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Optimum Design of Photovoltaic / Regenerative Fuel Cell Power System for a Remote Telecom Station

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Abstract - *In this paper a hybrid power system of photovoltaic / regenerative fuel cell (PV/RFC) is introduced. The role of this system is the production of electricity without interruption for a remote telecom station. The studied system is proposed PV subsystem work as a primary source that converting a solar irradiation into electricity. The second working subsystem is the electrolyzer part in RFC which produces hydrogen and oxygen from water as a result of an electrochemical process using surplus energy. Produced hydrogen is sent to a storage tank. The produced hydrogen is used by fuel cell part for producing electrical energy to supply loads during deficit times. Optimum sizing of this hybrid power system is introduced and the obtained results are presented and discussed.*

Key Words: **photovoltaic, Regenerative fuel cell, sizing, hydrogen production, usage, efficiency.**

1. INTRODUCTION

Telecommunication Networks have changed the way people live, work and play. Since many people around the world are connected by telecommunication networks, the challenge to provide reliable and cost effective power solutions to these expanding networks is indispensable for telecom operators. In remote areas, grid electricity is not available or is available in limited quantities. In the past, diesel generators with backup battery were used for powering these sites. These systems, usually located in areas with difficult accessibilities require regular maintenance and are characterized by their high fuel consumption and high transportation cost. Also, due to the rapid depletion of fossil fuel reserves and increasing demand of clean energy technologies. Thus, stand-alone renewable sources can be a feasible solution for powering these sites [1]. Renewable energy resources are regarded as the future of energy sector.

A fuel cell can be used as the efficient energy conversion device for a hybrid generation system. Fuel cells are electrochemical devices that convert chemical energy, typically from hydrogen, directly into electrical energy. Among all types of fuel cells, proton exchange membrane fuel cell (PEMFC) is the most attractive one due to its high power density, low operating temperatures, low local emissions, quiet operation, and lower corrosion, simplification of stack design, fast start-up and shutdown. Therefore, alternative energy conversion systems such as PV panels can be co-operated with PEMFC in various autonomous and grid connected systems [2].

In all telecommunication applications, it is most advantageous to have a power supply that is self-sufficient, easily refuellable and reliable. The 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 [3].

The availability of solar energy is limited only on shiny days. Therefore, it is important to store the solar energy in other form of energy for the usage at night and gloomy weather. Hydrogen has been identified to be an ideal medium for this purpose with an important energy carrier with low harmful emissions, high – efficiency conversions into useful energy forms [4].

The role of this power system is the production of electricity without interruption in remote areas [5]. The objective of this work is Optimum sizing of hybrid PV/RFC power system for a remote telecom station is introduced

2. System description

Figure 1 shows the system components (photovoltaic generator, Regenerative fuel cell, electrical loads, load management & control unit and batteries)

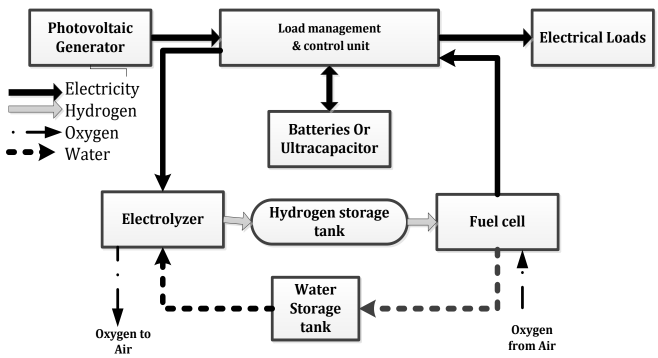

Fig -1: PV/RFC power system

3. Optimum Solar cells Area (OSCA) estimation

The output power of a PV panels can be obtained as follows [6]:

$$PVO(t) = SCA \times H_t(t) \times \eta_{cell} \times \eta_{pc} \times \frac{VF}{FS} \quad (1)$$

$$\eta_{cell} = \eta_{cr} \times [1 - 0.0062 \times (T_{cell}(t) - T_{cr})] \quad (2)$$

$$T_{cell}(t) = T_a(t) + \left(\frac{NOCT-20}{800}\right) \times H_T(t) \quad (3)$$

Where:

SCA: initial Solar Cell Area, m^2.

H_T: hourly solar radiation on the tilted surface, kW/m^2.

Ta: Ambient temperature, ^oC.

η_{cell}: hourly efficiency of the solar cell.

η_{pc}: efficiency of power condition.

VF: variation factor which influence on solar radiation from year to year. It is about 0.95,

FS: factor of safety includes data accuracy and weather conditions and dust (It is about 1.1),

T_{cell}: hourly cell temperature, ^oC

NOCT: Nominal Operating Cell Temperature, ^oC.

Energy balance is done between PV generated energy and energy required by loads, during yearly hours (8760 hour), that's for calculating optimum solar cells area. Energy balance can be done as follow:

$$\sum_{t=1}^{t=8760}\left(PVO(t) - P_{Load}(t)\right) = dE \quad (4)$$

Where,

$P_{load}(t)$: Hourly electrical load.

If dE> 0 then there is surplus energy, so SCA must be decreased by an incremental area and return calculations.

If dE< 0 then there is deficit energy, so SCA must be increased by an incremental area and return calculations.

If dE = 0 then there is no deficit or surplus energy, so SCA is the optimum area (SCA = OSCA)

4. Regenerative fuel cells

Generally RFCs come in two basic types: Discrete Regenerative Fuel Cells (DRFC) and Unitized Regenerative Fuel Cells (URFC). As shown in figure (2) DRFC has electrolyzer and FC stack in separate, and they can operate simultaneously. It would use an external power source (such as solar arrays) for hydrogen and oxygen production. This advantageous is not only for the energy storage, but also for life support and for auxiliary thrusters as well.

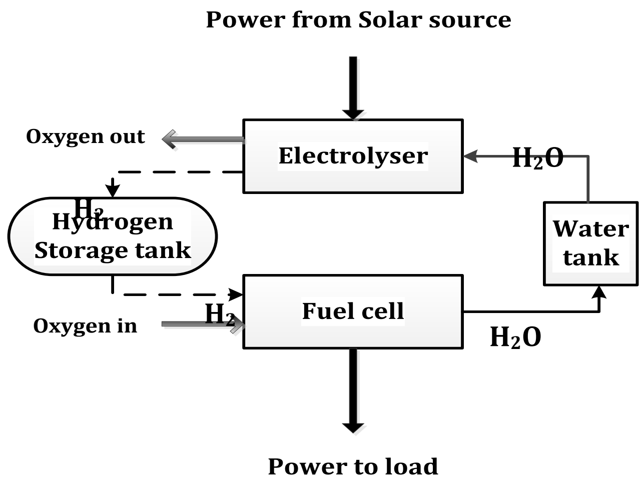

Fig -2: schematic diagram of DRFC.

URFC is a single device that has dual capability of functioning in either of two modes: Electrolyzer or Fuel Cell. Its essential difference compared to a DRFC is that in a URFC where the same physical cell is used both as the electrolyzer and fuel cell. In this paper DRFC is used in design.

4.1 DRFC operation and Methodology

Primary energy sources can be used to produce hydrogen by electrolyzer [8]. The basic equation of RFC is written as follows [9].

$$H_2O + Energy \leftrightarrow H_2(g) + \frac{1}{2}O_2(g) \quad (5)$$

It is required to design fuel cell power system for supplying telecommunication station with electric energy as backup power system. The communication station has certain hourly loads during year.

The input energy to electrolyzer for producing Hydrogen that stored and reused by FC part for generating electric energy that can be sufficient for supplying loads at deficit times. The hydrogen production from electrolyzer equals fuel cells hydrogen consumed and of course the generated electric energy from Fuel cell must be equal the deficit

$$P_{in} = \frac{P_{sur}}{(\eta_E * \eta_s * \eta_{FC})} \quad (6)$$

Where,

P_{in} : Input power must be inserted to electrolyzer.

P_{sur} : Surplus power that estimated from section (3).

η_E, η_s and η_{FC} : Efficiencies of electrolyzer, hydrogen storage and FC respectively.

The hydrogen production can be calculated as follow:

$$P_{in} = V_c \times I \times n \quad (7)$$

The hydrogen production flow rate (mole/s) can be expressed as [10]:

$$\dot{m}_{H_2} = \eta_E \frac{n_{cell} I_{in}}{2F} \quad [10, 11, 12] \quad (mol/s) \qquad (8)$$

From equation (7), (8) hydrogen flow rate is:

$$\dot{m}_{H_2} = \frac{P_{in}}{2 \times V_c \times F} \qquad (mole/s) \qquad (9)$$

Changing from mole/s to kg/s, the molar mass of hydrogen is 2.02×10^{-3} kg/mole, so this becomes

$$\dot{m}_{H_2} = 1.05 \times 10^{-8} \times \frac{P_{in}}{V_c} \qquad (kg/s) \qquad (10)$$

For converting hydrogen production flow rate to m³/h equation (10) is divided by hydrogen density ($\rho H_2 = 0.084$ kg/m³) and multiply by 3600 to have hydrogen production per hour

$$\dot{m}_{H_2} = 0.00045 \frac{P_{in}}{V_c} \qquad (m^3/h) \qquad (11)$$

The value of V_c can be calculated as:

$$V_{cell_{el}} = \frac{1.48}{\eta_E} \qquad [6] \qquad (12)$$

From equation (11), (12) hydrogen flow rate is:

$$\dot{m}_{H_2} = 3.04054 \times 10^{-4} \times \eta_E \times P_{in} \qquad (m^3/h) \quad (13)$$

Oxygen production flow rate is:

$$\dot{m}_{O_2} = \eta_E \frac{n_{cell} I_{in}}{4F} \qquad (mol/s) \qquad (14)$$

As in early Hydrogen production flow analysis, Oxygen production flow can be determined as follow:

$$\dot{m}_{O_2} = 1.52027 \times 10^{-4} \times \eta_E \times P_{in} \qquad (m^3/h) \quad (15)$$

The water consumption is 1 liter /Nm³ of hydrogen production [13].

Hydrogen Usage in fuel cell part

From previous analysis and the basic operation of the fuel cell, with output energy P_{eo} (kWh), hydrogen usage will be:

$$H_2\ usage = 0.00045 \times \frac{P_{eo}}{V_c} \qquad (m^3/h) \qquad (16)$$

The efficiency of FC is:

$$\eta_{FC} = \frac{V_{cell_{FC}}}{1.48} \qquad \text{(with referance to HHV)} \qquad [7] \qquad (17)$$

From equations (16), (17) hydrogen usage is:

$$H_2\ usage = 3.04054054 \times 10^{-4} \times \frac{P_{eo}}{\eta_{FC}} \qquad (m^3/h) \qquad (18)$$

Oxygen usage can be determined as above, so:

$$O_2\ usage = 1.52027027 \times 10^{-4} \times \frac{P_{eo}}{\eta_{FC}} \qquad (m^3/h) \qquad (19)$$

4.2 Efficiency of Regenerative fuel cell

If a RFC is used in a system to store electrical energy in the form of hydrogen and subsequently regenerate electricity from the hydrogen stored, the roundtrip energy efficiency of the overall energy storage system is given by:

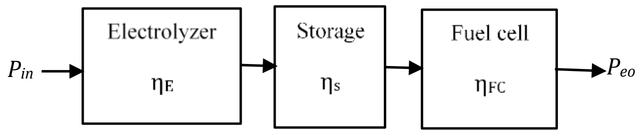

Fig -3: Scheme diagram of the efficiencies of RFC

From figure (3) P_{in} is the input power to RFC, η_E is the Electrolyzer efficiency, η_s is the storage efficiency, η_{FC} is the Fuel cell efficiency and P_o is the output and useful electric power from RFC, so,

$$P_{eo} = (\eta_E * \eta_s * \eta_{FC}) * P_{in} \qquad (20)$$

Thus

$$\eta_{RFC} = \eta_E * \eta_{FC} * \eta_s \qquad (21)$$

Efficiency of DRFC can be estimated from previous analysis as:

$$\eta_{RFC} = \frac{1.48}{V_{Cell_{el}}} \times \frac{V_{Cell_{FC}}}{1.48} \times \eta_s \qquad (22)$$

4.3 Hydrogen Storage

In general, there are three well-developed methods for storing hydrogen, i.e., 1) gaseous hydrogen storage, 2) liquid hydrogen storage, and 3) metal hydride storage [8] [14].

Compressed gas storage of hydrogen is the simplest storage solution. The only equipment required is a compressor and a pressure vessel. The only problem with compressed gas storage is low storage density, which depends on the storage pressure. Higher storage pressures result in higher capital and operating costs [15].

Compressed hydrogen gas tanks are the most popular because, unlike liquid hydrogen storage, they do not require refrigeration with the attendant insulation. Since the hydrogen molecule is small, compressed hydrogen systems demand greater care against leakage as compared with pressurized natural gas installations. Also, hydrogen tanks often are made from lighter materials, such as aluminum or carbon/ graphic compounds, than in the case for other gases. The advantage of liquid hydrogen is that its energy/mass ratio is three times greater than that of gasoline. It has the greatest energy density of any fuel in use (excluding nuclear fuels), and that is why it is employed in all space programs. However, its energy/volume ratio is low.

Most liquid hydrogen tanks are spherical, because this shape has the lowest surface area for heat transfer per unit volume. As the diameter of the tank increases, the volume increases faster than the surface area, so a large tank will have proportionally less heat transfer area than a small tank, reducing boil-off. Cylindrical tanks are sometimes used because they are easier and cheaper to construct than spherical tanks and because their volume/surface area ratio is almost the same [8].

Metal hydride hydrogen storage uses a specific metallic compound that acts as an absorber and releases hydrogen at constant pressure. The purity of hydrogen used has a direct relationship with the life of the metal hydride storage cylinder. This type of storage is suitable for hydrogen fuel cell cars, where empty cylinders can be exchanged easily for full cylinders [6].

Underground hydrogen storage is one of the most promising technologies for large-scale storage of low-pressure gas. Hydrogen can be stored in excavated rock caverns, salt domes, and depleted oil/gas fields.

Gas storage tank model

In the solar hydrogen power system, the simplest and most practical way to store the hydrogen gas is by compressing it, so we used cylindrical storage tank for the compressed hydrogen. The main parameters in designing the hydrogen gas storage were volume, pressure, and temperature. A cylindrical hydrogen storage tank was chosen. The storage volume was calculated based on a diameter of 1.5 m and a height of 2.60 m. Such a tank could be situated underground for safety reasons and to avoid excessive temperature fluctuations [8].

Since hydrogen behaves very much like an ideal gas in the ambient temperature. Therefore, the mathematical model for the hydrogen pressure p in a storage tank can be calculated from:

$$P = \frac{n\,R\,T}{V} \qquad [14]\ [15] \qquad (23)$$

Where
P: hydrogen pressure inside the tank, [Pa]
n: number of moles, [mol]
R: universal gas constant (8.31451), [J/K/mol]
T: temperature of the gas, [K] and
V: volume of the tank, [m^3]

Assume constant temperature then:

$$P_i \times V_i = P_f \times V_f \qquad [14] \qquad (24)$$

Where:
P_i : Initial pressure (bar)
P_f : Finial pressure (bar)
V_i : Initial volume (m^3)
V_i : Finial volume (m^3)

Then $$V_f = \frac{P_i \times V_i}{P_f} \qquad (25)$$

4.5 Materials balance

Hydrogen generated from Electrolyzer mode must be sufficient for storage and feed RFC at fuel cell mode to generate electric energy that can be feed load during defect hours

1. Hydrogen balance

Hydrogen is one of the products of Electrolyzer (mode or part). Hydrogen is stored in special tanks for reuse in fuel cell (mode or part) to generate electricity at deficit hours, so amount of generated hydrogen must be sufficient for generating electric energy that required in deficit hours, so Hydrogen produced from Electrolyzer part is equal to hydrogen consumed by fuel cell during yearly hours.

$$\sum_{i=1}^{i=8760} \left(H_{2_{consum.}} - H_{2_{prod.}}\right) = 0 \qquad (26)$$

Hydrogen storage tank can be estimated as follows:

Hydrogen storage tank size equals the maximum accumulated hydrogen produced during year divide by storage pressure

2. Water balance

There is water closed cycle [6] that take water to Electrolyzer (mode or part) in RFC to generate hydrogen and oxygen, then hydrogen is stored in special tanks, also in certain application, oxygen is stored in other tanks for reuse. Hydrogen and oxygen (pure or from air) are used to generate electricity from fuel cell (mode or part). During year hours:

$$\sum_{i=1}^{i=8760} (water_{consum.} - water_{prod.}) = 0 \qquad (27)$$

Also, consumed water equals product water during year.

Water tank storage size equals the maximum accumulated water during year

4.6 Solar cells Area required

OSCA that determined in item 3 makes surplus energy equal deficit energy but with using Fuel cell power system as backup power system there is energy loss as discussed earlier, so

$$SCA = \frac{P_{Tin_{sl}} \times OSCA}{P_{Tsur}} \qquad (28)$$

Where;

SCA: New Solar cells area, (m^2)
$P_{Tin_{el}}$: Total input power to electrolyzer during year.
P_{Tsur} : Total surplus power with OSCA.

5. Application and Results

Telecom stations must be covered all sites in any country. Any site can have one or more renewable energy source. In Egypt almost all sites have solar energy renewable energy. Other sites have wind energy beside solar energy as sites in Red Sea coast and Mediterranean Sea coast. The selected site is Marsa-Alam that located on southern red sea coast of eastern desert, the latitude and longitude of the selected site are: 25.0676° N and 34.8790° E [6]. Figure 3 shows the daily load curve for four months which represents the four seasons.

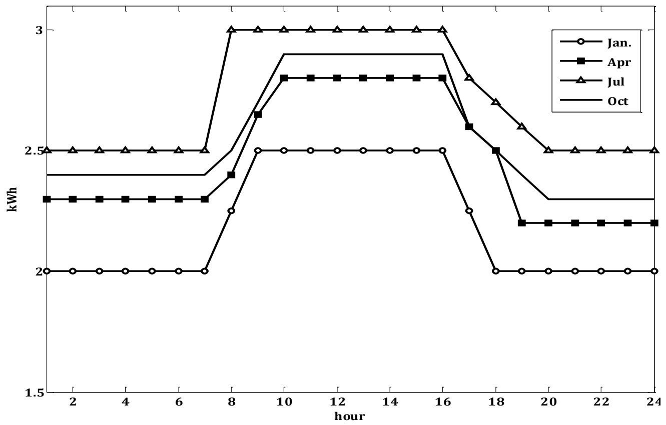

Fig -3: Average hourly electrical loads.

The characteristics of the selected PV modules (SPR-X22-360) can be found in [16].

From energy balance program results for selected PV module and monthly best tilt angle and latitude angle is OSCA = 50.262 m^2. Figure 4 displays the surplus and deficit energy through the year months.

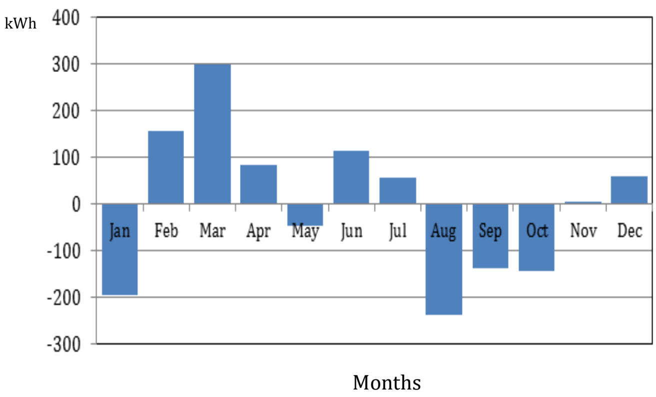

Fig -4: Surplus / Deficit Energy (kWh) during year

DRFC is used as backup power supply with electrolyzer part is HyLYZERTM-2, which has the specs in [17]. The fuel cell part of DRFC is H-3000 (FCS-B3000) that has specs in [18].

The output results from hydrogen balance is shown in figures 5 and 6

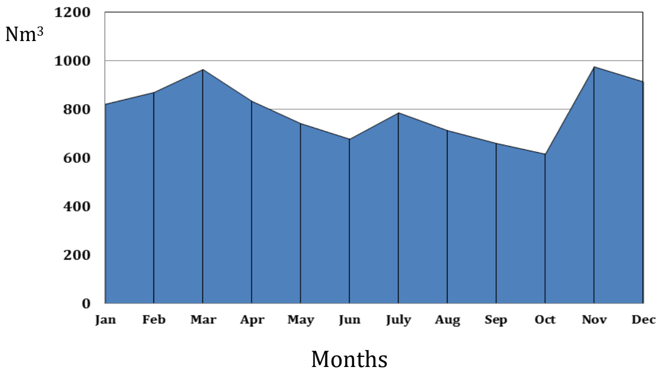

Fig -5: Hydrogen production during year, Nm^3.

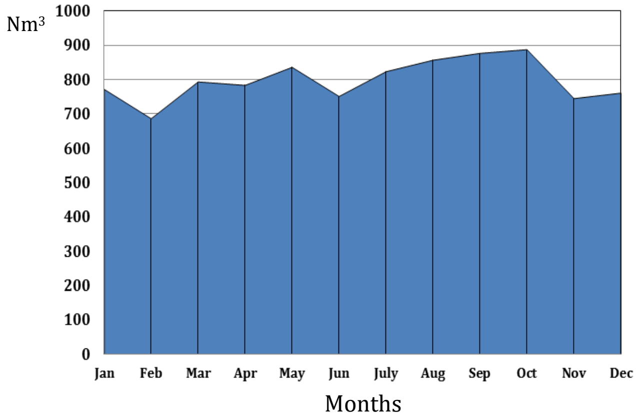

Fig -6: Hydrogen usage during year, Nm^3.

Figure 7 shows the hydrogen which can be stored in the tank and that taking from the tank during the year.

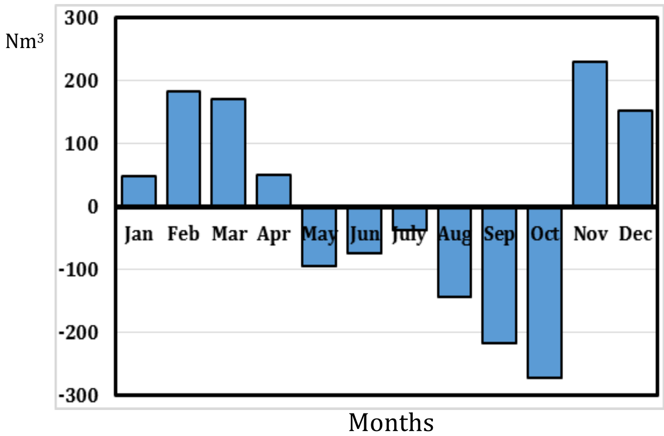

Fig -7: Hydrogen surplus/deficit during year, Nm^3.

From calculations and figure 7 hydrogen storage size equals 838.4367 Nm^3 at 1 bar (it equals the hydrogen surplus from Nov. to Apr.)

At 15 bar, hydrogen tank size is decreased to 56 Nm^3.

The value of total hydrogen surplus equals the value of total hydrogen deficit during year and this value is 838.437 Nm^3. Also the value of total water consumed equals the value of total water produced during year and this value is 0.838437 m^3, so, the required water storage tank size equals 0.8384367 m^3

At the end of year there is no surplus or deficit because surplus equals deficit during year, but it is advised to start the operation of this system at the first of November.

The required solar cells area (SCA) = 286.3677 m^2.
So, number of PV modules required = 175.7215 take 176 modules.

3. CONCLUSION

Sizing of (photovoltaic / Regenerative fuel cell) power system is introduced for remote telecom system. This system is one of the future power systems. Solar cells area and number of modules are determined, also size of hydrogen and water storage tanks are determined. There is no need for permanent source of water, because this system is closed so certain amount of water is cycling in electrolyzer and fuel cell.

REFERENCES

[1] Subodh Paudel, J.N. Shrestha, Fernando J. Neto, Jorge A.F. Ferreira, Muna Adhikari, " Optimization of Hybrid PV/Wind Power System for Remote Telecom Station", IEEE International Conference on Power and Energy Systems (ICPS), December 2011

[2] Yılser Devrim , Levent Bilir, " Performance investigation of a wind turbine–solar photovoltaic panels–fuel cell hybrid system installed at _Incek region – Ankara, Turkey" , Energy Conversion and Management 126 (2016) 759–766

[3] F. K. Swanepoel, MJ Case and Hcvz Pienaar , " A Unitised Regenerative Fuel Cell for Telecommunications Applications", The annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC 2005)

[4] A. Djafour, M.S. Aida, B. Azoui , " photovoltaic assisted fuel cell power systems", Energy Procedia 50 (2014) 306 – 313

[5] Djamila Rekioua, Samia Bensmail, Nabila Bettar, “Development of hybrid photovoltaic-fuel cell system for stand-alone application" international journal of hydrogen energy 39 (2014) pages: 1604-1611.

[6] Hassan A. Abu-ala, "Design and operation of PV/FC electrical power system as a stand-alone and as integrated with UG", Ph.D thesis, Faculty of Engineering, Elminia University, 2015.

[7] Arun Kumar Doddathimmaiah, " Unitised Regenerative Fuel Cells in Solar – hydrogen systems for remote area power supply", PhD thesis, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University June 2008

[8] Matouk M. Elamari , "Optimization of Photovoltaic-Powered Electrolysis for Hydrogen Production for a Remote Area in Libya", A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences, 2011

[9] Md Mamoon Rashid, Mohammed K. Al Mesfer, Hamid Naseem, Mohd Danish, “Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis” , International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-4 Issue-3, February 2015

[10] Joonas Koponen , Antti Kosonen , Vesa Ruuskanen , Kimmo Huoman , Markku Niemela and Jero Ahola, " Control and energy efficiency of PEM water electrolysers in renewable energy systems", international journal of hydrogen energy 42 (2017) pages:29648-29660),

[11] M. Hashem Nehrir, Caisheng Wang , "MODELING AND CONTROL OF FUEL CELLS Distributed Generation Applications", © 2009 by the Institute of Electrical and Electronics Engineers, Inc. Published by John Wiley & Sons, Inc

[12] H. Tebibel, R. Medjebour, "Comparative performance analysis of a grid connected PV system for hydrogen production using PEM water, methanol and hybrid sulfur electrolysis", international journal of hydrogen energy 43 (2018) pages: 3482-3498

[13] James Larminie and Andrew Dicks," Fuel Cell Systems Explained", book, 2nd ed., John Wiley & Sons Ltd, 2003

[14] Ugur Savas Selamogullari ," a systems approach for stand-alone residential fuel cell power system design", A Thesis Submitted PhD thesis, Electric Power Engineering, Rensselaer Polytechnic Institute Troy, New York, November 2005

[15] Abou El-Maaty M. M. Aly Abd El-Aal "Modelling and Simulation of a Photovoltaic Fuel Cell Hybrid System" PhD thesis, Faculty of Electrical Engineering, University of Kassel, Kassel, Germany, 2005.

[16] Sun Power® X-Series Residential Solar Panels | X22-360, www.sunpower.com/facts for more reference information.

[17] http://www.hydrogenics.com/

[18] http://www.tntrade.cz/horizon-h-series-pem-fuel-cell-systems-h-3000-fcs-b3000-3000w

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