ENERGY INJECTION INTO THE PUBLIC NETWORK FROM PARALLEL-CONNECTED SIMULATORS OF FUEL CELL AND ELECTROLYZER

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Abstract - **Difficulties in selecting fuel cells (FC) among the several types and commercial sizes hinder the development of FC energy systems not only because the inherent high costs and commercial varieties but by the danger of the hydrogen use during tests in inhabited places. Such difficulties and the need of demonstration of these innovations for the general public justify the development of a testing tool to obtain compatible results in real systems without much safety concerns. This paper proposes an energy system connected in parallel with the public network to be fed from fuel cell and electrolyzer simulators for evaluation of energy projects. They are useful in studies involving design and peak shaving of distribution systems. In general, residential loads have power peaks of some kW in between the 18 and 21 hours. Therefore, power simulators can be used for fine adjustments of the load factor of typical load curves, reducing the transmission, distribution and generation stresses and contributing for quality improvement of the delivered energy.**

Keywords - **Fuel cell, load curves, peak shave, hydrogen storage, power conversion, energy systems, grid connection.**

I. INTRODUCTION

The demographic growth, among other consequences, implicate in the increase of electric power demand. The generation, transmission and distribution systems of energy should follow this population growth in the same proportion. The typical consumption curve suffers accentuated increment in certain periods of the day, forcing an undue over sizing of the generation and distribution systems to attend the load peak, but being only partially used in other periods of the day [1]. This fact bring as a consequence the compromising with the quality of the available energy for consumption and the considerable increase of undesirable conditions in electric systems, such as the increase of reactive power, harmonic distortion, unbalance of voltage and/or current, over voltage, under voltage, electric noise, dips, sags, tilts, droops, frequency variation and increase of generation and distribution system stresses [4].

A way of smoothing the demand curve is to move the energy from the periods of low demand to the demand peak period throughout storage of energy under the form of hydrogen, which can be used later on to reduce the load peak [1]. Also, the system can serve as an auxiliary tool for study, demonstration, development, and design of production and energy storage under the form of hydrogen, converters for alternative energy as well as the interaction among most several types of fuel cell. As the cost and diversity of energy systems based on fuel cells is enormous, as much as in type, operation form and control, it becomes difficult for the planner to dispose and examine several models to select the best choice and configuration to be used for a given application. The commercial need for demonstration of energy systems based on FC for the general public turns the simulation of such system a powerful, flexible and no dangerous tool (because it does not use real fuel) along the decision studies.

Besides the existing basic topologies of fuel cell stacks and energy converters, there is in the literature a wide number of derivations and new solutions to solve specific problems [3,5,12]. This multiplicity brings plenty of attraction to simulators of real conditions of load to help in the final selection of which prototype and configuration to use. In addition to the reasons exposed above, it should also be deeply investigated the generation strategy and the more appropriate control technique for compensation of the increased electric power demand in the load peak period [8].

In this paper, it is assumed that the energy injected in the network to soften the load curve is generated by fuel cells fed by hydrogen locally produced by electrolysis. Additionally, storage of hydrogen is used in periods of lower electric delivery (dawn between 00:00 hs and 06:00 hs), to adjust the load factor of the demand curve.

II. DESCRIPTION OF THE SYSTEM FOR REDUCTION OF THE LOAD PEAK

Figure 1 depicts the diagram for the arrangement proposed in this paper using the public grid in parallel with the fuel cell and electrolyzer simulators for studies and project of alternative sources. The overall proposed systems is constituted by the public grid, production and storage of hydrogen, fuel cell stack, power converter connected to the public grid and an electric load curve representing the final consumer.

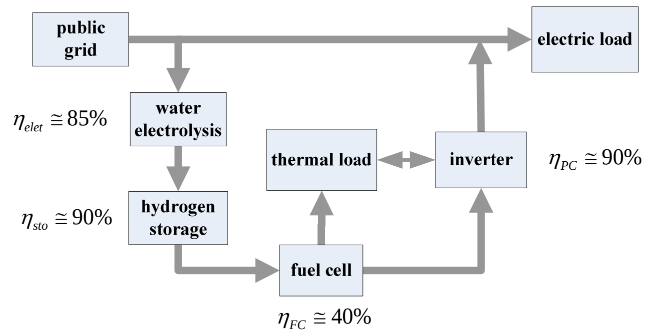

Fig. 1. Block diagram of the FC power peak shaving system

III. PRODUCTION AND STORAGE OF HYDROGEN

Hydrogen is one of the most promising ways for storage of energy in large scale and for long periods, due to the possibility of energy recycling aided by FC. It can be produced chemically by reform of hydrocarbons (methane, ethanol, methanol). This method, however, is not considered in this study by all the inconvenience of the constant need for hydrocarbon transport (very volatile combustible, typical odors and due to possible problems caused in the atmosphere, the toxity and, also for the contamination of the resulting hydrogen in this process). So, this work is focused on water electrolysis as a viable solution for production of hydrogen.

Among the several known methods for water electrolysis [6], the solid polymer water electrolyzer (SPWE) seems to bring the most comprehensive and ecological approach, since it operates only with water and electric energy [7]. Reference [21] observe that the power increase due to pressurized operation of SPWE is lower than the power consumption of the ordinary electrolyzer and compressor operation. SPWE can produce hydrogen from 1 to 135 bars at the cathode side. At present, this seems to be the most promising commercial technology.

So far, the most used methods to store hydrogen in large scale are pressurized tanks and cryogenic storage [6]. The pressurized tanks technology has the most mature technology and the best economical ratio, since it is been used for gas storage for decades.

The power needed for electrolysis and gas storage system operation depends on the electrochemical and thermodynamic relations. The electrolyzer is characterized by its current (1), related to the exchange current density at reference state i_{0ref}, operation temperature T, roughness factor γ_M, and stack voltage expressed by (2) [19,20].

$$i_{elet} = \gamma_M \exp\left[-\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right] i_{0ref} \qquad (1)$$

$$V_{elet} = V_0 + \frac{R.T}{F}\sinh^{-1}\left[\frac{1}{2}\left(\frac{i_{elet}}{i_{A0}}\right)\right] + \frac{R.T}{F}\sinh^{-1}\left[\frac{1}{2}\left(\frac{i_{elet}}{i_{C0}}\right)\right] + \left(\frac{L_B}{\sigma_B}\right) i_{elet} + R_I i_{elet} \qquad (2)$$

Where:

- F - Faraday constant.
- R - universal gas constant.
- V_0 - Nernst potential. -
- E - activation energy.
- i_{A0} - anode exchange current density.
- i_{C0} - cathode exchange current density.
- i_{0ref} - exchange density current at reference state.
- L_B - thickness of polymer electrolyte.
- σ_B - conductivity of electrolyte
- R_I - interfacial resistance.

In a similar way, the electrolysis process demands power as stated by (3).

$$P_{elet} = V_{elet} . i_{elet} \qquad (3)$$

In this paper the electrolyzer is fed by a AC/DC six-pulse buck converter.

The amount of the produced hydrogen Q_{H_2} [11], is expressed by (4)

$$Q_{H_2} = \frac{P_{elet} E_o}{F V_{elet}} \eta_{elet} \qquad (4)$$

The hydrogen produced by the electrolyzer is stored in metallic tanks [21]. The gas flows to the tank until the pressure of the tank is equaled to the pressure at the cathode side of the electrolyzer.

Figure 2 depicts the electrolyzer operating at several pressures as obtained from (1), (2) and (3), using the package Matlab.

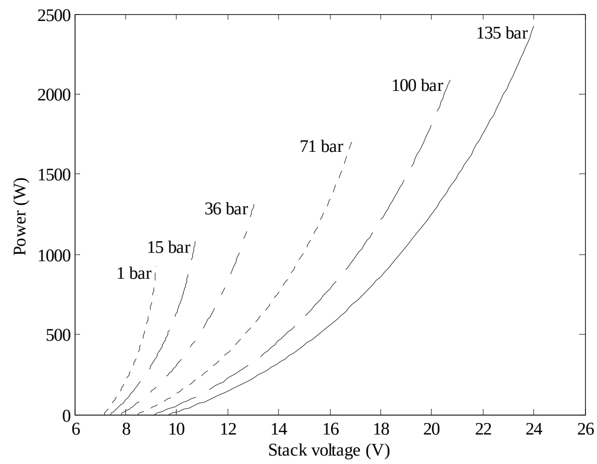

Fig. 2. Power characteristic of pressurized electrolyzer.

IV. FUEL CELL STACK SIZING

By the reasons commented in the introduction of this paper, the public grid is connected in parallel with fuel cell. The use of an FC simulator shows that not just the electric variables are important, but also the electrochemical variables. Among the electric variables (voltage, current and power) used in this FC simulator, this paper includes: humidity and temperature of the membrane, temperature of the heat exchangers, pressure of the hydrogen and oxygen or air.

The electrochemical variables do change with a moderate elevation of the operating temperature (something around 50 °C and 80 °C) and make possible recovery of the heat generated during the FC operation for usage with water or ambient heating [7,9]. Such kind of energy source can be used in residences, condominiums, small industries, "shopping centers", hospitals, public buildings and tends, for instance. The resulting simulator can operate in several conditions and configurations, programmed in computer in agreement with costs and technical needs of the load to be fed. The FC have its dynamic behavior according to the current density and terminals voltage [13,19]. The current density may be obtained through the Butler-Volmer relationship:

$$i_{FC} = i_o\left[\exp\left(\frac{-2\alpha F V_{act}}{RT}\right) - \exp\left(\frac{2(1-\alpha)FV_{act}}{RT}\right)\right] \quad (5)$$

Where:

i_{FC} - fuel cell current.
α - transfer coefficient.
V_{act} - activation overpotential.

the exchange density current, i_{FC} depends on the temperature and the oxidizer and reducer concentrations.

The voltage across the FC terminals is the result of a summation of the activation, mass transport, Nernst overvoltages and the ohmic losses [13].

$$V_{FC} = V_o - \frac{RT}{2F}\ln\left(\frac{P_{H_2O}}{\sqrt{P_{H_2}P_{O_2}}}\right) - b\ln\frac{i_{FC}}{i_o} - iR_{\text{int}} + \alpha_1 i^{-k}\ln(1-\beta i_{FC}) \quad (6)$$

Where:

P_{H_2O} - water pressure
P_{H_2} - hydrogen pressure
P_{O_2} - oxygen pressure
b - Taffel slope.
R_{int} - interfacial resistance
α_1 - molar mass concentration of O_2
β - molar mass concentration of H_2

The stack output power formed by N cells is given by (7):

$$P_{stack} = NV_{FC}i_{FC} \quad (7)$$

and the efficiency is given by (8):

$$\eta_{FC} = \frac{\mu_f . V_{FC}}{HHV}100\% \quad (8)$$

Where:

μ_f - fuel utilization factor.
HHV - high heating value of hydrogen.

V. SIMULATION OF THE POWER SYSTEM AND CONVERTER

The resulting voltage from the electrochemical conversion accomplished by the FC has a continuous behavior. In this case, the FC electricity is interfaced in parallel with the public grid by a power converter. To attend international norms [15,16,17] the converter is modulated by a space vector in high frequency For such, the active power supplied is maintained constant in order to minimize the harmonic distortion of current and/or voltage at the interconnection point [10]. The reactive power is maintained close to zero for an unit power factor operation. The converter is controlled by a proportional-integral technique, the reference voltages are transformed to the synchronous frame by the Park transform, processed by a control algorithm and used as the reference voltage for generation of the space vector pwm pattern (SVPWM).

The choice of SVPWM is indicated by the best use of the DC bus, reduced commutation losses and smaller current undulation [3], providing the best use for the FC energy.

The mathematical representation of the possible states for the semiconductor switches is stated by (9) as

$$u_k = \frac{2}{3}V_{FC}\exp\left(j(k-1)\frac{\pi}{3}\right) \text{ for } k = \{1,2,...,6\},$$
$$u_k = 0 \text{ for } k = \{0,7\} \quad (9)$$

The complex power S [17] supplied to the load is obtained from (10).

$$S = P + jQ = VI^* \quad (10)$$

where I^* is the conjugated complex of the inverter supplied current, given by (11):

$$I^* = \left[\frac{E\cos\delta + jEsen\delta - V}{j\omega Z}\right]^* \quad (11)$$

Where:

E - FC inverter voltage.
V - public grid voltage.
δ - power angle.

In a similar way, the active power P and reactive power Q supplied by the inverter is obtained from (12) and (13):

$$P = \frac{VE}{\omega Z}\sin\delta \qquad (12)$$

$$Q = \frac{VE\cos\delta - V^2}{\omega Z} \qquad (13)$$

Where:

Z - characteristic impedance.

The harmonic content generated by the inverter is always of a high order and it is easily filtered by components of small size. Figure 4 depicts the voltage and current waveforms obtained at the common coupling point at a switching frequency of 10 kHz

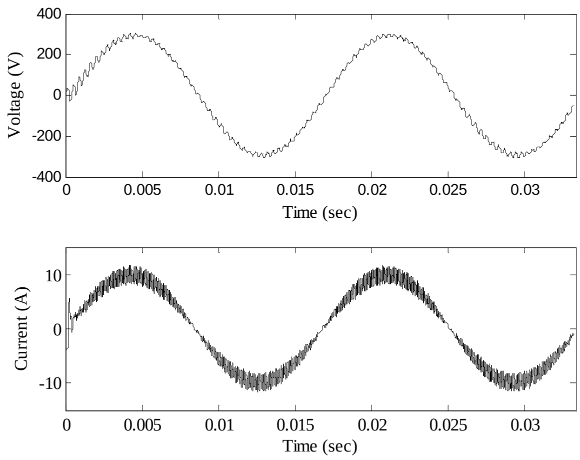

Fig. 4. Inverter output voltage and current

The THD calculated for the inverter output voltage waveform is 1.67 %, and 3.94% for current.

VI. INTERACTION WITH THE PUBLIC DISTRIBUTION NETWORK

Distributed generation (DG) presents attractive characteristics, since the point of view of quality of electric distribution systems to the decrease of transmission losses. The distributed generation power plants can be connected to medium and low voltage networks, located close to the consumers, reducing so considerably the losses associated to the long transmission systems. Besides that, the generation can receive or supply reactive power to the system, relieving the reactive power from the utility grid, turning the system stable under the point of view of voltage regulation, and improving the load factor of the installation, defined by (14):

$$load\ \ factor = \frac{kWh/hr}{peak\ demand} \qquad (14)$$

Figure 5 depicts the block diagram of the injection of energy system using the public network in parallel with simulators of fuel cell stacks and electrolyzers.

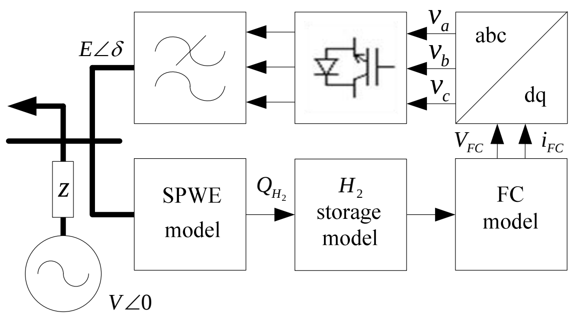

Fig. 5. Block diagram of the FC system operation in parallel with the public grid.

VII. COGENERATION SYSTEM

The excess heat of the operation of each energy subsystem of the FC simulator can be used for heating of water. The thermal energy of a given equipment (D) is $Q_{D\,k}$ $(k = 1, 2, 3, ..., M)$. The thermal amount stored as hot water is obtained from (15):

$$S_{sto} = \sum_{i=1}^{M} Q_{D\,k} - Q_{use} \qquad (15)$$

where Q_{use} is the amount of extracted heat.

Equation (16) determines the heat Q_{FC} produced by the FC stack operating at P_{stack}, during nh_{FC} hours.

$$Q_{FC} = P_{stack}\left(\frac{1.48}{V} - 1\right).nh_{FC} \qquad (16)$$

As stated by [18] the necessary power to heat up an amount of hot water estimated for 1 person (52.5 *l*) is (17):

$$P_{FC} = \frac{\left(52.5 n_p c\Delta T + Q_a + Q_{other}\right)V_{FC}}{\left(1,48 - V_{FC}\right)nh_{FC}} \qquad (17)$$

VIII. FINAL RESULTS

In the final results of this work, the overall efficiency is lower than the one given in (8), due to the non inclusion of efficiency of the production process and storage of the fuel, to the energy conditioning of the cell and the necessary energy for the subsystems. The global efficiency, therefore should be obtained through (19):

$$\eta_{system} = \eta_{elet}\eta_{sto}\eta_{FC}\eta_{PC} \qquad (19)$$

where the power converter efficiency η_{PC}, also includes the parasitic losses.

Figure (5) presents a typical load curve of the installation described in table 1. The adjustment of the load factor is accomplished by operation of the system, where a portion of energy is consumed during the period of dawn for production and storage of hydrogen. The use of an FC simulator in parallel with the public grid resulted in decreased demand peaks and improvement of the load factor.

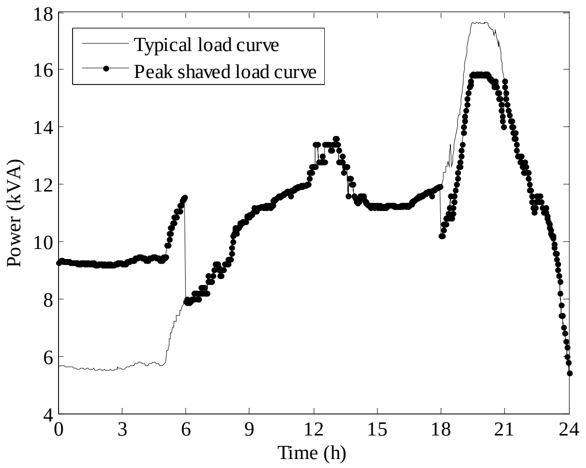

Fig. 6. Peak shaved load curve with power injected from the simulator

Simulation of fuel cell systems demands for several resources, as energy, water for electrolysis, hydrogen, oxygen for operation of an FC. As a project criterion, for injection of effective 2 kW in the public grid, the result obtained for this operation is considered and summarized in tables I and II.

TABLE I

subsystem	rated power	efficiency	result	observation
FC	5 kW	40 %	2 kWe and 2.3 *kJ*	electric/thermal
SPWE	3.5 kW	85 %	186.27 *l/hr* and 0.37 *kJ*	H_2 /thermal
inverter	2.4 kW	90 %	6.591% and 0.24 *kJ*	THD/thermal

During the electrolyzer operation there were consumed 592 l/h of de-ionized water, in a similar way, during the FC operation were produced 314 l/h of water at 75°.

TABLE II

subsystem	hydrogen	oxygen	water
FC	262 *l/hr*	524 *l/hr*	314 *l/hr*
SPWE	186.27 *l/hr*	372.54 *l/hr*	186.27 *l/hr*

In this simulation, for the operation of FC were used 192.75g of compressed hydrogen at the pressure of 135 bar.

Figure 7 depicts in the upper frame the public grid current and in the lower, the injected current by the fuel cell simulator.

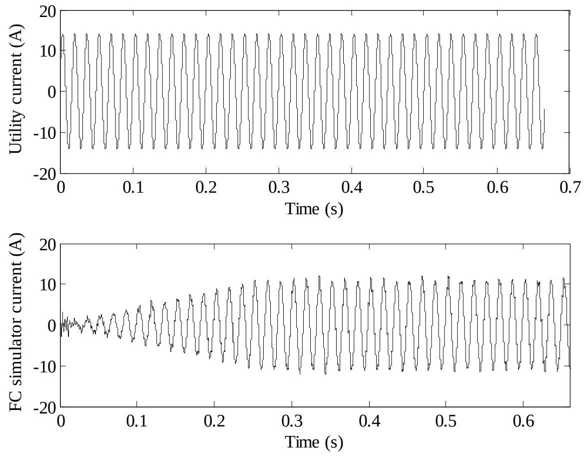

Fig. 7. Current at PCC

The resulting current of fuel cell simulator parallel operation with the public grid is presented by figure 8.

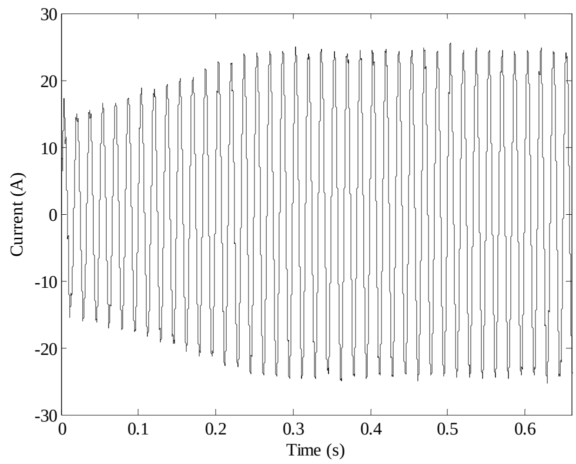

Fig. 8. Resulting current by the parallel operation

IX. CONCLUSION

Use of simulators for injection of energy into the public network can be as a powerful auxiliary tool in the evaluation of commercial, demonstrative, and didactic energy systems. Project development and adjustments can be easily and safely made according to the technical and economical needs or the relative efficiency. It can contribute for studies, development and consolidation of new technologies and techniques, and for the consequent reduction of the design costs and operation of FC systems.

Under operation of the parallel simulator, the temporary load factor during the load peak period was altered from 0.884 to 0.6750. In the dawn period, during the production and storage of the excess energy under the form of hydrogen, the load factor passed from 0.41 to 0.64.

The high cost of FC energy systems reinforces motivation for use of energy simulators, where several types of FC, power converters, production and storage systems of energy under the form of hydrogen can be safely tested, as well as the variation of parameters, conditions of operation of all related equipments.

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REFERENCES

[1] F.A. Farret, L.N. Canha, V.A. Popov, M.D. Zancan, J.B. Parizzi, F. Gonzatti, "Experimental Basis and Simulation Methodology for Fuel Cell Fed Converters Connected to Distribution Networks to Improve the Load Curve", *Power electronics specialists confrence*, pp. 1642-1646, 2005.

[2] S. Busquet, C. Hubert, J. Labbé, D. Mayer, R. Metkemeijer, "A new approach to empirical electrical modelling of a fuel cell, an electrolyzer or a regenerative fuel cell" *Journal of Power Sources*, vol. 134, pp. 41-48, 2004.

[3] N. Mohan, T. Undeland, W. Robbins, *Power electronics, Converters, applications and design*, John Wiley & Sons, 1995.

[4] E. Acha, *FACTS - Modelling and Simulation in Power Networks*, John Wiley & Sons, 2004.

[5] W. Vieltstrich, A. Larnm, H. Gasteiger, *Handbook of Fuel Cells: Fundamentals Technology and Applications, Volume 3: Fuel Cell Technology and Applications Part 1*., John Wiley & Sons, 2003.

[6] V. Ananthachar, J. Duffy, "Efficiencies of Hydrogen Storage Systems Onboard Fuel Cell Vehicles", Solar Energy, vol. 78, issue 5, pp. 687-694, 2005.

[7] I. Dincer, "Technical, Environmental and Exegetic Aspects of Hydrogen Energy Systems", *Int. Journal of Hydrogen Energy*, vol. 27, pp. 265-285, 2002.

[8] D. Asber, S. Lefebvre, M. Huneault, "Transient behavior of a distribution network incorporating decentralized generation" *Electrical Power and Energy Systems*, vol. 27, pp 195-203, 2005.

[9] E. Carcadea, H. Ene, D. Ingham, R. Lazar, M. Pourkashanian, I. Stefanescu, "Numerical simulation of mass and charge transfer for a PEM fuel cell", *International Communications in Heat and Mass Transfer*, vol. 32, pp. 1273-1280, 2005.

[10] M. Tanrioven, M. Alam, "Modeling, Control and Power Quality Evaluation of a PEM Fuel Cell Based Power Supply System for Residential Use", *IAS*, pp. 2808-2814, 2004.

[11] F.J. Barclay, *Fuel Cells, Engines and Hydrogen: an Exergy Approach*, John Wiley & Sons, 2006.

[12] F. Barbir, *PEM Fuel Cells: Theory and Practice*, Elsevier Academic Press, 2005.

[13] J. Larminie, A. Dicks, *Fuel Cell Systems Explained*, John Wiley & Sons, 2nd Edition, 2003.

[14] M. Tanrioven, "Reliability and cost–benefits of adding alternate power sources to an independent micro-grid community", *Journal of Power Sources*, 150, pp. 136-149, 2005.

[15] IEEE Standard 929, *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems*, IEEE, Inc., New York, NY, January 2000.

[16] IEEE Standard 1547, *Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE, Inc., New York, NY, July 2003.

[17] IEEE Std 399-1997 *Recommended Practice for Industrial and Commercial Power Systems Analysis*, IEEE, Inc., New York, NY, July 1997.

[18] L. Canha, V. Popov, F. Farret, "Optimal Characteristics of Fuel Cell Generating Systems for Utility Distribution Networks", *37th Intersociety Energy Conversion Engineering Conference (IECEC)*, 2002.

[19] S. Srinivasan, *Fuel Cells from Fundamentals to Applications*, Springer Link Inc., England, 2006.

[20] P. Choi, D. Bessarabov, R. Datta, "A simple model for solid polymer (SPE) water electrolysis", *Journal of Solid State Ionics* 175, pp. 535-539, 2004.

[21] D. J. Shapiro, M. Duffy, M. Kimble and M. Pien, "Solar-Powered renegenrative PEM Electrolyzer/Fuel Cell System", *Journal of Solar Energy*, vol. 79, issue 5, pp. 544-550, November 2005.