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Modeling Design of Solid Oxide Fuel Cell Power System for Distributed Generation Applications

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***Abstract*— Fuel cell technology is a relatively new energy-saving technology that has the potential to compete with the conventional existing generation facilities. Among the various Distributed Generation or onsite generation or localized generation technologies available, fuel cells are being considered as a potential source of electricity because they have no geographic limitations and can be placed anywhere on a distribution system. Fuel cells have numerous benefits which make them superior compared to the other technologies. The integration of the fuel cell system is to provide the continuous power supply to the load as per the demand. In this paper, design and modeling of Solid Oxide Fuel cell (SOFC) is discussed for the distributed generation applications. Modeling and simulations are carried out in MATLAB Simulink platform. Solid oxide fuel cells operate at temperatures near l0000C these are highly efficient combined heat and electric power. Modeling of SOFC is done by using by using Nernst equation. In that the output power of the fuel cell can be controlled by controlling the flow rate of the fuels used in the process. The fuel cell source is integrated with the DC – DC boost converter to stabilize the voltage from the fuel cell. CUK converter is used for Power Factor Pre-regulators in discontinuous Conduction Mode. The output of the CUK type boost converter is then fed to the three phase PWM inverter to get the suitable form three phase output voltages for the grid connected applications.**

***Index Terms*— Fuel Cell, SOFC, Distributed Generator, DC-DC converter, Simulink**

I. Introduction

Distributed generation is referred in general to small generators, starting from a few kW up to 10 MW, whether connected to the utility grid or used as stand-alone at an isolated site. Normally small DGs, in the 5-250 kW range serve households to large buildings (either in isolated or grid-connected configuration). DG technologies can be categorized to renewable and nonrenewable DGs. Renewable energy technologies are in general sustainable (i.e., their energy source will not run out) and cause little or no environmental damage; they include: Solar photovoltaic, Solar thermal, Wind, Geothermal, Tidal, Low-head (small) hydro, Biomass and biogas and Hydrogen fuel cells (hydrogen generated from renewable resources). Nonrenewable energy technologies are referred to those that use some type of fossil fuel such as gasoline, diesel, oil, propane, methane, natural gas, or coal as their energy source. Fossil fuel-based DGs are not considered sustainable power generation sources as their energy source will not renew. They include: Internal combustion engine (ICE), Combustion turbine, Gas turbine, Micro turbine and Fuel cells (using some type of fossil fuel, e.g. natural gas to generate hydrogen).

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Both types of DGs (renewable and nonrenewable) are popular and widely used around the world. The downside of renewable resource DGs is the intermittent nature of their renewable energy source; and the disadvantage of fossil fuel-based DGs is that they generate environmentally polluting, and in some cases poisonous exhaust gases, such as SO_2 and NO_x, which are similar to the pollutants from conventional centralized power plants. However, considering the increasing need for electricity, the benefits of the nonrenewable DG technologies with low emission of polluting gasses exceed their disadvantages and are expected to be used in the foreseeable future.

Fuel cell technology can belong to either of the above categories. If the hydrogen fuel needed to power the fuel cell is generated from a renewable source, the fuel cell power generating unit is considered a renewable energy technology. i.e., wind and solar energy used to generate hydrogen to fuel a fuel cell stack. On the contrary, if hydrogen is produced from a fossil fuel source (e.g., natural gas or methane), the fuel cell is considered a nonrenewable energy technology. Through careful design, selected fossil fuel driven DGs can be built to oxidize some of the fossil fuel (by combining with oxygen) to produce heat. Such operation modes, whether in electromechanical (rotational) or electrochemical (fuel cell) systems, are referred to as combined heat and power (CHP) operation mode.

Most of the new DG technologies include power electronic devices to provide usable output power. These DGs are often referred to as power electronically interfaced DGs. Enormously improved power control of these generation sources has become possible by controlling their power electronic interfacing units. In a common approach the output voltage of these generation devices whether dc or ac is converted to a controlled output voltage.
Fuel cells are being considered as a potential source of electricity among the various Distributed Generation technologies available. Fuel cells have numerous benefits

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which make them superior compared to the other technologies. The integration of the fuel cell system is to provide the continuous power supply to the load as per the demand. In the fuel cell energy system which is used for the distributed generation applications, the source is integrated with the DC – DC boost converter to stabilize the voltage from the fuel cell. The output of the boost converter is then fed to the three phase PWM inverter to get the three phase ac voltage for the grid connected applications. The overall block diagram of the fuel cell energy system is shown in figure 1.

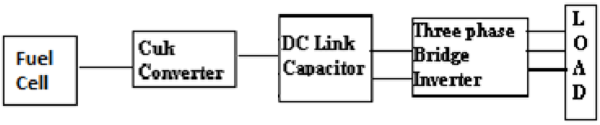

Figure 1 Block Diagram of Hybrid Wind/Fuel cell energy System

II. Fuel Cells

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into dc electrical energy. Fuel cells have a wide variety of potential applications including micro power, auxiliary power, transportation, stationary power for buildings, and cogeneration applications. Fuel cells have various advantages compared to conventional power sources, such as internal combustion engines or batteries. Although some of the fuel cells' attributes are only valid for some applications, most advantages are more general. However, there are some disadvantages facing developers and the commercialization of fuel cells as well. Fuel cells eliminate pollution caused by burning fossil fuels; the only by product is water. Since hydrogen can be produced anywhere where there is water and e lectricity, production of potential fuel can be distributed. The other advantages with fuel cells are as follows; Installation of smaller stationary fuel cells leads to a more stabilized and decentralized power grid, Fuel cells have a higher efficiency than diesel or gas engines, Most fuel cells operate noise less, compared to internal combustion engines, Low temperature fuel cells (PEM, DMFC) have low heat transmission which makes them ideal for military applications, Earning of carbon credits by using this fuel-cell technology. However, they are attributed to some of the drawbacks; Fuelling fuel cells is still a problem since the production, transportation, distribution and storage of hydrogen is difficult, Reforming hydrocarbons via reformer to produce hydrogen is technically challenging and not clearly environmentally friendly. Fuel cells are in general slightly bigger than comparable batteries or engines. However, the size of the units is decreasing. Some fuel cells are expensive.

Fuel cells Working principle:

The structure and the functioning of a fuel cell are similar to that of a battery except that the fuel can be continuously fed into the cell. The physical structure of a fuel cell consists of two porous electrodes (anode and cathode) and an electrolyte layer in the middle. The Schematic of individual fuel cell is shown in figure 2(a). Figure 2(b) shows the basic workings of a fuel cell with positive ion flow through the electrolyte, which is based on electrochemical principles. Hydrogen and oxygen molecules combine to form water. The process is caused by the fact that charged particles migrate toward regions of lower electrochemical energy. The charged hydrogen and oxygen particles move toward each other and bond to one another because the final product of this reaction has a lower overall electrochemical energy. Electrical energy is generated as a result of the movement of the charged hydrogen and oxygen particles, which is essentially the controlled movement of electrons.

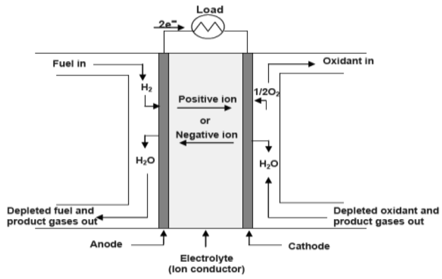

Figure 2(a): Schematic of individual fuel cell

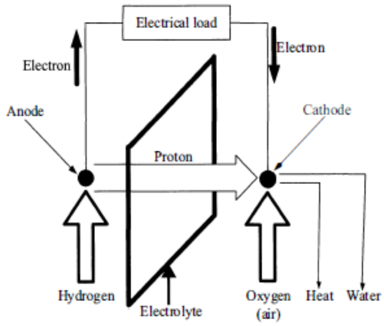

Figure 2(b): Working of individual fuel cell

By breaking the hydrogen molecules to electrons and positive ions (protons), with the help of a catalyst to facilitate faster reaction, the protons move from the cathode to anode through the membrane (electrolyte), but the electrons cannot. The electrons travel through an external electrical circuit (load) to recombine with the hydrogen protons and oxygen molecules at the cathode (again, with the help of the catalyst) to produce water. The actual chemical reaction inside a hydrogen fuel cell can be broken down into two half reactions, the oxidation half reaction and the reduction half reaction. The oxidation half reaction, represented by (1), shows the dissociation of hydrogen molecules to protons and electrons at the anode. After the dissociation, the protons are free and pass through the electrolyte, and recombine with the electrons (which move through the external circuit) at the cathode. In this process, which is often called the reduction half reaction, the electrons and hydrogen protons combine with the oxygen molecules from the surrounding air, according to (2), to form water.

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

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

The type and chemical properties of the electrolyte used in fuel cells determine their operating characteristics and internal operating temperature. The polarity of an ion and its transport direction can differ for different fuel cells, determining the site of water production and removal. If the working ion is positive, like shown in Fig. 2(b), then water is produced at the cathode. On the contrary, if the working ion is negative, like in solid oxide fuel cell and molten carbonate

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fuel cell, water is formed at the anode. In both cases electrons pass through an external circuit and produce electric current.

An individual fuel cell produces less than a volt of electric potential. A large number of cells are stacked on top of each other and connected in series (with bipolar connects) to produce higher voltages. Figure shows cell stacks which consists of repeating units, each comprising an anode, cathode, electrolyte and a bipolar separator plate. The number of cells depends on the desired power output.

Types of fuel cells:

Fuel cells are generally classified by the type of electrolyte they use, and the choice of electrolyte dictates the range of their operating temperature and the degree of fuel processing required. Low-temperature fuel cells are generally limited to temperatures below or around 200°C because high-temperature vapor causes rapid degradation of their electrolyte material. The most common type of low-temperature fuel cells are alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), and polymer electrolyte membrane (PEMFC). In these fuel cells all the fuel must be converted to hydrogen prior to entering the fuel cell. In addition, the catalyst used in these fuel cells (mainly platinum) is strongly poisoned by carbon monoxide (CO). Therefore, the hydrogen entering these fuel cells needs to be pure. This is a downside of the low-temperature fuel cells. In high-temperature fuel cells, CO and even hydrocarbons (e.g., CH4) can be internally converted to hydrogen or even directly oxidized. The
most common types of high-temperature fuel cells are molten carbonate fuel cell (MCFC) with operating temperature range of 600-700°C, and solid oxide fuel cell (SOFC) operating in the temperature range of 600-1000° C. As SOFC are highly efficient combined heat and electric power [5], they are considered for the study in this paper. Modeling of SOFC is done by using by using Nernst equation. In that the output power of the fuel cell can be controlled by controlling the flow rate of the fuels used in the process [6][7].

The different types of fuel cells have slightly different chemical reactions, but the same electrochemical reaction is the backbone of all of them. Because of the differences in their operating characteristics and fuel used, different types of fuel cells are suited for different applications.

In addition to the above types of fuel cells, there is another category of fuel cells, which can utilize non-hydrogen fuels directly without internal or external reforming process. Two common types in this category are direct methanol fuel cell (DMFC) and direct carbon fuel cell (DCFC). DMFC, also called direct alcohol fuel cell (DAFC), is a low-temperature polymer electrolyte fuel cell, which uses alcohol as fuel without reforming.

III. SOLID OXIDE FUEL CELL (SOFC)

The SOFC is a high-temperature operating fuel cell which has high potential in stationary Applications. The efficiency of SOFC is in the range of 45-50%. It is a solid-state device that uses an oxide ion conducting non-porous ceramic material as an electrolyte. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. Corrosion is less compared to MCFC and no water management problems as in PEMFCs due to the solid electrolyte. High temperature operation removes the need for a precious-metal catalyst, thereby reducing the cost. It also allows SOFCs to reform fuels internally. The electrolyte used is a ceramic oxide (yttrium stabilized zirconium). The anode used is nickel-zirconia cermets and the cathode is a strontium doped lanthanum magnetite. The use of ceramic materials increases the cost of SOFCs. High operating temperature requires stringent materials to be used which further drives up the cost. Intermediate-temperature SOFCs cannot be used for all applications. Higher temperature is required for fuel cell micro-turbine hybrid systems. However, for smaller systems intermediate temperature SOFCs would be ideal.

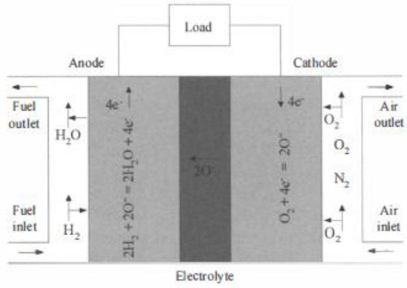

Fig. 3 Schematic of solid oxide fuel cell

Since SOFCs have fuel-flexibility, the input to the anode can be hydrogen, carbon monoxide or methane. Hydrogen or carbon monoxide may enter the anode. At the cathode, electrochemical reduction takes place to obtain oxide ions. These ions pass through the electrolyte layer to the anode where hydrogen is oxidized to obtain water. In case of carbon monoxide, it is oxidized to carbon dioxide. In this analysis, a reduced model of the fuel cell has been taken into account, neglecting the activation and concentration losses as well as the double charging effect. The loss due to internal resistance of the stack is basically due to the resistance to the flow of ions in the electrolyte as well as the material of the electrode. In general, it is mainly caused by the electrolyte. Figure shows the typical volt-amp characteristics of SOFC. Fuel cells have drooping voltage characteristics: an increase in the load current causes a decrease in the stack voltage. The number of cells is taken to be 450 and the standard cell potential is 1.18V.

Fuel Cell Plant Description:

Fuel cell produce dc power, water and heat from the combination of hydrogen produced from the fuel and oxygen from the air. In procedure where CO and CH_4 react in the cell to produce hydrogen, CO2 is also a co-product. Reactions in fuel cells depend substantially on the temperature and pressure inside the cell. A system must be built around the fuel cell to supply air and clean fuel, convert the energy to a more usable form such as grid quality ac power, and remove the depleted reactants and heat that are produced by the reactions in the cells. The block diagram representation of the SOFC dynamic model is shown in the Figure 4.

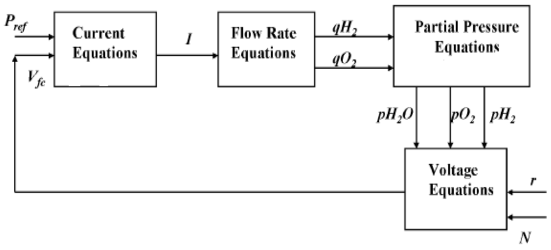

Fig.4 Block diagram for dynamic model of SOFC

IV. Modeling of SOFC Cell

The modeling of SOFC is carries out based on the assumptions made 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 is given by the

$$V_{fc} = N_0\left[E_0 + \frac{RT}{2F}\ln\left[\frac{pH_2\,pO_2^{0.5}}{pH_2O}\right]\right] - rI_{fc} \quad \rightarrow(3)$$

Where

V_{fc} – Operating dc voltage (V), Eo – Standard reversible cell potential (V), Pi – Partial pressure of species i (Pa), r – Internal resistance of stack (S), I – Stack current (A), N_0 – Number of cells in stack, R – Universal gas constant (J/ mol K), T – Stack temperature (K), F – Faraday's constant (C/mol),

The main equations describing the slow dynamics of a SOFC can be written as follows.

$$P_{ref} = V_{fc} * I_{ref}$$

→(4)

$$\frac{dI_{fc}}{dt} = \frac{1}{T_e}[-I_{fc} + I_{ref}]$$

→(5)

$$\frac{dq_{H_2}^{in}}{dt} = \frac{1}{T_f}\left[-q_{H_2}^{in} + \frac{2k_r}{U_{opt}}I_{fc}\right]$$

→(6)

$$\frac{dP_{H_2}}{dt} = \frac{1}{\tau_{H_2}}\left[-P_{H_2} + \frac{1}{K_{H_2}}\left[q_{H_2}^{in} - 2k_r I_{fc}\right]\right]$$

→(7)

$$\frac{dp_{O_2}}{dt} = \frac{1}{\tau_{O_2}}\left[-P_{O_2} + \frac{1}{K_{O_2}}\left[\frac{1}{r_{H_2O}}Q_{H_2}^{in} - 2k_r I_{fc}\right]\right]$$

→(8)

$$\frac{dp_{H_2O}}{dt} = \frac{1}{\tau_{H_2O}}\left[-P_{H_2O} + \frac{2k_r I_{fc}}{K_{H_2O}}\right]$$

→(9)

qH_2 – Fuel flow (mol/s)

qO_2 – Oxygen flow (mol/s)

KH_2 – Valve molar constant for hydrogen (kmol/s atm)

KO_2 – Valve molar constant for oxygen (kmol/s atm)

KH_2O – Valve molar constant for water (kmol/s atm)

τH_2 – Response time for hydrogen (s)

τO_2 – Response time for oxygen (s)

τH_2O – Response time for water (s)

τe – Electrical response time (s)

τf– Fuel response time (s)

Uopt – Optimum fuel utilization

rHO – Ratio of hydrogen to oxygen

Kr – Constant (kmol/s A)

Pref – Reference power (kW)

DC-DC converters:

CUK chopper is used to as dc-dc a converter which is used to boost up the dc voltages. In the cuk converter operation individual control of the output voltage of each non-convectional source is effective. In the cuk converter the magnitude of the voltage is controlled by controlling the duty-cycle of the converter. The converter circuit consists of a buck/buck-boost fused multi-input dc–dc converter and a full-bridge dc – ac inverter. The input dc voltage sources are obtained from the fuel cell is given to converter circuit. Cuk converter is also do the same operation as buck/buck-boost operation of the unbalanced source voltage.

V. Results and Discussion

The block diagram models for Matlab simulink platform are developed based on the fuel cell design made. The fuel cell system is connected to the grid by using cuk converter and by means of three phase inverter system. The performance of the system is analyzed in the presence of both converters. The results are described in the following section.

Simulink Models of Fuel Cell System

The fuel system designed in this work for distributed generated grid connected applications consists of the solid oxide fuel cell, CUK converter, three phase inverter and the load. The three phase inverter is selected because most of the loads are three phases in general. The overall simulink model diagram is shown in figure 5 and followed by the model designs of the individual blocks of SOFC, converters.

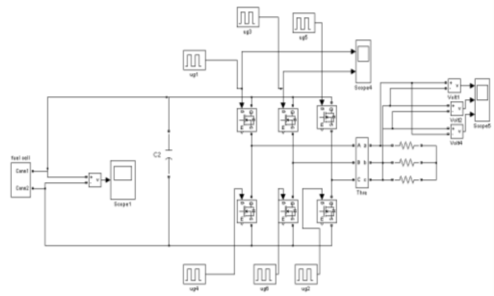

Fig.5 the overall simulink model of fuel cell power system

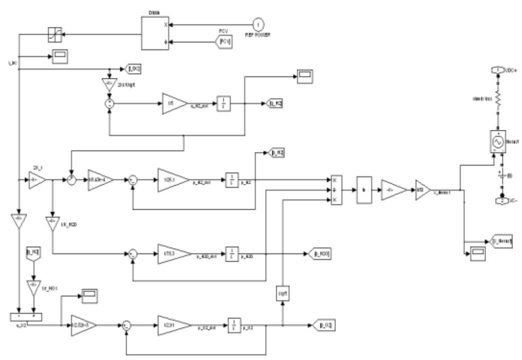

Fig. 6Simulink Model of SOFC fuel cell

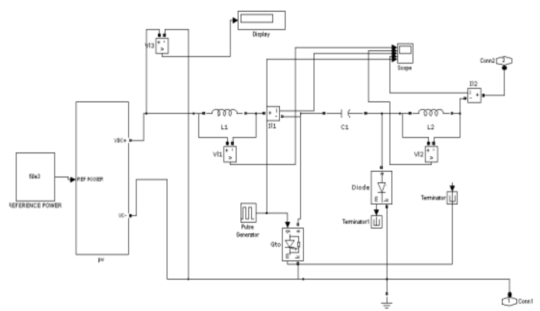

Fig. 7Simulink Model of SOFC fuel cell with Cuk Converter

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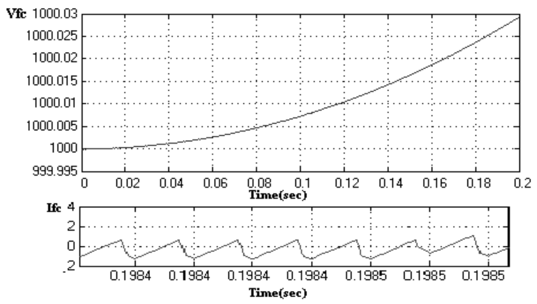

Fig.8 Fuel Cell Output Voltage and Current waveforms fed to Cuk converter

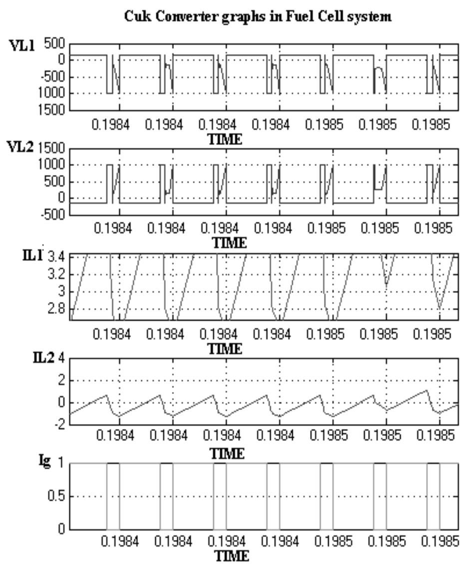

Fig.9Output voltage and current waveforms CUK Converter in Fuel Cell System

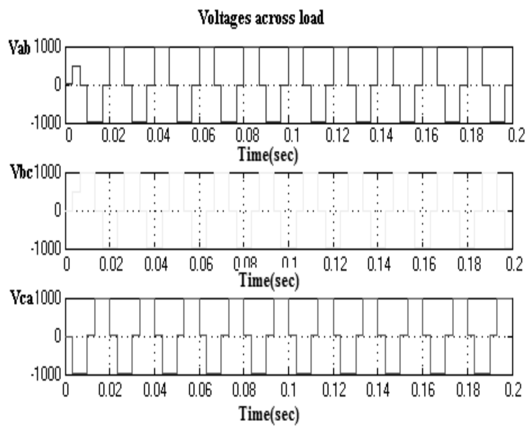

Fig.10 Fuel Cell system Output Voltage and Current waves forms to the load

From the above simulation results it can be identified to meet the load changes in the power system can be effectively be controlled by incorporating the FC system as they are fed constant output voltages. The FC output can be controlled by controlling the internal parameters of the fuel cell.

VI. CONCLUSION

Dynamic modeling of solid-oxide fuel cell 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. The Simulation results are presented for various dynamic characteristics of the Fuel system control scheme, which enables comprehensive quantitative and qualitative analysis.

APPENDIX

The parametric values considered for design of SOFC for simulation

Variable	Representation	Value
T	Absolute temperature	1273K
F	Faraday's constant	96487C/mol
R	Universal gas constant	8314J/(Kmol K)
E_o	Standard reversible cell potential	1.18V
N	Number of cells in stack	450
K_r	Constant K_r =N/4F	$.996*10^{-6}$ Kmol/(s A)
U_{max}	Maximum fuel utilization	0.9
U_{min}	Minimum fuel utilization	0.8
U_{opt}	Optimum fuel ratio	0.85
K_{H_2}	Value molar constant for hydrogen	$8.43*10^{-4}$ Kmol/(s atm)
K_{O_2}	Value molar constant for oxygen	$2.81*10^{-4}$ Kmol/(s atm)
K_{H_2O}	Value molar constant for water	$2.52*10^{-5}$ Kmol/(s atm)
τ_{H2}	Response time for hydrogen flow	26.1s
τ_{H2O}	Response time for water flow	78.3s
τ_{O2}	Response time for oxygen flow	2.91s
R	Ohmic loss	0.126 Ω
T_e	Electric response time	0.8s
T_f	Fuel processor response time	0.03s
r_{HO}	Ratio of hydrogen to oxygen	1.145

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