Performance Evaluation of a 1.2 kW Fuel Cell

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Abstract – **Fuel cell (FC) systems have emerged as a promising alternative to conventional power technologies over the past decade owing to their high efficiency, low aggression to the environment, excellent dynamic response and superior reliability and durability. In this paper, the results of the evaluation of a 1.2 kW FC including the electrochemical model are reported. The FC stack dynamic simulation using SIMULINK^{TM} and the experimental results are also presented. In the end the dynamic behaviour and modelling results are used to predict the output voltage, power, efficiency and the polarisation curves of the FC.**

***Index terms*- Proton exchange membrane (PEM), Fuel Cell (FC), Modeling, Simulink, Performance Evaluation**

I. INTRODUCTION

The global energy consumption is rising steadily and a lot of pressure is put on electricity utilities to increase their generation capacity. In South Africa, most of the power generated is from coal and an increase in power generation is an increase in greenhouse emissions into the atmosphere.

The development of energy systems that generate power efficiently and cleanly is becoming more and more important for telecommunications [1]. This has shifted the attention towards the use of FC systems globally. The use of these systems is expected to become more widespread owing to better power quality, reliability, portability, lack of moving parts, silent operation and low adverse effects on the environment [2].

Fuel cells are electrochemical devices that convert chemical energy of a fuel into electricity at high efficiency without combustion. They are viewed as viable power sources for many applications including automobiles, distributed power generation and portable electronics.

Among the various types of hydrogen-oxygen fuel cells, the phosphoric acid fuel cell is the most mature and advanced, however the proton exchange membrane (PEM) fuel cells are the most attractive for residential and telecommunications use due to its low operating temperature and fast start up characteristics.

As part of the FC research project at the Vaal University of Technology (VUT) in Vanderbijlpark, South Africa, modelling and testing of various FC stacks capabilities is part of an ongoing process in the development of FC technologies and hence the work presented in this paper.

II. FUEL CELL POWER SYSTEM

A FC stack consists of a number of cells referred to as the membrane electrode assembly (MEA) sandwiched between two porous gas diffusion electrodes, a cathode and an anode, see Figure 1. In a typical FC, gaseous fuels are continuously fed to the anode and an oxidant is continuously fed to the cathode. Basic electrochemical reactions take place at the electrodes to produce electric current. The porous electrodes provide a surface site where gas/liquid ionization or de-ionization reactions take place as well as conduction of ions.

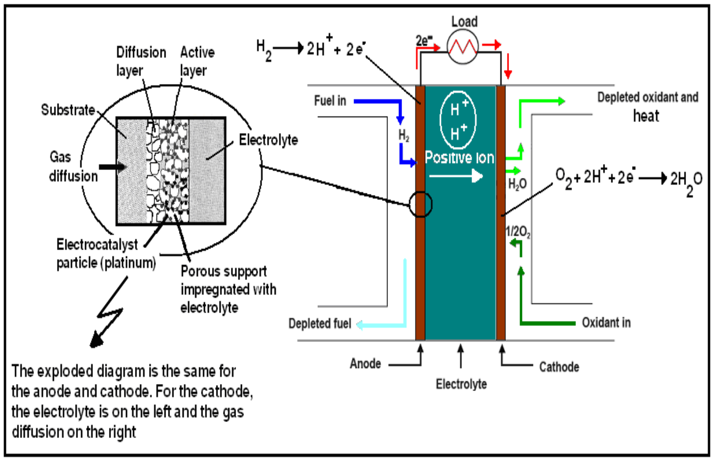

Figure 1. A basic schematic of a Fuel Cell structure [3].

A FC power system mainly consists of a FC stack which determines the output voltage while current is determined by the active cell area of the cells. Other parts of a FC system include the pumps and blowers, compressors, cooling systems, power conditioning unit and a fuel processing unit (reformer) which is needed only if the fuel does not use pure hydrogen.

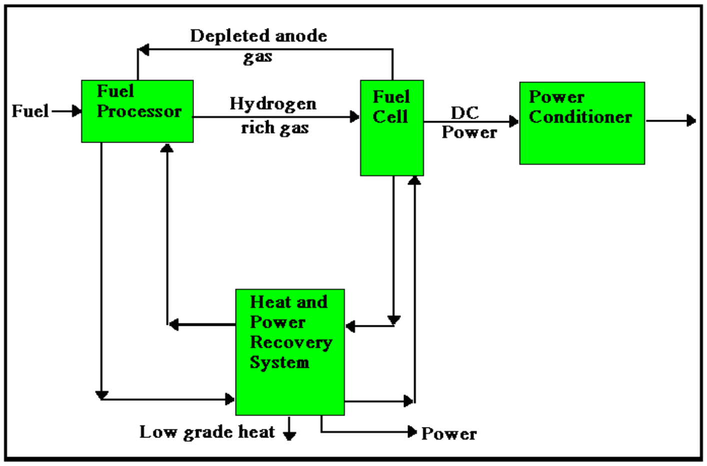

Figure 2. Block diagram of a FC power plant

A simplified schematic of the FC system is shown in Figure 2 above. A controller is also needed to control the parts of the system. A control and monitoring software may be incorporated into the whole system.

III. PRINCIPLES AND MODELING

A. Principles of Operation

In a FC, two half cell reactions take place simultaneously, at the anode an oxidation reaction and a reduction reaction at the cathode. These reactions make up the total oxidation-reduction (redox) reaction of the FC and the by-product water. Electrical energy is obtained from the FC only when a reasonable current is drawn. When dealing with chemical energy, the Gibbs free energy and enthalpy are often used. In FCs, change in Gibbs free energy of formation is considered, as this change is responsible for the energy released. This change is the difference between the free energy of the products and the reactants, as shown in equation 1 [4].

$$\Delta G_f = G_f \text{products} - G_f \text{reactants} \qquad (1)$$

where:

$\Delta G_f \equiv$ change in Gibbs free energy

In a FC using hydrogen and oxygen as fuel and oxidant respectively, for each molecule of hydrogen used, two electrons are released and passed through the external circuitry and through the load as electricity. The by-product water results from the recombination of the electrons and protons together with oxygen. Heat is also generated. The charge that flows per mole of hydrogen consumed is therefore:

$$-2N_A e = -2F \qquad (2)$$

where:

$N_A \equiv$ Avogadro's number
$-e \equiv$ charge on an electron
$F \equiv$ the Faraday's constant (96 485 C/mole)
$E \equiv$ voltage in Volts

If E is the voltage of the cell, then the energy required to move this charge around a circuit is:

$$\text{Electrical work done} = \text{charge x voltage} = -2FE \text{ Joules} \qquad (3)$$

Assuming the FC system was totally reversible, this work would be equal to ΔG_f such that:

$$\Delta G_f = -2FE \qquad (4)$$

Equation (4) can then be re-arranged to equation (5). This is an expression that gives the Electromotive Force (EMF) of the cell. This fundamental equation gives the open circuit voltage (OCV) of the FC and assumes that the FC has no losses (i.e. 100 % efficiency) and that it is fuelled by hydrogen and oxygen at standard temperature and pressure.

$$E = \frac{-\Delta Gf}{2F} \text{ V} \qquad (5)$$

And from Table 1, the E can be calculated.

Table 1. ΔG_f for the reaction of H_2O and O_2 at various temperatures.

Form of H_2O Product	Temperature (°C)	ΔG_f (KJmol^{-1})
Liquid	25	-237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

The negative sign in the table means that energy is released.

$$E = \frac{-\Delta Gf}{2F} \text{ V}$$

$$E = \frac{-\left(-237.2 \times 10^3\right)}{2(96485)}$$

$$= 1.229 \text{ V}$$

An analysis of the FC reaction shows that the OCV of the FC shown from the result above of 1.229 V is achievable. This OCV is also known as the ideal standard potential (E^o) and is only theoretical because it does not take into account the losses incurred by the FC. When oxygen is supplied from the air, it is equivalent to supplying it at a lower pressure. This is taken into account by using the Nernst equation. This is described in detail by equation (7).

The electrochemical model can be used to predict the dynamic behaviour of the FC stack. The electrochemical equations of the FC are given by:

At the Anode: $H_2 \rightarrow 2H^+ + 2e^-$ (6)

At the Cathode:

$$2H^+ + 2e^- + \tfrac{1}{2}O_2 \rightarrow H_2O + heat \qquad (7)$$

Overall reaction:

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O + heat \qquad (8)$$

The amount of hydrogen needed to meet the load and the amount of oxygen needed to maintain the reaction are determined by equations (6) and (7) respectively, while equation (8) gives the amount of water produced.

The actual cell potential of a single cell however in practice is lower than the voltage given in equation (5) because of the irreversible losses in voltage. The losses which are called polarisation or overvoltage originate from three principal sources: 1) activation polarisation, 2) ohmic polarisation and 3) concentration polarisation. This actual output voltage can be defined as follows:

$$V_{FC} = E_{nernst} - V_{act} - V_{ohmic} - V_{conc} \qquad (9)$$

where:

E_{nernst} ≡ Thermodynamic potential

V_{act} ≡ Activation potential due to the three phase interface

V_{ohmic} ≡ Ohmic potential due to resistance to flow of ions

V_{conc} ≡ Concentration polarisation due to a decrease in concentration of the reactants at the interface

And for n cells connected in series forming a stack, the voltage, V_{stack}, can be calculated as follows:

$$V_{stack} = n.V_{FC} \qquad (10)$$

B. Modelling and Simulation

Fuel cells are often analysed from an electrochemical perspective and hence yields many mathematical models that are important for improving the design of FC components as well as determining the optimal operating conditions [4].

The static behaviour of the FC as shown by equations (6) to (8) can be used to develop an equivalent electrical circuit model shown in Figure 3 [5].

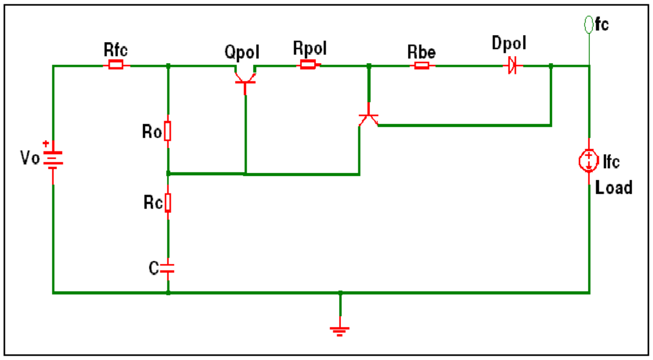

Figure 3. FC electrical circuit model

In the circuit model in Figure 3, the diode, two transistors and a resistor model the static model. The diode models the activation polarisation with its principle of the potential barrier which inhibits the migration of charge carriers across the PN-junction. The ohmic polarisation is modelled by the parasitic resistances of the diode. The two transistors and the resistor form a current limiting circuit that models the concentration polarisation while the capacitor and an inductor constitute the dynamic portion of the electric circuit model.

Although the basic concept of FCs is quite simple, creating new designs and optimising their performance takes serious work and a mastery of several technical areas [6]. The dynamic modeling and the response prediction is necessary in order to evaluate the FC response and the performance behaviour on parameters such as hydrogen consumption, efficiency and output power of the stack [7].

The electrical circuit model as well as equation (9) was used to simulate a model of the FC to give the output resembling the curves in Figures (9) and (10). The simulation program has been developed within the Matlab programming environment, using both the Matlab programming language and Simulink. Equation (9) forms the basis of all parameters that are analysed in Matlab for the FC. Examples of the script files used to produce the polarisation curve and curves of Figures 9, 12 and 14 can be found in [8] and [9] respectively.

IV. EXPERIMENTAL

The work presented here was carried out with Nexa^{TM} power module from Ballard Power Systems Inc. at the Vaal University of Technology. The power module is shown in Figure 4 below.

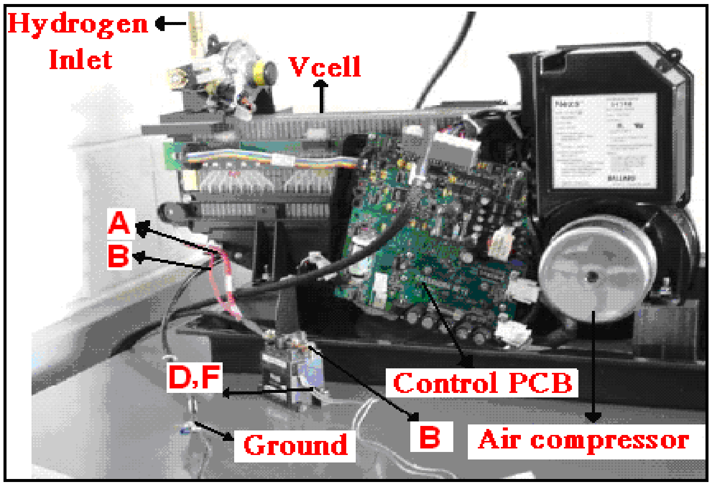

Figure 4. A 1.2 KW PEM Nexa^{TM} FC

The Nexa system provides up to 1200W unregulated DC power at a nominal output voltage of 26V DC. The output voltage varies with power, ranging from about 43V at the system idle to about 26 V at full load. The stack consisted of 47 cells. The stack voltage, current and temperature were monitored using the onboard sensor monitoring system (NexaMon OEM2.0).

The power module is a fully integrated system that produces unregulated DC power from a supply of hydrogen and air. The system is very reliable and includes the PEM FC stack as well as all the auxiliary equipment necessary for FC operation. The FC stack is pressurised with hydrogen during operation and is continually being replenished by the regulator assembly. A small compressor provides oxidant air to the FC stack in order to sustain the FC reaction. The FC initially starts from a DC power supply or batteries and the start up is instantaneous and can be started remotely. The FC turns on within approximately 15 seconds.

The setup is as shown in Figure 5. Hydrogen fuel gas and air were supplied to the stack and the fuel gas flow channel was dead end. The stack was air cooled and the oxidant was not humidified.

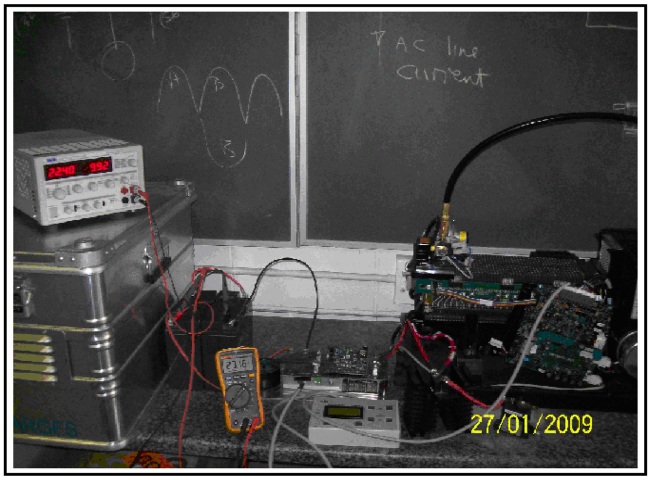

Figure 5. Experimental set-up of the Nexa FC system.

A 300W digital electronic load from TTI which allows operating the cell in constant current/voltage and resistance mode and other external loads to optimise for 1200 W of power were used. The electronic load is the driving force for the entire FC testing. Applying the load to the FC at the wrong time can cause serious damage to the device. Because of this, the load applied to the stack must be adjustable and have the capability of being disengaged quickly. The experimental setup shown in the block diagram of Figure 6 was used to obtain the steady state characteristics of the FC system. Measurements were taken at points A, B, C and E. Basic data, monitoring, logging and diagnostic features were acquired using the logging software interfaced through serial messaging.

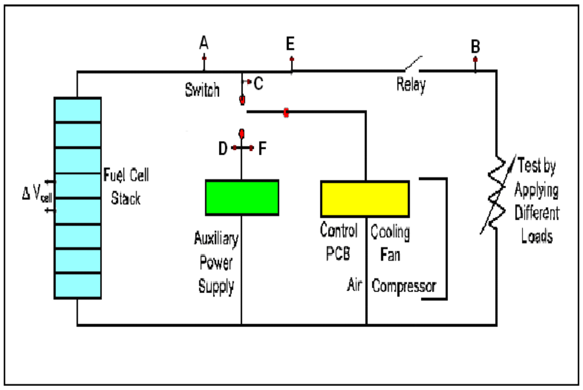

Figure 6. Block diagram of FC system

The calculation of hydrogen usage rate is also useful in determining the performance of the FC as it determines the electrical energy that could be produced from a given volume of hydrogen [10]. From the basic FC reaction in equation (4), 2 electrons are transferred for each mole of hydrogen,

$\therefore$ Charge = 2F * amount of hydrogen

$\therefore$ Hydrogen usage = I/2F moles/s

where: (F) Faraday constant = 96 485 C/mole

For a stack of (N) cells:

H_2 usage = IN/2F moles/s

And, since $P = V_{FC} \times I \times N$

Then $I = P/NV_{FC}$

where: P is the fuel cell power and
V_{FC} is the voltage of each cell.

$\therefore$ H_2 usage = P/2F V_{FC} moles/s

Molar mass H_2 is $2.02*10^{-3}$ Kg/mol.

$\therefore$ H_2 usage = $1.05*10^{-8}$ (P/V_{FC}) Kg/s.

V.RESULTS AND DISCUSSION

The performance of a FC in most cases is determined by the use of a polarisation curve. Measuring polarisation curves is widely acknowledged and used in FC performance testing. Polarisation curves together with resistance measurements provide information on the polarisations incurred in FCs. Polarisation curves are normally measured by generating a current sweep with a load unit and recording the cell voltage as a function of current density. The voltage is measured for a given time after each step so as to achieve a steady state operation.

Figures 7 and 8 shows the polarisation curve under load condition and power curve respectively. Both the polarisation and power curves agreed approximately with the simulation results presented in Figures 9 and 10. Note should be taken that, on the simulation curves, current is normalised to show current density per square centimetre.

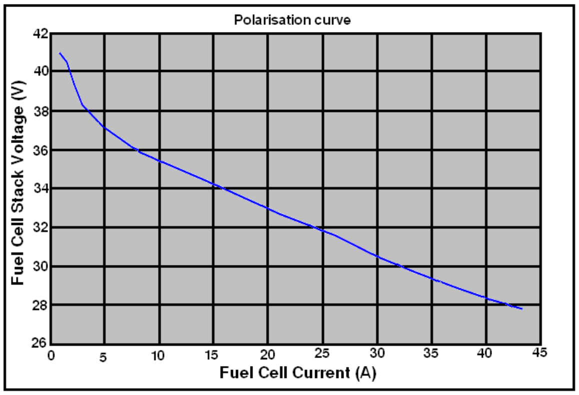

Figure 7. Polarisation Curve

The output voltage varies with the operating load according to the polarisation characteristics of the FC shown in Figure 7. From Figure 8, the net power ranges from zero at system idle or open circuit voltage to 1200 W at rated power while the current ranges from zero to 46 Amperes across the whole operating range of the FC.

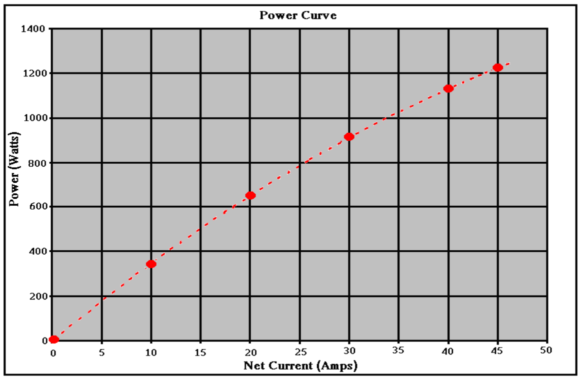

Figure 8. Power Curve

The shape of the curve of the output voltage in Figure 9 is non linear terms as activation loss occurs at low current densities and mass transport loss at high current densities. Ohmic polarisation affects the FC output voltage in the middle of current densities and produces a linear relationship between voltage and current density.

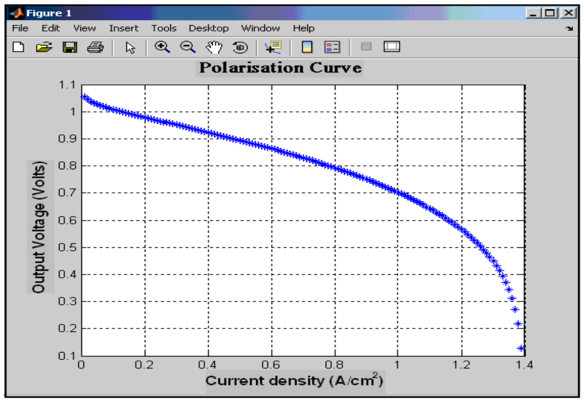

Figure 9. Polarisation Curve of FC system

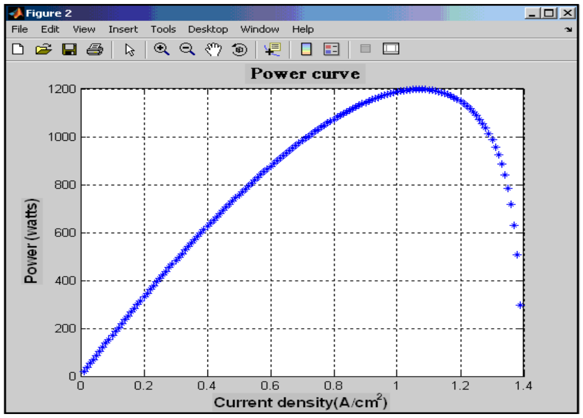

Figure 10. Power curve of FC system

Figure 11 illustrates the FC hydrogen consumption with respect to the FC output current. As also shown from the graph the maximum hydrogen consumption is approximately 16 slpm at the maximum power, however, the manufacturer rates it at 18.58 slpm.

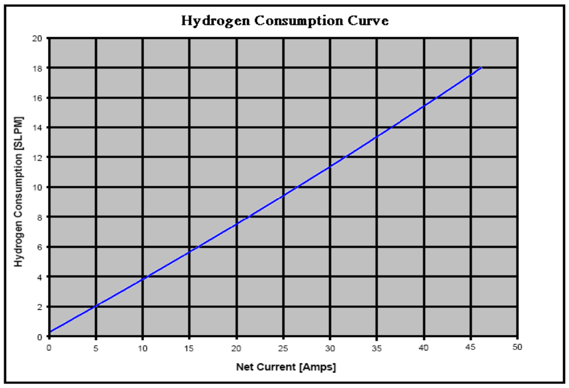

Figure 11. Hydrogen Consumption Curve

It can also be observed that the hydrogen consumption rate is proportional to the FC current demand. Figure 12 refers. This again means that there is a relation between consumption and power output.

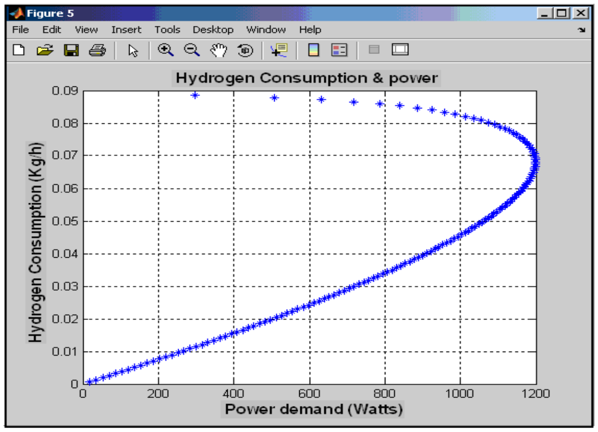

Figure 12. Hydrogen Consumption

As power output increases, consumption of the hydrogen also increases. The simulated hydrogen consumption shown in Figure 12 is 0.07 Kg/h against the practical consumption rate of 0.3622 Kg/h. The difference in consumption is due largely to the power used for auxiliary components of the FC like blowers and pumps for cooling the stack which is not accounted for in the simulation. When charging a bank of 24 V batteries from 18 V to 24 V, the total hydrogen consumption was 35 slpm and after the initial charge cycle and thereafter settled at 18 slpm for the idle state or standby mode before recharging.

The graph of Figure 13 presents the FC efficiency as a function of the FC output current. The efficiency of the FC is the ratio of the output power to the lower heating value of hydrogen consumed in the FC reaction. The efficiency curve almost exhibits the same curve as the voltage current density curve at the operational region which is largely due to the fact that FC efficiency is directly proportional to voltage at a given current density. This is also confirmed by the simulation graph of Figure 14. From Figure 13, the FC efficiency is 38 % from an efficiency of 50 % at system idle. As explained earlier, this is contributed largely to part of the power being used for auxiliary devices of the FC for system cooling.

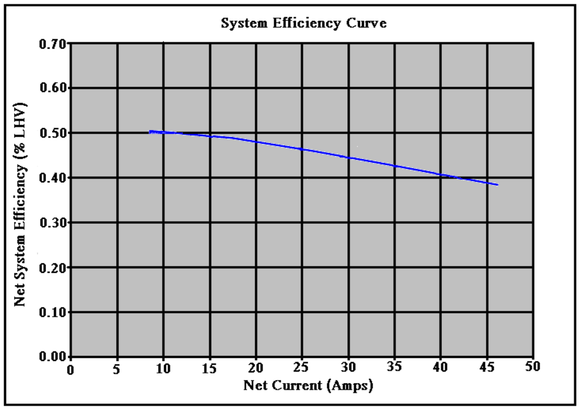

Figure 13. System Efficiency

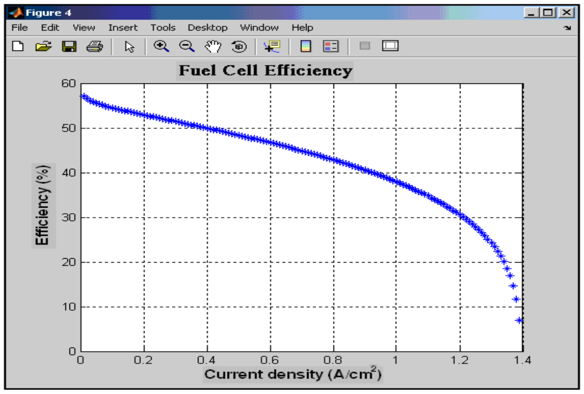

Figure 14. System Efficiency

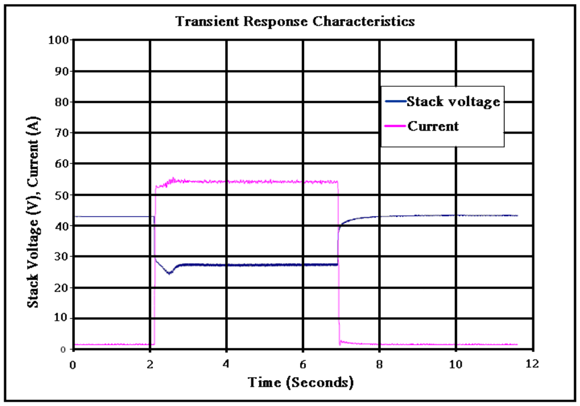

Figure 15. Transient Response Characteristics

The transient response characteristics of the FC as depicted in Figure 15 above illustrates the system's response towards the step changes in the load. In case of any load step changes, the FC immediately provides enough current to support the said change and the hydrogen flow rate is also supported by the regulator assembly provided the pressure is maintained. The output voltage and the current are inversely proportional; an increase in the current provided will result in a decrease in voltage. However this happens for a short time of approximately 0.5 seconds and then the voltage recovers and stabilises at its nominal value, in this case at 43 V.

VI.CONCLUSION

FC systems are increasingly showing a promising alternative due to their efficiency and dynamic response.

This paper presents the simulation and performance evaluation of a PEM NEXA FC stack and possible integration in replacing the conventional sources of electrical energy in stand-by power supply systems, particularly for use in the telecommunications industry. This application requires highly reliable DC power, and therefore the FC can replace the commonly used lead acid batteries as an uninterruptible power supply module (UPS).

The electrochemical model and the FC parameter influences are also presented and based on the stack performance to the simulated results. Evaluation of the stack polarisation curve, power curve and are discussed.

ACKNOWLEDGEMENTS

Telkom SA Ltd., M-TEC and TFMC for graciously providing funding on this project

REFERENCES

[1] M. Ishizawa, S. Okada and Takashi Yamashita, *Highly efficient heat recovery system for PAFCs used for cooling telecommunication Equipment,* FCDIC fuel cell symposium proceedings, vol 6, pp 120-124, 1999.
[2] M. Tanrioven and M.S. Alam, *Modelling, control and power quality evaluation of a PEM fuel cell based power supply system for residential use*, IEEE transaction industry applications, vol, 42, no6:1582-1589.
[3] T. Pholo, *Design and development of a portable phosphoric acid fuel cell*, M-Tech Dissertation, Vaal University of Technology, 2008.
[4] J. Larminie and A. Dicks, *Fuel cell systems explained* 2nd edition, John Wiley and Sons Ltd, 2003, England.
[5] J. Du Toit, *Design and development of a 100W proton exchange membrane fuel cell,* M-Tech Dissertation, Vaal University of Technology, 2006.
[6] C. Spiegel, *PEM fuel cell modelling and simulation using matlab,* Elsevier Inc., Burlington, MA, USA, 2008.
[7] M. H. Nehrir and C. Wang, *modelling and control of fuel cells*, John Wiley and sons Ltd, 2009, New Jersey.
[8] S. Srinivasan, *Fuel cells, from fundamentals to applications,* Springer Science + Business Media, New York, 2006.
[9] Hamit Turan and Halil Osmanoglu, *Modelling of polymer electrolyte membrane fuel cell with a cogeneration application,* T.R Marmara University, Istanbul, 2005.
[10] D. Morsi Ali and S.K. Salman, *Investigation into the modelling of a fuel cell stack system,* Robert Gordon University, UK.

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