

A Unitised Regenerative Fuel Cell for Telecommunications Applications

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Abstract— Telecommunication service providers around the world have many remote sites that are often powered by renewable resources such as wind and solar. Renewable resources are plagued by unreliability due to uncertain weather and the cyclic nature of the seasons. Unitised Regenerative Fuel Cells overcome this obstacle by converting renewable energy into a seasonally storable energy form such as hydrogen and oxygen. This is then converted, when required into electrical energy by the Unitised Regenerative Fuel Cell. This paper concerns some design aspects of a Unitised Regenerative Fuel Cell that will be used as either a primary or secondary power supply using excess renewable energy to supply remote customer premises equipment.

Index Terms— Regenerative Fuel Cells (RFC), Customers Premises Equipment (CPE), Efficiency, Discrete Regenerative Fuel Cell (DRFC), Unitised Regenerative Fuel Cell (URFC), Proton Exchange Membrane (PEM), Membrane Electrode Assembly (MEA).

I. INTRODUCTION

Fuel cells are currently finding use in various facets of technology. These devices are used in applications ranging from portable devices such as cell phones, where it replaces the battery supply, to automobile power trains and large-scale urban power stations. In each of these applications, the fuel cell is found to be a highly efficient, powerful and a remarkably clean form of power conversion. It is capable of transferring the energy stored in hydrogen or hydrogen rich fuels into electrical energy with almost no emissions.

Hydrogen is increasingly used as a form of energy storage that replaces batteries in uninterruptible power supplies

(UPS) used in grid-connected applications where power interruptions are encountered on a regular basis. In the telecommunications environment, fuel cells are finding commonplace as battery back up for cellular telephone repeater sites and as primary power supplies in integrated remote telecommunications sites [1,2]. The use of fuel cell technology is not confined to remote radio repeaters; it can also be use in powering fibre optic repeater stations, multiplexing stations and Internet backbone facilities [3].

In all telecommunication applications, it is most advantageous to have a power supply that is self-sufficient, easily refuellable and reliable. The renewable fuel cell (RFC) can oblige in all of these requirements and has the added benefit of been environmentally friendly which is a benefit to the impact/environmental assessment study of future telecommunications sites.

The RFC technology was originally developed for space exploration where it was used in the closed system environment to convert and store excess solar energy. When considering which fuel cell to use, the technology of choice for the regenerative application described in this paper is the proton exchange membrane (PEM). Other variations are available such as the alkaline, solid oxide and zinc/air fuel cells.

A problem encountered with the original discrete component RFC (DRFC) system was that the various components took up too much volume and was too bulky for use in satellites that required high power density power supplies for longer missions.

Members of the Lawrence Livermore National Laboratories (LLNL) under the supervision of F. Mitlitsky have developed a PEM unit that operates as both a electrolyser and a fuel cell. This combined unit is called a unitised regenerative fuel cell or URFC. The URFC has achieved specific energy content values of greater than 600 Wh.kg^{-1} . The unit was originally designed to replace the secondary batteries in highflying solar aircraft and satellite and has a much higher energy density than any rechargeable battery. It also has the fast refuelling benefits of a primary fuel cell and the recharging benefits of a secondary battery [4]. A comparison of various battery and storage technologies is shown in Figure 1.

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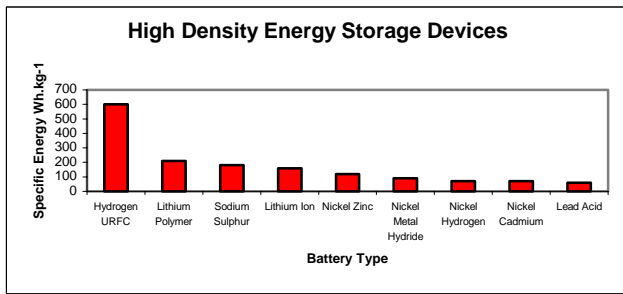


Figure 1. Comparison of high-density storage devices [4]

II. OPERATION OF THE REGENERATIVE FUEL CELL

The fuel cell and its operation are explained using the PEM cell as the basis model. All other fuel cell technologies use the same principle of operation.

The RFC system consists of a PEM electrolyser that is used to generate the reactant gases from pure water using electrical power. A PEM fuel cell can then be used to reconvert the reactant gases back into water, in the process heat and electrical energy is required and obtained from the respective reactions.

The two PEM devices in the RFC follow the same operational process, the one being exactly the reverse operation of the other. It is this common operational process that allows the two devices to be combined into a single unit.

The heart of the PEM device is the membrane electrode assembly (MEA). It consists of the proton conducting membrane that is coated with an electro-catalyst layer that in turn is backed up with a gas diffusion layer (GDL).

A. Fuel Cell Operation

The MEA operation in principle is as follows: In the fuel cell mode reactant gas (hydrogen) is introduced at the anode electrode (this is the negative electrode in this operation), the gas is diffused by the GDL and spread out evenly across the entire anode electrode surface area. This area is coated with an electrocatalyst, usually in the form of platinum or a platinum alloy, which encourages the redox reaction of the hydrogen atoms. The hydrogen atoms are oxidised and the electrons, which cannot move through the non-conductive membrane, are drawn into an external circuit. The hydrogen protons are conducted through the membrane and move from the anode to the cathode.

At the cathode electrode (positive electrode), the GDL diffuses pure oxygen gas over the same type of catalyst that is used at the anode. The catalyst in this instance promotes the reduction of the oxygen atom; the atom accepts the electrons from the external circuit and then combines with the hydrogen proton arriving from the anode electrode. In the process heat and pure water is formed.

An analysis of the reaction shows that an open circuit voltage (OCV) of 1.23 V is achievable from the reaction of pure hydrogen and oxygen, the operational voltage is in the region of 0.6 to 0.7 V. The current that the cell is able to supply to the external circuit is dependant on the active surface area of the electrode, temperature of operation and the pressure at which the reactions take place. In the typical cell, the average current is in the region of 4 mA.mm⁻². The

developed current is highly dependant on the amount of catalyst that is used in the electrode.

B. Electrolyser Operation

The operation of the PEM device as an electrolyser is the reverse of the fuel cell operation; pure water is introduced into the anode (Note this is now the positive electrode) of the device. The GDL layer allows the water molecules to be evenly distributed over the catalyst layer of the electrode. The GDL also aids in the removal of product gases from the reactions sites. When a voltage of more than 1.23 V is maintained across the electrodes the water molecules begin to dissociate into hydrogen and oxygen atoms. In the average cell this voltage is in the order of 1.6 V to 2.2 V. The hydrogen atoms are oxidised at the anode and the electrons move through the external circuit from the anode to the cathode. The membrane of the PEM device is acidic in nature, its operation as an electrolyser is dependant on the hydrogen proton being conveyed by means of a hydronium ion in the membrane. The oxygen atoms are reduced forming an O₂ molecule that is removed as gas while the hydrogen protons move across the membrane to the cathode (negative terminal) where they are recombined with the electrons from the external circuit forming H₂ molecules. The purity of the product gases should be in the region of 99.9999% purity with only small traces of water vapour to found [5].

In the manner that the fuel cells current was dependant on the amount of catalyst used in the MEA, the current required to ensure that the reaction proceeds depends on the amount of catalyst in the electrolyser MEA.

Aside from the membrane, catalyst and GDL the PEM cell consists of bipolar plates that are used to electrically connect the cells in series. The design parameters followed in the development of all the components of the PEM cell will influence the performance and outputs of the unit considerably.

III. DESIGN PARAMETERS

A RFC stack consists of a number of cells connected electrically and physically in series to form a complete unit of any DC voltage that is required. In this instance, the RFC is designed to supply a 100 W primary load. The fuel cell is designed to incorporate easily obtainable materials (besides the MEA, which is currently imported).

A. Membrane

The membrane forming the heart of the RFC MEA is Nafion N-115 manufactured from 127 µm thick perfluorosulphonic PTFE copolymer. This durable membrane is chemically resistant, mechanically strong and allows hydrogen protons to move freely through it when hydrated. The membrane used in the RFC needs to be relatively robust in order to withstand the extreme effects of the electrolyser phase including the change over to the fuel cell operation. The Nafion N-115 membrane is coated with a catalyst in the form of Iridium/Ruthenium Oxide (IrRuO) at a rate of 0.04 mg.mm⁻² on the positive (oxygen) bi-functional electrode. The negative (hydrogen) bi-functional electrode is coated with a Platinum (Pt) black catalyst. Pt

black is a mixture of pure Pt particles that are mixed with Vulcan XC72 carbon powder so as to reduce the amount of Pt required, in the RFC the amount of Pt required at the negative electrode is in the order of 0.02 mg.mm^{-2} . The amount of catalyst used in the RFC is relatively high due to the bi-functional ability of the electrodes; in the modern discrete PEM devices, the amount of catalyst required could be as low as 0.002 mg.mm^{-2} . This amount of catalyst equates to a cost of around R65.00 per 1 kW of fuel cell [6].

The reactions at the electrode require the reactants to be well distributed over the catalyst Pt sites; this is achieved by using a gas diffusion layer.

B. GDL and Current collectors

The operation of the PEM device depends heavily upon three factors:

- Catalyst type and loading, this is required to promote the reactions at lower temperatures.
- Water management of the cell.
- Reactant type, flow rate and concentration used in the device.

The water management in the cell revolves around keeping the membrane hydrated enough with water molecules so as to ensure proton transfer, this takes place via osmotic-drag of the proton from the anode to the cathode. While the membrane needs to remain hydrated, it must not become too hydrated which results in the catalyst reaction sites becoming encased in water, known as flooding. Flooding prevents the reactant gases reaching the Pt particles with detrimental effects to the performance of the cell.

The GDL layer acts as a diffuser for the reactants and as an electrical connection between the membrane and bipolar plates. It ensures the series connection of one cell to the next while removing excessive water products from the reaction sites. Fuel cell designers refer to this action as the three-phase connection.

In the RFC cell the GDL plays a crucial role in both the electrolyser and the fuel cell phase. There are two basic types of materials used as the GDL for this purpose; these are carbon paper and carbon cloth. In this RFC, the material used is a woven carbon cloth that is filled in with carbon material and treated with a TEFLON type product; the complete carbon cloth is known as ELAT. ELAT like all other good GDL materials aids in the diffusion of the oxygen and hydrogen to the active electrodes while removing the product water and gases from the active sites ensuring good mass transport of reactants and products [7]. The ELAT used in the RFC is the LT1400. This ELAT is a low temperature woven material.

The GDL transfers electrons from the cathode of the cell to the anode of the next cell that is connected in series via a current collector plate known as the bipolar plate.

C. Bipolar plates

When more than one cell is used in the device these are connected in series via bipolar plates that transfer the electrons from the one cell to the next. The plates not only

act as the current collectors, they also transfer the reactant gases and liquids from one cell to another and assist in the removal of products. Bipolar plates are manufactured from a number of materials; the main aim of the designer is to ensure that the material used is as conductive (both electrically and thermally) as possible while being lightweight. The material of choice seems to be resin impregnated graphite plates that are machined into various designs. Graphite has a number of drawbacks such as cost of material and it is very abrasive making it difficult to machine in large quantities.

Two alternative materials have been used in the RFC in this project, they are a polymer composite known as ertacetal, this is non conductive but very easy to machine (a separate stainless steel mesh is joined to this material to act as the current collector). The other material of choice is aluminium (grade 2014), this is very conductive but in the chemical environment the aluminium is easily oxidised, therefore the plate is electroplated with a noble metal such as nickel that is stable in this corrosive environment. Various other authors have suggested a number of materials such as stainless steel, titanium and polymer composites bonded with carbon that are used as bipolar plates [1,3,6]. These are in their early stages of development and require extensive manufacturing processes.

The bipolar plate has various designs of grooves machined into the face of the material. These grooves or channels transport the products and reactants to and from the GDL. The various channel designs are extensive, however various authors [1-6] recommend using a variation of one specific design, the serpentine channel, seen in Figure 2.

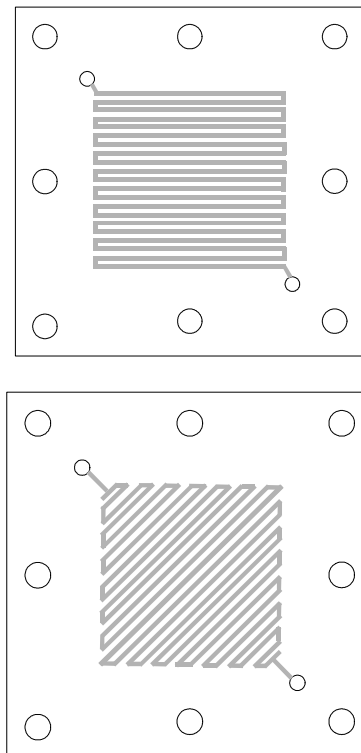


Figure 2 Various Serpentine (square and slanted) flow channels of RFC cell

This design is used in the RFC and has the benefit of preventing stale areas of un-reacted products from occurring

due to a constant pressure drop been maintained from the input to the exit. This prevents a build-up of water products or un-reacted products from occurring in any one area, which would prevent a flow of the reactants from occurring that in turn results in further un-reacted areas and a loss in cell performance.

The channels are designed to allow both liquid and gas to pass through them at the minimum of surface tension, the grooves are 1.15 mm wide, 1 mm deep with the area between successive grooves (called the land area) been optimally spaced at 1.2 mm.

Enough land area must be given in order to ensure low contact resistance losses between the MEA, GDL and bipolar plate while not been too excessive to prevent enough open area for reactants to flow through and make contact with the GDL.

The serpentine channels used in this design were machined into the various plates using a CNC milling machine (Roland MDX650) that was programmed using AutoCad design software and Dr. Engrave software. The aluminium plates were electroplated to a thickness of 20 microns using nickel.

Hydrogen is the smallest molecule known to man, it is very difficult to contain due to its size. Keeping this in mind various precautions had to be undertaken in order to ensure that the gas does not escape or move over from the anode to the cathode, the mixing of pure hydrogen and oxygen is very explosive and numerous cells have been lost due to this occurring. Thin silicon gasketing material, 500 microns thick, is used between the various components of the RFC to ensure gas tightness.

D. Reactants, pressure and temperature

The reactants used in the device, their concentration and the rate and temperature at which they are supplied have a dramatic effect on the working of the PEM device. The reactions and voltage obtainable from the device follows the Nernst equation closely, this equation takes the temperature, pressure and activity state of the reactants into account. The Nernst equation is:

$$E = E^0 + \frac{RT}{\alpha F} \ln \left[\frac{P_{H_2} \cdot P_{O_2}^{1/2}}{P_{H_2O}} \right]$$

Where

E \equiv Nernst Voltage, V

E^0 \equiv Reversible Voltage, V

R \equiv Universal Gas Constant = 8.3145 J.mol⁻¹.K⁻¹

T \equiv Absolute temperature, K

α \equiv molar transfer coefficients of the reactants

F \equiv Faraday Constant = 96,485 C.mol⁻¹

P_{H_2, O_2, H_2O} = Pressure Differentials of the Various reactants and products

It was seen theoretically and practically found that the devices operates at a higher efficiency and better voltages

when the temperatures were increased, the same effects were seen to occur at higher pressures. The effect of temperature is demonstrated for the electrolyser and the fuel cell in Figure 3.

The operating currents or rather the exchange current density (i_0) of the cell in either mode is obtainable from the Tafel slope equation and is related to the amount of electrons transferred and the temperature at which this takes place. The Tafel slope equation relates to the Nernst equation in the following way:

$$E = E^0 + b \log \left(\frac{i}{i_0} \right)$$

Where

b \equiv Tafel constant,

i_0 \equiv exchange current density, A

i \equiv actual current, A

Where

$$b = \frac{RT}{\alpha F}$$

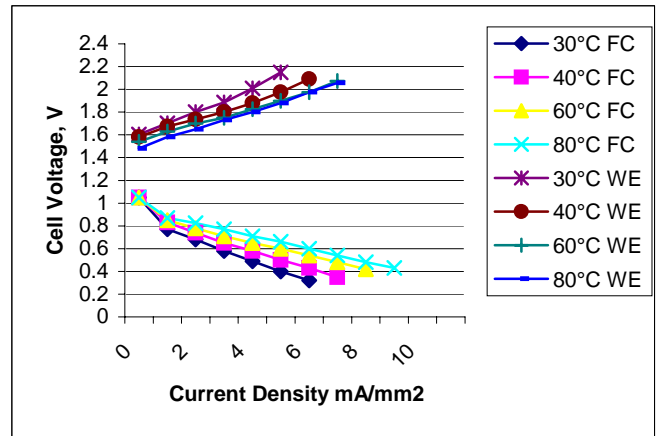


Figure 3 Effects of temperature on the operation of the Fuel Cell (FC) and Water Electrolyser (WE) reaction performed at 1atm pressure

The voltage that is obtainable in the reaction depends on the reactants used. Pure hydrogen and oxygen develops the greatest potential difference in the fuel cell. If air is used as the oxidant in the fuel cell instead of oxygen then the voltage is reduced due to thermodynamic losses, air contains approximately 21% oxygen, various authors state that the power difference between pure oxygen and air in a matched system differ by at least 30%. Taking this into consideration a greater amount of flow would be needed on the air electrode for the same voltage to be obtained in the hydrogen/air cell when compared against the voltage obtainable from the hydrogen/oxygen cell. In the RFC, the electrolyser produces pure products of hydrogen and oxygen thus it makes sense to rather use pure

It is found that in the 100 W fuel cell, 0.650 slm of oxygen and 82.13 x 10⁻³ slm of hydrogen gas must be supplied and completely used up to obtain a cell voltage of 0.65 V.

$$\begin{aligned}
O_2 \text{ used} &= 8.29 \times 10^{-8} \times \frac{P_e}{V_c} \text{ kg.s}^{-1} \\
&= 8.29 \times 10^{-8} \times \frac{100}{0.65} \\
&= 1.275 \times 10^{-5} \times 5.1 \times 10^4 \text{ (To get slm value)} \\
&= 0.650 \text{ slm} \\
H_2 \text{ used} &= 1.05 \times 10^{-8} \times \frac{P_e}{V_c} \text{ kg.s}^{-1} \\
&= 1.05 \times 10^{-8} \times \frac{100}{0.65} \\
&= 1.615 \times 10^{-6} \times 5.1 \times 10^4 \\
&= 82.13 \times 10^{-3} \text{ slm}
\end{aligned}$$

Where

P_e \equiv effective power, W

V_c \equiv cell voltage of a single cell, V

This amount of reactant flow that is calculated is known as the stoichiometry of one or $\lambda = 1$ of the fuel cell. A stoichiometry of one is the flow rate required of the reactants where all the reactants will theoretically be converted to produce the voltage of 0.65 V. The stoichiometric flow rates vary with temperature, pressure and current density. In the RFC at a temperature of 20 °C and pressure of 1 atmosphere, flow rates below $\lambda = 24$ can be used without drying out the membrane. This all depends on the relative humidity of the membrane and the temperature of reaction.

The humidity that the reactants are supplied has a huge effect on the water management of the cell; this varies from cell to cell. It was found that stacks operating even at the low power ranges of a few hundred watts require humidification. Units that do not use any form of humidification at high flow rates were found to perform up to 40% worse than the humidified versions.

It is found that stacks operating below 100 W effective power do not need extra cooling, normal convection and radiation is enough to remove the heat generated by the fuel cell. The electrolyser, as is seen in Figure 3, benefits from the heating of the water reactant up the temperature of 90 °C.

The pressure that the fuel cell operates at can be between one and three atmospheres. The higher the pressure the greater the power that can be obtained, this is due to the reduced oxygen electrode overvoltage [7]. Although the increased pressure increases the operating ability of the cell this come at a price to the system as the parasitic loss required to run the compressors are much higher than the power gained through the pressurised operation. RFC's can operate naturally at high pressure; the electrolyser of the RFC can store product gases in a bubble fashion up to pressures such as 3 atmospheres without mechanical stresses on the membranes. Larminie and Dicks [7] state that small systems lower than 1 kW in power should operate at ambient pressures while larger systems above 5 kW require the higher pressure in order to gain enough efficiency to make them worth while to operate.

IV. COMPARISON OF DRFC AND URFC

The planner of a remote telecommunication site must take a number of factors into consideration when deciding upon the type of fuel cell to replace the power supply and back-up power system. This includes whether the system will be made up of discrete components (DRFC) or of a combined unit (URFC). The decision on the type of setup will be determined by the size, cost limitations and the efficiency of both the electrolyser and the fuel cell (includes overall efficiency).

The DRFC consists of a separate electrolyser and a separate fuel cell that joins up to a common storage facility. The benefits of this set-up are that each of the components can be optimised for the best efficiency and power of operation. It allows both units to operate simultaneously and should one go faulty only the unit that needs replacing would require attention. The negative aspects of this system are that the size, weights and cost are greater than the URFC.

The URFC is a combined unit with greater energy density, less cost to power ratio and is very compact (it has greater power density and specific power ratios than the discrete system). The unit can only operate in one mode at any one time, either recharging the storage by electrolysis or delivering power via the fuel cell. Should the unit go faulty the entire stack would require replacement.

In the telecommunications environment the URFC would be ideal for the remote and cell site operation, as it is lightweight, durable and quasi maintenance free. The DRFC or URFC easily function as primary sources of power for sites with no grid connection, charging the system via renewable resources such as wind or solar converters. The DRFC requires a smaller storage unit for the hydrogen as compared to the URFC system.

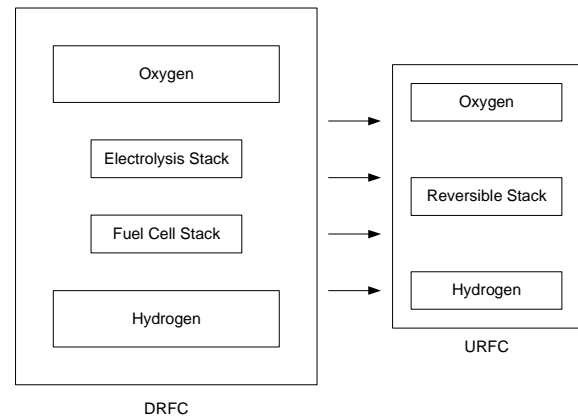


Figure 4 Comparison of the DRFC and the URFC

A. Efficiency of the RFC

The thermodynamic efficiency of the fuel cell at 25 °C and 1 atmosphere is found with the equation for the higher heating value (HHV), to be:

$$\begin{aligned}
\text{Max. efficiency possible, } \eta_{\max} &= \frac{\Delta \bar{g}_f}{\Delta \bar{h}_f} \\
&= \frac{237.13 \text{ kJ.mol}^{-1}}{285.84 \text{ kJ.mol}^{-1}} \times 100\% \\
&= 83\%
\end{aligned}$$

$\Delta \bar{g}_f$ is the Gibbs free energy of formation and $\Delta \bar{h}_f$ is the enthalpy of formation.

However if all the energy of formation is transferred into electrical energy and all overvoltage losses are considered then for the voltage at the HHV is:

$$E_R = \frac{-\Delta \bar{h}_f}{2F} = \frac{285.84 \text{ kJ} \cdot \text{mol}^{-1}}{2(96485 \text{ C})} = 1.48 \text{ V}$$

where

$E_R \equiv$ theoretical reversible voltage, V

$\Delta \bar{h}_f \equiv$ enthalpy of formation, $\text{kJ} \cdot \text{mol}^{-1}$

F \equiv Faraday Constant of 96485 C

The practical efficiency for the fuel cell is

$$\begin{aligned} \text{Cell Efficiency, } \eta_{\text{cell}} &= \frac{V_c}{E_R} \times 100\% \\ &= \frac{0.65}{1.48} \times 100\% \\ &= 43.9\% \end{aligned}$$

V_c is the average stack single cell voltage. The efficiency for the water electrolyser makes use of the same equation, but just as the fuel cell is the reverse action of the water electrolyses, so the principle and operation of the electrolyser are the reverse of the fuel cells:

$$\begin{aligned} \text{Cell efficiency} &= \frac{1.48}{V_c} \times 100\% \\ &= \frac{1.48}{1.59} \times 100\% \\ &= 93\% \end{aligned}$$

The water electrolyser suffers from the many of the same losses that the fuel cell encounters. Most of the energy losses and therefore the efficiency losses of the fuel cell arise due to heat that is given off by the reaction and expansion of the volume of the system. The electrolyser does not suffer from the heat management problems, it has fewer losses and is theoretically more efficient.

V. CONCLUSION

The PEM device can be operated as an electrolyser, converting excess renewable energy into long-term storable hydrogen, or as a fuel cell that converts the stored hydrogen into electrical energy. This set-up will remove the unpredictable nature of renewable resources and allows the telecommunications site planner greater freedom for design of the customer premises equipment (CPE) systems.

The PEM device's operation revolves around the transfer of the hydrogen proton; this is a characteristic of an acidic electrolyte reaction. A number of design aspects were analysed and found that the RFC can be used as a primary power device for remote site. The power capacity of this unit is 100 W; the device consists of a MEA, aluminium bipolar plates coated with nickel. These plates are machined into serpentine designed flow fields that allow the correct distribution of the reactant gases.

The supply rate of the reactants was calculated and the

flow rate analysed. It was found that for a 100 W system the supply pressure would remain at 101 kPa. The temperature of the reaction could be varied between 25 and 90 °C to improve the efficiency and power of the system.

The RFC is obtainable in two basic versions, the DRFC and the URFC. Both are suited for primary power supply with the URFC having the added benefit of having a greater specific power density and lower volume, this translates into a cheaper but more complex system. The efficiencies of the systems were then calculated and found to be significantly higher than the normal modes of energy conversion.

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