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# Fuel Cell: Survey and Analysis

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***ABSTRACT:*** *This paper reviews fuel cell technology status and some of its challenges worldwide. Fuel cells have emerged as an important technology in various non-linear loads in industrial, commercial and residential sectors. A mathematical model of hydrogen fuel cell is described with control parameters. A hydrogen fuel cell design is simulated using MATLAB/SIMULINK and the results are discussed.*

***Keywords–****Fuel*, hydrogen, *model, parameters, simulation*

## I. INTRODUCTION

The potential effects of climate change are irreversible and very serious. A sustainable high quality of life demands clean, safe, reliable energy system at affordable prices. Fuel cells lead the way in clean and efficient energy conversions. They are powering innovations in a wide range of products, ranging from very small portable devices such as mobile phones, laptops and in applications like cars, delivery vehicles, buses and ships. Energy demands at present are met by thermal, hydro-electric, nuclear and solar power plants. Unfortunately efficiency is very low (20%) and environmental pollution is very high due to the production of greenhouse gases like carbon dioxide, carbon monoxide etc. These gases will increase atmospheric temperature and causes the reduction of ozone layer. Hydroelectric power plants demand source and space whereas nuclear power plants demands fuel reuse and disposal to a safe place.

Fuel cells have been called as the “microchip of the hydrogen age,” this clean renewable energy source is seen as alternative to fossil fuel used in running world’s economy. Drivers, limitations, and opportunities in the fuel cell market in India have been discussed [1]. A description of fuel cell operating principles is followed by a comparative analysis of the current fuel cell technology together with issues concerning various fuels [2].From today's perspective, the present status of an industrialized world requires new approaches to solve most urgent energy and environmental problems. Fuel cell technology seems to offer promising, sustainable options for the future energy scenario. Though fuel cells have been in existence for over 160 years, recent commercialization is driven by an increase in their efficiency. An increasing consciousness of the pollution caused by traditional fuels, a deregulation of energy markets and realization that world oil supplies are declining are described [3]. A brief review and comparison of polymer electrolyte fuel cells (PEFCs) and solid oxide fuel cells (SOFCs) with significant scientific challenges are discussed [4].The primary transportation alternatives which hold the greatest potential for averting societal threats are evaluated [5].The fuel cell cars turned out to be the most promising to meet future environmental demands. In addition to an efficient process to produce the mechanical energy, recuperation of energy is a potential step to increase mileage of passenger cars [6]. The design and manufacturing alternatives for Proton Exchange Membrane (PEM) fuel cells are described and analyzed within the context of vehicle applications [7]. Fuel cell technology is recently becoming one of the most interesting fields for the car companies to invest in. This interest is because of their high efficiency and zero environmental pollution. Polymer electrolyte membrane fuel cells (PEMFC) are the most appropriate type of fuel cells for use in vehicles due to their low performance temperature and high power density [8]. Environmental, sustainability issues and the role of hydrogen and fuel cell technologies have emerged as potential solutions to these issues. The commercialization plans in various industrialized countries (USA, Canada, Japan, etc.) have started identifying the most likely early markets for hydrogen as an energy carrier and fuel cell as energy producing device [9]. Intelligent Energy has developed a proprietary fuel cell stack, cooled via evaporation rather than by use of separate cooling channels. As a case study, a conventional London Taxi black cab is discussed [10]. With fuel cell/battery, city buses the output power of the fuel cell is controlled by a D.C. converter and the output ports of the converter and the battery are connected in parallel to supply power for the electric motor. A closed-loop control algorithm is necessary to eliminate the errors between the output and target power of the fuel cell system [11]. The potential for Solid-Oxide Fuel Cells (SOFC) to provide electrical generation on-board commercial aircraft has been described [12].

## II. MATHEMATICAL MODEL

The simplified model of a fuel cell stack operating at nominal conditions of temperature and pressure is as shown in Fig (1).

The parameters of the equivalent circuit can be modified based on the polarization curve as shown in Fig (2). The inputs are the value of the voltage at no load, as well as the nominal and the maximum operating points, for the parameters to be calculated. A diode is used to prevent the flow of negative current into the stack.

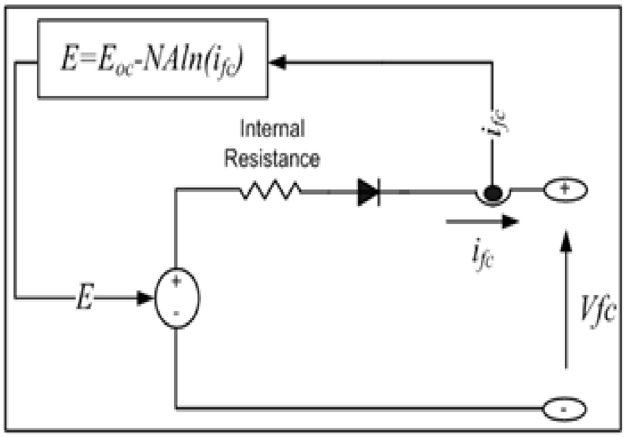

Fig.1: Equivalent circuit of fuel cell stack

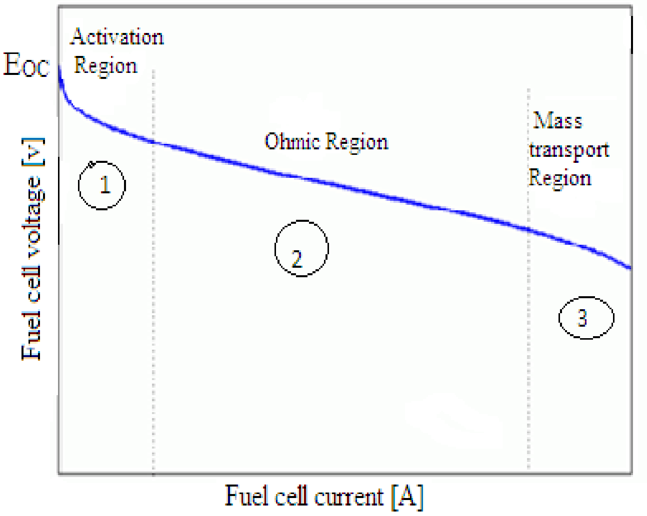

Fig 2: Polarization curve

The polarization curve in Fig (2) consists of three regions:

### 2.1 Region 1

The first region represents the activation voltage drop due to the slowness of the chemical reactions taking place at electrode surfaces. Depending on the temperature and operating pressure, type of electrode, and catalyst used, this region is more or less wide.

### 2.2 Region 2

The second region represents the resistive losses due the internal resistance of the fuel cell stack.

### 2.3 Region 3

Finally, the third region represents the mass transport losses resulting from the change in concentration of reactants as the fuel is used.

## III. DETAILED MODEL

The detailed model represents a hydrogen fuel cell stack when the parameters such as pressures, temperature, compositions, and flow rates of fuel and air vary. These variations affect the open circuit voltage as well as the Tafel slope. The equivalent circuit and the simplified model are as shown in Fig 3.

The open circuit voltage and the Tafel slope are modified as follows:

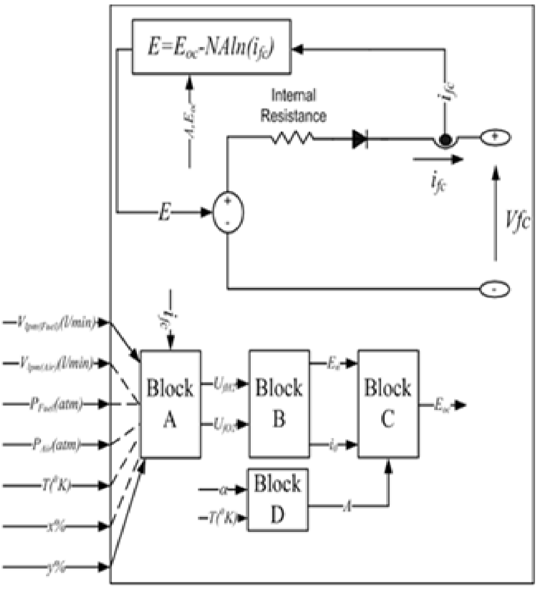

Fig 3: Simplified model of the fuel cell stack

$$E_{OC} = N(E_n - A\ln(i_0)) \quad (1)$$

$$A = \frac{RT}{z\propto F} \quad (2)$$

Where,

$E_{OC}$ = Open circuit voltage (v)
A = Tafel slope
R = 8.3145 J/ (mol K)
F = 96485 A s/mol
z = Number of moving electrons
$E_n$= Nernst voltage, which is the thermodynamics voltage of the cells and depends on the temperatures and partial pressures of reactants and products inside the stack
$i_0$= Exchange current, which is the current resulting from the continual backward and forward flow of electrons from and to the electrolyte at no load. It depends also on the temperatures and partial pressures of reactants inside the stack.
$\propto$ = Charge transfer coefficient, which depends on the type of electrodes and catalysts used
T = Temperature of operation (°K)
For a given Air and Fuel flow rate, the Nominal rate of conversion of hydrogen and oxygen is given by:

$$U_{f_{H_2}} = \frac{6000\,RTNi_{fc}}{zFP_{Fuel}\,V_{lpm\ (fuel\ )}Xx\%}\ 0 \le U_{f_{H_2}} < 1 \quad (3)$$

$$U_{f_{O_2}} = \frac{6000\,RTNi_{fc}}{2zFP_{air}\,V_{lpm\ (air\ )}Xy\%}\ 0 \le U_{f_{O_2}}\ 1 \quad (4)$$

Where,

$U_{f_{H_2}}$= Nominal rate of conversion of hydrogen
$U_{f_{o_2}}$= Nominal rate of conversion of oxygen

$P_{Fuel}$ = Absolute pressure of fuel (atm)
$P_{air}$ = Absolute supply pressure of air (atm)
$V_{lpm\,(fuel\,)}$= Fuel flow rate (l/min)
$V_{lpm\,(air\,)}$= Air flow rate (l/min)
x = Percentage of hydrogen in the fuel (%)
y = Percentage of oxygen in the oxidant (%)

The Nernst voltage( $E_n$ ) for a given exchange current density ($i_o$) for a partial pressure of hydrogen ($P_{H_2}$) and oxygen ($P_{O_2}$ ) inside the stack is given by :

$$E_n = \begin{cases} 1.229 + (T - 298)\frac{-44.43}{zF} + \frac{RT}{zF}\ln( P_{H_2} P_{O_2}^{1/2})\, T \leq 100°C \\ 1.229 + (T - 298)\frac{-44.43}{zF} + \frac{RT}{zF}\ln( P_{H_2}\, P_{O_2}^{1/2})\, T > 100°C \end{cases} \tag{5}$$

$$i_0 = \frac{zFk\,(PH_2 + PO_2)}{Rh} e^{\frac{\Delta G}{RT}} \tag{6}$$

$E_n$ = Nernst voltage
$i_o$ = Exchange current
$P_{H_2}$= Partial pressure of hydrogen inside the stack
$P_{O_2}$= Partial pressure of oxygen inside the stack
$P_{H_2O}$= Partial pressure of water vapor inside the stack
k = Boltzmann's constant =1.38 x $10^{-23}$ J/°K
h = Planck's constant =6.626 x $10^{-34}$ J s

ΔG = Size of the activation barrier which depends on the type of electrode and catalyst used

The partial pressures $P_{H_2}, P_{O_2}$ and $P_{H_2O}$ are determined in steady state as follows :

$$P_{H_2} = P_{Fuel}\, x\%(1 - U_{f\,H_2}) \tag{7}$$

$$P_{O_2} = P_{Air}\, y\%\left(1 - \ U_{f\,o_2}\right) \tag{8}$$

$$P_{H_2O} = P_{Air}\,(w\% + 2y\%U_{f\,o_2}) \tag{9}$$

Where,

W = Percentage of water vapor in the oxidant (%)
Block C and D calculate the new values of the open circuit voltage ($E_{OC}$) and Tafel slope, respectively.

The material parameters ∝, ΔG are calculated based on the polarization curve at nominal conditions of operation along with some additional parameters, such as the low heating value (LHV) efficiency of the stack, composition of fuel and air, supply pressures and temperatures, etc. They can be easily obtained from the manufacturer's data sheet.

The nominal rates of conversion of gases are calculated as follows:

$$U_{f\,H_2} = \frac{\eta_{nom}\ \Delta h^0(H_2o(gas\,))N}{zF\,V_{nom}} \tag{10}$$

$$U_{f\,O_2} = \frac{6000\,RT_{nom}\ NI_{nom}}{2zF\,P_{air\ nom}\ V_{lpm\ (air\ )_{nom}}\ \times 0.21} \tag{11}$$

Where,

$\eta_{nom}$ = Nominal LHV efficiency of the stack (%)
$\Delta h^0\left(H_2O(gas)\right) = 241.83\ X\ 10^3$J/mol

$V_{nom}$ = Nominal voltage (V)
$I_{nom}$ = Nominal current (A)
$\boldsymbol{V_{lpm(air)nom}}$=Nominal air flow rate (l/min)
$P_{airnom}$ = Nominal absolute air supply pressure (Pa)
$T_{nom}$ = Nominal operating temperature $(0°K)$

## IV. EXTRACTION OF PARAMETERS FROM DATASHEET

This example uses the Ned Stack PS6 data sheet from Ned Stack as shown in Appendix-1

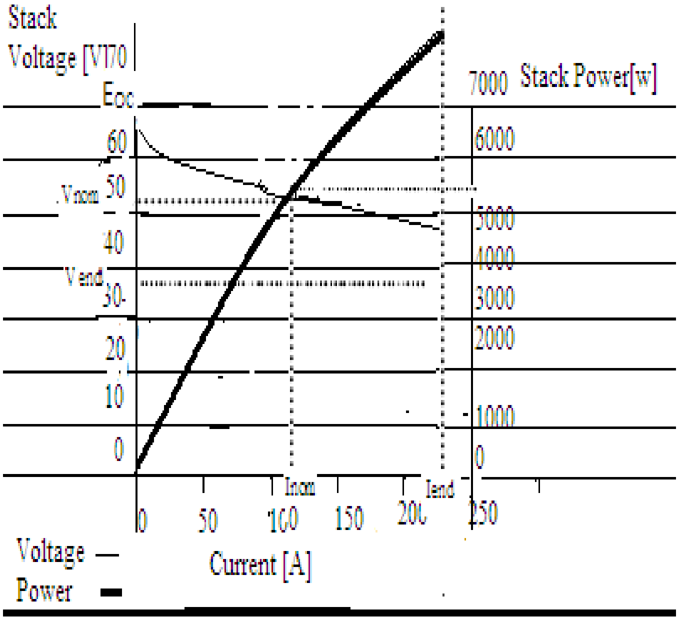

Fig 4: Ned stack PS6 curves from datasheet

The rated power of the stack is 5.5kW and the nominal voltage is 48 V. The following detailed parameters are deduced from the data sheet.

Open circuit voltage (Eoc) = 65 V
Nominal operating point [I nom, Vnom] = [133.3, 45]
Maximum operating point [I end, Vend] = [225, 37]
Nominal stack efficiency ($\eta_{nom}$) = 55 %
Operating temperature = 65℃
Nominal supply pressure [$H_2$Air] = [1.5 1]

If the pressure given is relative to the atmospheric pressure, add 1 bar to get the absolute pressure.

Nominal composition (%) [$H_2$,$O_2$,$H_2O$(Air)] =[99.999, 21, 1]

If air is used as oxidant, assume 21% of $O_2$and 1% of $H_2O$ in case their percentages are not specified.

### 4.1 Number of cells:

Can be estimated from the formulas below:

$$N = \frac{2\ X\ 96485.V_{nom}}{241.83\ X\ 10^{3}.\eta_{nom}} \tag{12}$$

$$N = \frac{2\ X\ 96485.45}{241.83\ X 10^{3}.0.55} = 65.28 = 65\ cells$$

### 4.2 Nominal air flow rate:

If the maximum air flow rate is given, the nominal flow rate can be calculated assuming constant oxygen utilization at any load. The current drawn by the cell is linearly dependent on air flow rate and the nominal flow rate is given by:

$$V_{lpm\,(air\,)_{nom}} = \frac{I_{nom}\,x V_{lpm\,(air\,)nom}}{I_{nom}} \tag{13}$$

In this case,

$$V_{lpm\,(air\,)_{nom}} = \frac{133.3\ x\ 500}{225} = 297 litres/min$$

Assume the rate of conversion of oxygen to be 50% (as it is usually the case for most fuel cell stacks) and the nominal air flow rates:

$$V_{lpm\,(air\,)_{nom}} = \frac{6000\,RT_{nom}\ NI_{nom}}{2zFP_{air\ nom}\ 0.5\ x\ 0.21} \tag{14}$$

### 4.3 Fuel cell response time = 10 s

With the above parameters, the polarization curve of the stack operating at fixed nominal rate of conversion of gases is close to the data sheet curves as shown below. The orange dotted line shows the simulated stack voltage and green dotted line shows the simulated stack power.

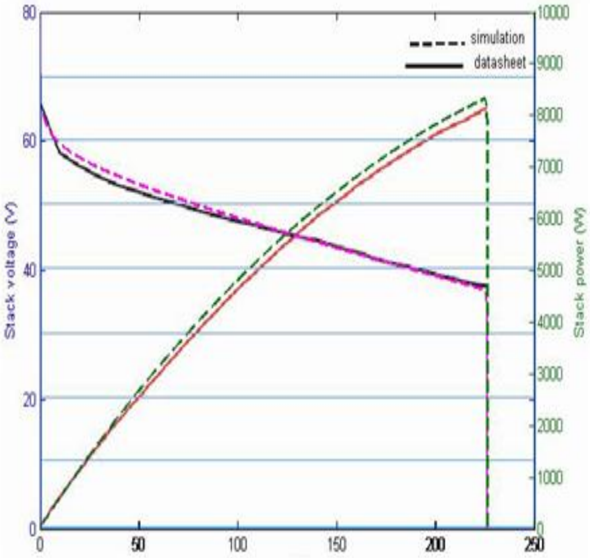

Fig 5: The polarization curve of the stack close to the data sheet curves

Above the maximum current, the flow rate of gases entering the stack is maximum and the stack voltage decreases abruptly as more current is drawn.

## V. SIMULATION RESULTS

Figure 6 shows the simulation model of the hydrogen fuel cell stack with a 6 kW, 45 V proton exchange membrane (PEM) fuel cell stack feeding an average value 100 Vdc, DC/DC converter.

The converter is loaded by an RL load of 6 kW with a time constant of 1s. During the first 10s, the utilization of the hydrogen is constant to the nominal value (Uf_H2 = 99.56%) using a fuel flow rate regulator. After 10s, the flow rate regulator is bypassed and the rate of fuel is increased to the maximum value of 85 lpm and the variation in the stack voltage is observed. This will affect the stack efficiency, the fuel, and the air consumption.

The simulation produces the followings results:

At t = 0 s, the DC/DC converter applies 100 $V_{dc}$ to the RL load (the initial current of the load is 0 A). The fuel utilization is set to the nominal value of 99.56%. The current increases until the value of 133 A. The flow rate is automatically set to maintain the nominal fuel utilization.

At t = 10 s, the fuel flow rate is increased from 50 liters per minute (lpm) to 85 lpm during 3.5 s, reducing by doing so the hydrogen utilization. This causes an increase of the Nernst voltage so the fuel cell current will decrease. Therefore, the stack consumption and the efficiency will decrease.

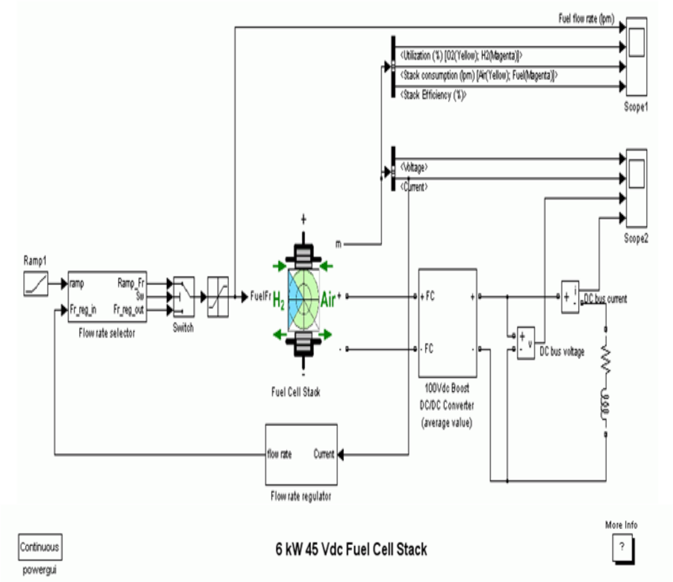

Fig 6: shows the simulation model of the hydrogen fuel cell stack with a 6 kW, 45 V proton exchange membrane

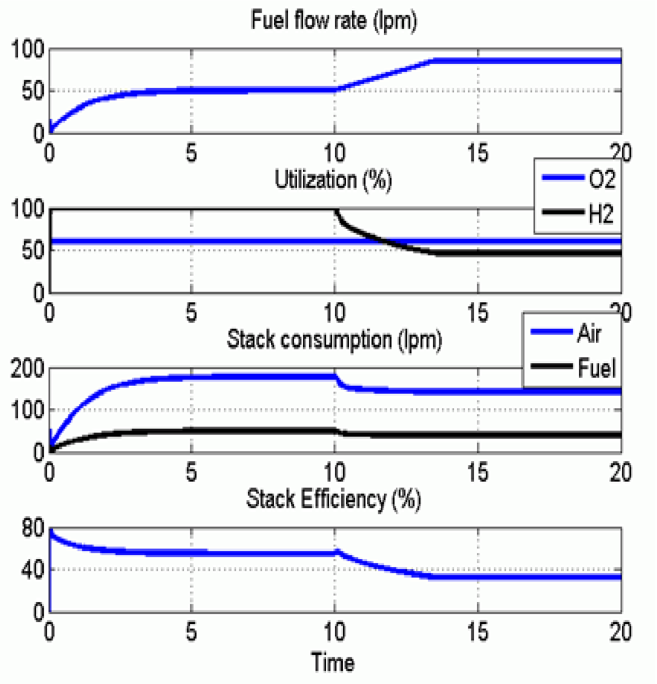

Fig 7: Simulation results showing fuel flow rate, utilization, stack consumption and efficiency

The DC bus voltage, which is very well regulated by the converter. The peak voltage of 122 $V_{dc}$ at the beginning of the simulation is caused by the transient state of the voltage regulator.

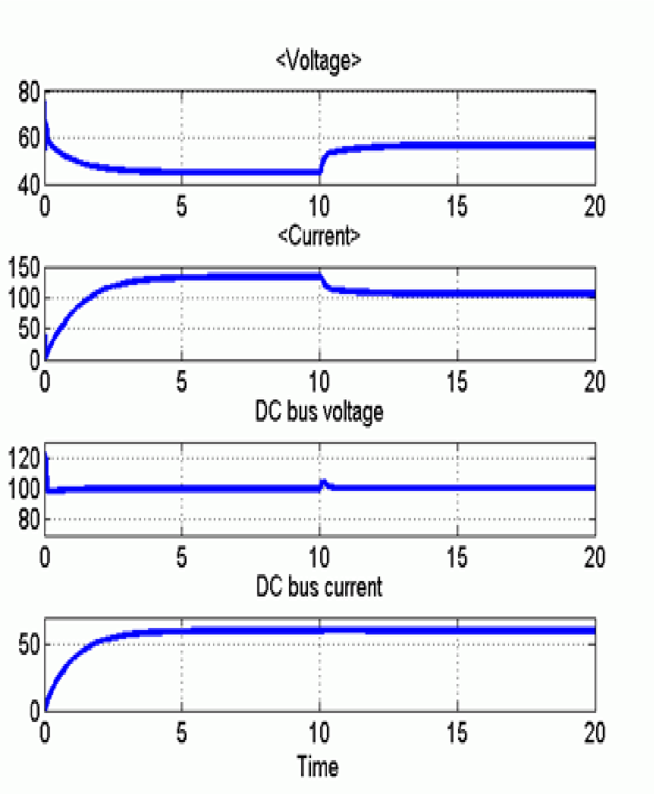

Fig 8: Simulation Results showing voltage, current, DC bus voltage and current

## VI. CONCLUSION

This paper has presented the mathematical model of a hydrogen fuel cell with different control parameters in mat lab/Simulink environment. The simulated results show an increase of the Nernst voltage, so the fuel cell current will decrease. Therefore, the stack consumption and the efficiency will decrease. With this initial survey and analysis of hydrogen fuel cell, challenges of hydrogen fuel cell will be compared with other types of fuel cells for different linear and non-linear loads are the future scope of the work.

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**APPENDIX-1**

| Type | 6 K W fuel cell system | Ned stack PS6 |
|---|---|---|
| Performance | Net Rated electrical peak power | 7 KW (DC) |
| | Net Rated nominal power | 5 KW (AC) |
| | Output voltage | 60-30V (DC) |
| | Operating current range | 0-225 A (DC) |
| | Typical beginning of life voltage range | 42 V at Nominal |
| | Efficiency - LHV | 55% [stack]/<br>50% [system] |
| | Time from off model to idle | Within 3 Min |
| | Time from 10% to full power | Approx. 10 s |
| | Expected Life | 20.000 h [stack] |
| | Maintenance Routine | 2.000 h [system] |
| | Operational Ambient Temperature | -20 - +40°C |
| Fuel | $H_2$ or Reformat | |
| | Purity | 99.999% $H_2$ or Reformat(<50ppm CO) |
| | Supply pressure | 0.5-5 bar |
| | Stack operating pressure | ambient |
| | Maximum consumption | 12.5 slpm/KW |
| Air delivery system | Flow rate | Max 500l/Min |
| | Supply Pressure | Ambient |
| Physical | Dimensions | 400x600x1600 mm |
| | Mass | Approx. 80kg |
| Emissions | Water collected | 75 l /min |
| | $NO_X$ , $SO_X$ | 0 |
| Cooling system requirements | Heat Rejection to coolant at maximum power | 10 KW |
| | Maximum Ambient temperature | 45°C |
| | FCPM Operating temperature | 65°C |
| | Cooling Method | Radiator Fan |
| | | |