set point.

Current i_{dc} is regulated the VSC firing angle α by mean of controller.

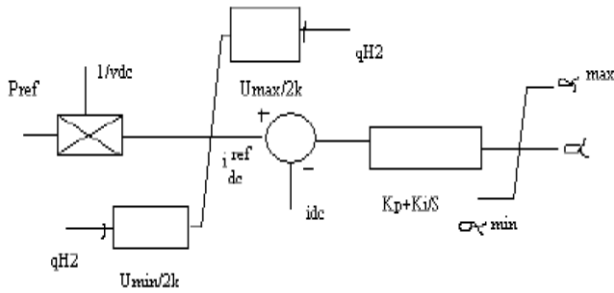


Fig. 5: Power control of Solid Oxide Fuel Cell

A. Voltage Source Converter Model

It is a simplified dynamic model. VSC can be modeled taking in to account only power balance and simplified control equation.

If the power flow is from dc side to ac one, power balance is

$$0 = V_{ac}i_{dc} - P_{ac} - P_{loss}(i_{dc}v_{dc}) \quad (16)$$

P_{loss} is commutation and conduction loss of switch diodes and capacitor.

Simplified control equations do not explicitly include the firing angle α and the modulating amplitude is a_m , but only

considers input and output variables. Hence to regulate active and reactive powers on the ac side, the control differential equations can be written as

$$P_{ac} = (P^{ref} - P_{ac})T_p \quad (17)$$

And

$$q_{ac} = (q^{ref} - q_{ac})T_q \quad (18)$$

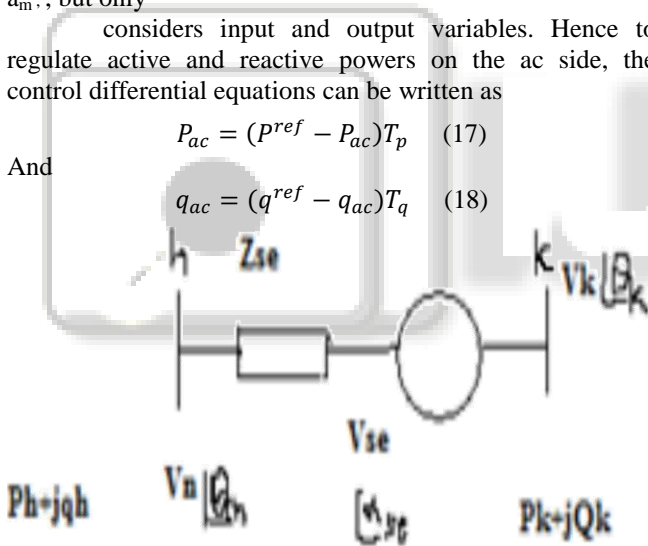


Fig. 6: Modelling Of Mixed Load as Utility

B. Modelling Of Infinite Bus

Utility has two main parameters voltage and frequency. Also since utility is modeled as infinite bus which is represented as constant voltage bus with $V_t=1pu$. Thus modeling of utility (infinite bus) can be as voltage dependent and also as frequency dependent either as dependable or as independent source.

Figure shows combination of voltage and frequency dependent representation while figure shows voltage and frequency dependent inputs to a constant (v,f) representation as independent representation. Output variables are vector

V_h and X_0 .

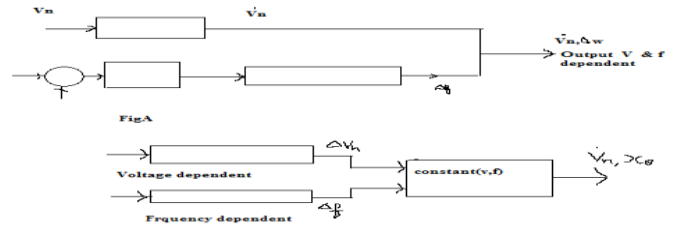


Fig. 7: Model for Infinite Bus

V. CIRCUIT DESCRIPTION

The system consists of a SOFC which is connected to a 3 ϕ Infinite Bus through an IGBT inverter. The inverter uses hysteresis switching and controls active power by manipulation of direct axis current while holding reactive power at 0Var. The measurement blocks are rated at 50KW. Therefore, an active power reference of 1pu=50Kw.

Simulation:

At $t=0s$, an active power reference (P_{ref}) of 0.3pu is commanded. Observe that the reference is captured within 0.2s. At $t=0.4s$, $P_{ref}=1pu$ is commanded. Again the ref is captured within 0.2s. Observations of the H_2 , H_2O and O_2 pressure shows that the fuel cell does not reach a new equilibrium for the simulation of duration 1sec. Extended simulation periods are required to observe the dynamics of chemical reaction.

VI. PARAMETER OF SOFC SYSTEM MODEL

We assume the rated power of this SOFC system is 100 kW. The model parameters are updated from [5] and listed in Table 1.

| Parameter | Representation | Value |
|---------------|--|-------------------------------------|
| P_{rate} | Rated power | 100 kW |
| P_{ref} | Real power reference | 100 kW |
| T | Absolute temperature | 1273 K |
| F | Faraday's constant | 96 487 C/mol |
| R | Universal Gas constant | 8314 J/(kmol K) |
| E_0 | Ideal standard potential | 1.18 V |
| N_0 | Number of cells in series in the stack | 384 |
| K_r | Constant | 0.996×10^{-6} kmol/(s A) |
| U_{max} | Maximum fuel utilization | 0.9 |
| U_{min} | Minimum fuel utilization | 0.8 |
| U_{opt} | Optimal fuel utilization | 0.85 |
| K_{H_2} | Valve molar constant for hydrogen | 88.43×10^{-4} kmol/(s atm) |
| K_{H_2O} | Valve molar constant for water | 2.81×10^{-4} kmol/(s atm) |
| K_{O_2} | Valve molar constant for Oxygen | 2.52×10^{-4} kmol/(s atm) |
| τ_{H_2} | Response time for hydrogen flow | 26.1 s |
| τ_{H_2O} | Response time for water flow | 78.3 s |
| τ_{O_2} | Response time for oxygen flow | 2.91 s |
| r | Ohmic loss | 0.126 Ω |
| T_e | Electrical response time | 0.8 s |
| T_f | Fuel processor response time | 5 s |
| r_{H_2O} | Ratio of hydrogen to oxygen | 1.145 |
| PF | Power factor | |

VII. SIMULATION CIRCUIT

This simulation circuit basically divided into four main sections these are as follows

- (1) Solid Oxide fuel Cell/Battery It acts as source for the simulation circuit in this battery there are 450 fuel cells are connected in series.
- (2) Lead acid Battery
- (3) Power Conditioner The power conditioner converts dc power to ac power out and includes current, voltage and frequency control.

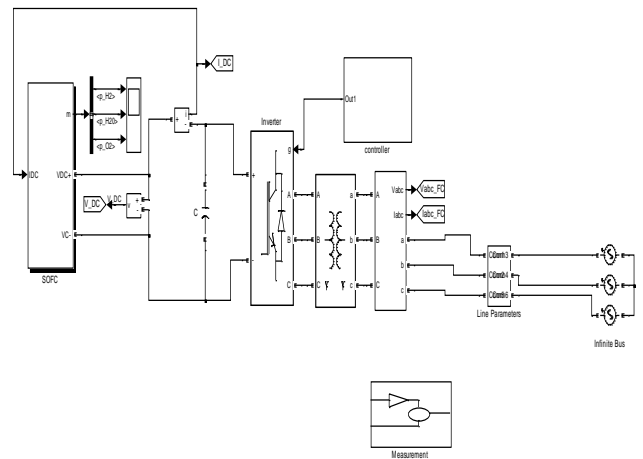


Fig.8.Solid Oxide Fuel Cell connected to Three-Phase Electrical system

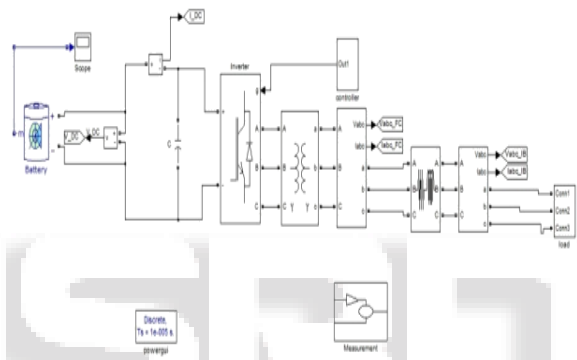


Fig. 9:Li-ion Battery connected to Three-Phase Electrical System

VIII. RESULT AND DISCUSSION

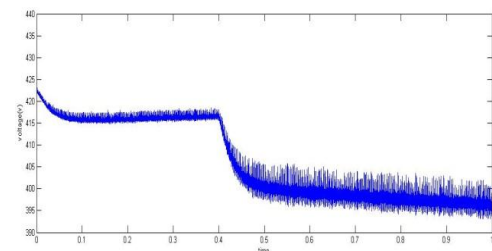


Fig. 9: D.C. Output voltage of Solid oxide fuel cell having settling time of.4s and output voltage is 420pu.

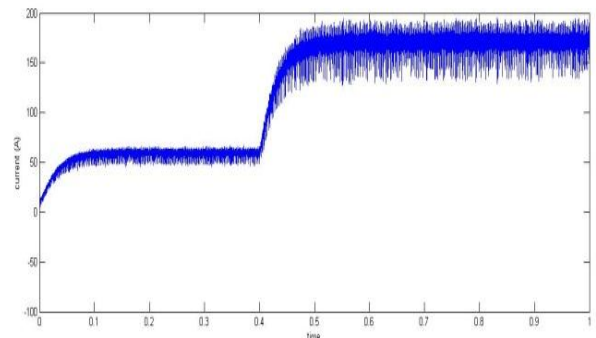


Fig. 10: D.C. Output Current of Solid oxide fuel cell having settling time of.4s and Output current is 200pu.

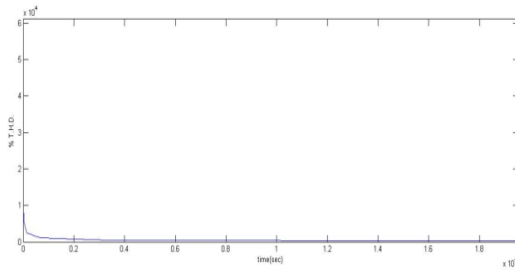


Fig. 11: %THD at Load terminal of Solid oxide fuel cell

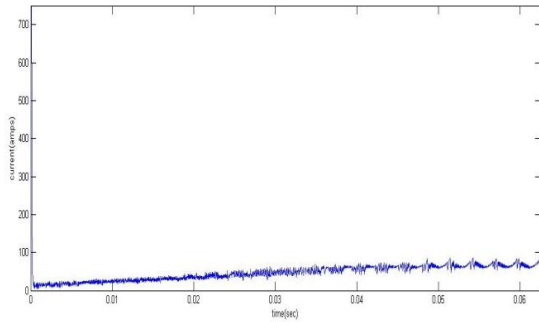


Fig. 12: D.C. Output voltage of Lead Acid baatery

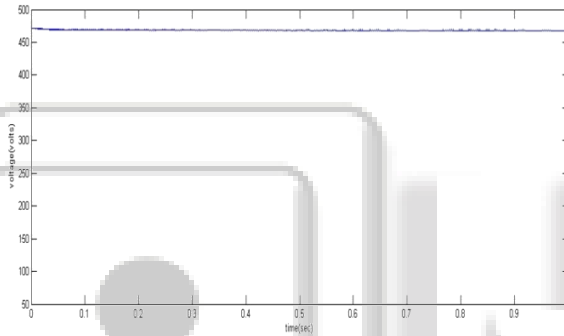


Fig. 13: D.C. Output current of lead acid battery

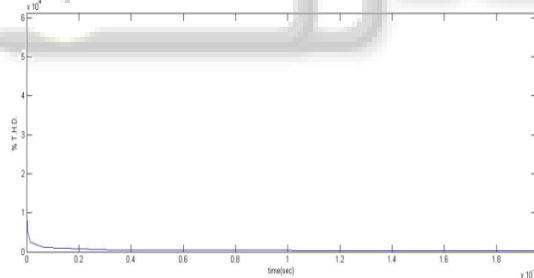


Fig. 14: %THD at Load terminal of Solid oxide fuel cell

| Parameter | SOFC | Lead Acid |
|------------|------------|------------|
| Efficiency | Nearly 60% | Nearly 70% |
| V_{dc} | 420 Volts | 425 Volts |
| T.H.D. | 3.5% | 5.2% |

Table 8.2: Comparison between SOFC and Storage Battery

We have developed a fuel cell which has 450 numbers of fuel cells in series connection. The FC is designed for 420 DC output voltages as shown in Fig.9. The DC current of the FC is shown in Fig. 10. It has a value typically 200 A .The Fig 11 is the graph between % THD and time for fuel cell. Fig 12 and Fig 13 represent the output current and voltage of battery storage system and figure 14 is the graph between %THD and time for lead acid battery

IX. CONCLUSION

Interfacing of solid oxide fuel cell with utility (infinite bus) is obtained with simulation in MATLAB.Interface between solid oxide fuel cell and utility was based on power electronics DC/AC conversion technology. Simulation results V_{dc} , I_{dc} , PQ , V_{abc} & I_{abc} suggest application of SOFC interface with utility for isolated consumer or isolated installation. SOFC interface with infinite bus can be distributed generation application.Thus proposed work has established and developed SOFC interface with utility. Dynamic modeling of solid-oxide fuel cell with three phase inverter has been performed to analyze its load behavior as distributed generator in a grid connected power system. The response of the system to step changes in load demand are presented along with the analysis of the simulated results. It has been observed that the fluctuations in the output voltages in the power system due to load variations are taken care of by the SOFC very closely. An efficient dynamic model of Solid Oxide Fuel Cell has also been developed which can supply active power maintaining inverter voltage as desired. The combined system reduces the cost of power generation as well as the level of pollution reducing the fuel consumption enables comprehensive quantitative and qualitative analysis

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