Modelling and simulation of solar-PV-wind fuel cell hybrid system for off-grid applications

ChogeD. K[1],. Rotich S. K[1], Waswa D[2], Tonui J. K[2], and Maritim J. K[1]

[1]*School of Science, Department of Physics, Moi University, P.o Box 3900-30100, Eldoret, Kenya*

[2]*University of Eldoret, P.o Box 1125-30100, Eldoret, Kenya*

Correspondence: *cdismas2004@yahoo.com*

Abstract

Developing countries have abundant renewable energy resources including solar energy, wind power, geothermal energy, hydro energy and biomass. With the increasing demand of sustainable energy, there is need to integrate these renewable energy sources to feed a stand-alone system. However, the biggest challenge is the need for energy storage systems, owing to the fact that energy from solar and wind are intermittent in nature. The combination of hydrogen storage using fuel cells may be a solution for long term storage of solar PV and wind power. Such a system when used for off-grid applications can provide energy solution to about one third of world's population leaving in isolated regions and have no access to grid connected electricity. The purpose of this proposed

study is to model and simulate a stand-alone hybrid power system that utilizes a hydrogen fuel cell for energy storage. This system couples a photovoltaic (PV) generator, an alkaline water electrolyser, a storage gas tank, a proton exchange membrane fuel cell (PEMFC) and power conditioning units (PCU) to give different system topologies. The system is expected to provide an environmentally friendly energy solution to populations living in remote areas far from the national grid.

Keywords: *renewable energy, fuel cell, Photovoltaic, wind power*

Introduction

Storage of electrical power generated in offgrid remote locations for longer has become a challenge in renewable energy field. Lead acid batteries can only be used for a few days. There is therefore need to introduce long term storage of electrical energy. This can be achieved by converting the generated electrical energy into hydrogen using an electrolyzer for use later in fuel cells. A lot of research work on fuel cells have been carried out by many workers in the field of renewable energy. Agbossow *et al*. (2000), described an intergrated renewable energy system for powering remote communication stations based on hydrogen. Their system was based on producton of hydrogen by electrolysis using 10kW wind turbine and 1kW PV array. From their findings, they noted that excess energy produced during strong winds can be used to produce hydrogen. When the wind conditions were low, the stand alone site produces electricity using PEMFC. They also showed that PEMFC stack can respond to fast load switching through a dc/dc converter
with efficiency-shatter>42%*etal*(2001). deisgnedTh. andE. El simulated hybrid photovoltaic (PV)-fuel cell generation system
using an electrolyser for hydrogen generation. Their study employed fuzzy regression model (FRM) for maximum power point tracking

to extract maximum available solar power from PV arrays under variable insolation conditions. Their system was suited for applications in remote areas. Their results however revealed that the output power from the FC is independent on the fluctuation in the solar insolation. Their study recommended use of electrolyser togenerate hydrogen during excess power from PV and storage of hydrogen in a tank for lower insolation levels or at night for FC operations. Giacomo and Gianhuca (2003), reviewed the state of the art of fuel cell systems and simulated the operation of a hybrid fuel cells plant in a 'typical hospital'. They analysed how this could optimize the hospitals energy requirements . Their results indicated hat 86 % of electrical energy could be provided by fue cells for the whole year. Sommer *et al*. (2004), modeled and simulated the dynamic behaviour of a fuel cell system using Matlab/Simulink. This sytem consisted of of an auto thermal gasoline reformer (ATR). The system under study was capable of adjusting to load changes within 20 seconds for load increase (10-90 % of full load) and within 3 seconds for load decrease (90-10 % of full load). An energy system consisting of PV, Wind and fuel cells was proposed by T. F. El-shatter (2005). In this study, the three energy sources were controlled to deliver optimum energy to a load using fuzzy logic control. A deisgn of management system to tame power flow between the system components for load requirements throughout the day was all carried out. From this study, they proved the accuracy of the fuzzy logic controllers in regulating the dc bus voltage in the whole range of wind speeds and solar insolation from the data used. They achieved this by studying the change in output voltage following an abrupt change in wind speed and/ or solar insolation in the presence of controllers. Their study aimed at supplying he load with its full demand while monitoring the pressure in the hydrogen tank. During the same year, Khan and Igbal proposed a small 500 W wind fuel cell hybrid system for stand alone operation in isolated communities. They further recommended a study of using ultra capacitors or other short term energy storage devices. In their study on dynamic modeling and simulation of small wind- fuel cell hybrid energy system , they used a 400 W small wind turbine, a PEM fuel cell, ultra capacitors, an electrolyser and a power converter. In this system, excess wind energy when available is converted to hydrogen using an electrolyser for use in fuel cell later. They noted that voltage variation at the output was within the acceptable limits. Mori and Hirose (2009), described the latest material and development for hydrogen storage technologies for fuel cell vehicles. Their discussion was based on the fact that vehicles cannot store enough hydrogen, thus the need to either compress hydrogen or to make it absorbed into a solid material. Sarawalee and Mali (2010), studied the effect of Membrane electrode assembly fabrication techniques on the cell performance of pt-pd/c electrocatalyst for oxygen reduction in PEM fuel cell. Their results indicated that the fabrication technique had very slight effect on the Ohmic resistance of the PEM fuel cell but significantly affected the charge transfer resistance and open circuit voltage (OCV). The department of electrical engineering at university of Basque country, spain, in 2010, reviewed and analysed the main characteristics of electrical micro-grids and the systems based on fuel cells for polygeneration and hybridization processes. The characteristics of micro-grids studied, combine energy systems to produce superior overall efficiency as compared to separated operation. The configuration allows for compensating the limitations of same technologies in terms of fuel flexibility, utilization of waste heat, pollution etc. Modeling and off-design performance of a 1 kW HT-PEMFC (high temperature proton exchange membrane fuel cell)-based micro-CHP (combined heat power) system was done by Alexandros et al (2011) for a Danish single family house hold. The system was simulated in labview™ environment to provide the ability of data acquisition of actual components. They proposed a system that can provide electric power, hot water and space heating for a single family. The efficiencies obtained in this study verified great potential for the HT-PEMFC. Soroush and shamiri (2011), reviewed mathematical modeling of SOFC. They pointed out modeling as a low cost method for studying and investigating the FC in order to optimize and control the FC behavoiur, increase its efficiency and performance and eventually decrease installation costs.Hydrogen storage technologies remain a challenge to overcome globally. Xiao et al (2012), developed a lumped parameter model for cyro-adsorptive hydrogen storage system. They used variational isosteric heat of adsorption based on Dubinin-Astakhov isotherm of adsorption. Simulation for charge-discharge cycle of adsorptive hydrogen storage system at cryogenic temperature was carried out using Matlab/Simulink. They studied material-based hydrogen storage besides available technologies such compressed hydrogen storage and liquid hydrogen storage. They further developed an axysymmetric geometry model of an activated carbon tank under room temperature (295 K) and moderate pressure (9mpa) using Fluent™, which analysed the heat and mass transfer during the charge process. They also developed a finite element model based on Cosmol multiphysics™ which adopts the variational adsorption heat and has been used for simulating the charge and discharge cycle of the hydrogen storage system.

Methodology

Electricity is by an array of PV solar panels and from a wind generator enough to meet the requirements of the user load. Whenever there is enough solar radiation and wind speeds, the generated electricity can be totally used to meet the users requirements. Any excess power is used to run an alkaline high pressure water electrolyser to produce hydrogen and oxygen at a pressure of maximum 30 bar. The gases are compressed in cylinders and can therefore be transported to other areas for use. A proton exchange membrane fuel cell (PEMFC) is used to keep the systems reliability at the same level as the conventional power systems. The PEMFC utilizes the gases produced by the electrolyser to meet the user load demand whenever the PV generator and wind generator energy is not enough, so that it works as an auxiliary generator. Power conditioning units (PCU) are used for conversion and dispatch of energy between the components of the system. The model library ISET-Alternative Power Library (ISET-APL) developed by the institute of solar energy supply technology (ISET) is used for the simulation of the hybrid system. The physical, analytical and empirical equations of each component are programmed and implemented separately in this library for the simulation software program Simplorer by C++ language. MATHCAD 2000 is used for computation of different parameters in the system. The model parameters are derived from manufacturers performance data sheets or measurements obtained from literature. The identification and validation of the hybrid system component models are evaluated according to the measured data of the components, from the manufacturers data sheet and actual system operation. The overall system is simulated at intervals of one hour each by using solar radiation and wind speeds as primary energy inputs and hydrogen as the energy storage for one year operation. Issues of cost is another challenge for such hybrid systems. Optimization and control strategies are necessary to optimally benefit from such systems. To fully understand the interaction between the renewable energy sources considered, multi-stage modeling using PVYST and HOMER for optimal sizing through modeling of different configurations in order to improve efficiency.

Expected output

A stand-alone renewable energy high efficiency system with hydrogen production and storage capable of meeting varying load demands.

References

Arashi H, Naito H, Miura H. Hydrogen production from high temperature steam electrolysis using solar energy.

International Journal of Hydrogen Energy 1991; 16(9): 603-608.

Badwal SPS, Ciacchi FT, Milosevic D. Scandia–zirconia electrolytes for intermediate temperature solid oxide fuel cell operation. Solid State Ionics 2000; 136-137: 91-99.

Bak T., Nowotny J., Rekas M., Sorrell C.C., Photo-electrochemical hydrogen generation from water using solar energy: materials-related aspects.International Journal of Hydrogen Energy 2002; 27(10): 991-1022.

Baker R., Future directions of membrane gas-separation technology. Membrane Technology 2001; 2001(138): 5-10.

Balachov II, Crouch-Baker S, Hornbostel M, McKubre M, Sanjurjo A, Tanzella F, Modular system for hydrogen generation and oxygen recovery. US DOE Hydrogen Program, FY Progress Report, pp. 363-366.

Berman A., Epstein M., The kinetics of hydrogen production in the oxidation of liquid zinc with water vapor. International Journal of Hydrogen Energy 2000; 25(10): 957-967.

Brahim C, Ringuede A, Cassir M, Putkonen M, Niinisto L, Electrical properties of thin yttria-stabilized zirconia overlayers produced by atomic layer deposition for solid oxide fuel cell applications. Applied Surface Science 253 (2007) 3962- 3968.

Chan SH, Xia ZT, Polarization effects in electrolyte/electrode-supported solid oxide fuel cells. Journal of Applied Electrochemistry 2002; 32(3): 339-347.

Chan S.H., Ding O.L., Simulation of a solid oxide fuel cell power system fed by methane. International Journal of Hydrogen Energy 2005; 30(2): 167-179.

Chen X.J., Chan S.H., Khor K.A., Simulation of a composite cathode in solid oxide fuel cells. Electrochimica Acta 2004; 49(11): 1851-1861.

Demirbas A., Hydrogen-rich gas from fruit shells via supercritical water extraction. International Journal of Hydrogen Energy 2004; 29(12): 1237-1243.

Doenitz W, Schmidberger R, Steinheil E, Streicher R, Hydrogen production by high temperature electrolysis of water vapour. International Journal of Hydrogen Energy 1980; 5(1): 55-63.

Douvartzides S., Coutelieris F., Tsiakaras P., Exergy analysis of a solid oxide fuel cell power plant fed by either ethanol or methane. Journal of Power Sources 2004; 131(1-2): 224-230.

Dunn S, Hydrogen futures: Toward a sustainable energy system. International Journal Hydrogen Energy 2002; 27(3): 235-264.

Dutta S, Morehouse JH, Khan JA, Numerical analysis of laminar flow and heat transfer in a high temperature electrolyzer. International Journal of Hydrogen Energy 1997; 22(9): 883-895.

Fuel cell handbook, Seventh Edition, EG&G Technical Services, Inc., U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, P.O. Box 880, Morgantown, West Virginia, USA, November 2004, pp. 57-60.

Goltsov VA, Veziroglu TN, Goltsova LF, Hydrogen civilization of the future – a new conception of the IAHE. International Journal of Hydrogen Energy 2006; 31(2): 153-159.

Hallenbeck P.C., Benemann J.R., Biological hydrogen production: fundamentals and limiting processes. International Journal of Hydrogen Energy 2002; 27(11-12): 1185-1193.

Hino R, Haga K, Aita H, Sekita K, R&D on hydrogen production by high-temperature electrolysis of steam. Nuclear Engineering and Design 2004; 233:363-375.

Hwang G.J., Onuki K., Simulation study on the catalytic decomposition of hydrogenm iodide in a membrane reactor with a silica membrane for the thermochemical water-splitting IS process. Journal of Membrane Science 2001; 194(2): 207-215.

Kogan A., Direct solar thermal splitting of water and on site separation of the products I. Theoretical evaluation of hydrogen yield. International Journal ofHydrogen Energy 1997; 22(5): 481-486.

Kreuter W., Hofmann H., Electrolysis: The important energy transformer in a world of sustainable energy. International Journal of Hydrogen Energy 1998; 23(8):661-666.

Licht S, Efficient solar generation of hydrogen fuel – A fundamental analysis. Electrochemistry Communication 2002; 4(10): 790-795.

Litster S, Mclean G. PEM fuel cell electrodes. Journal of Power Sources 2004; 130(1-2): 61-76.

Martinez-Frias J, Pham A, Aceves SM,. A natural gas-assisted steam electrolyzer for high-efficiency production of hydrogen. International Journal of Hydrogen Energy 2003; 28(5): 483-490.

Ni M., Leung M.K.H., Sumathy K., Leung D.Y.C., Water electrolysis – A bridge between renewable resources and hydrogen. Proceedings of The International Hydrogen Energy Forum, Volume I, p475-480, 25-28 May 2004, Beijing, P.R. China.

Steinfeld A., Kuhn P., Reller A., Palumbo R., Murray J., Tamaura Y., Solar-processed metals as clean energy carriers and water-splitters. International Journal of Hydrogen Energy 1998; 23(9): 767-774.

Tamaura Y., Steinfeld A., Kuhn P., Ehrensberger K., Production of solar hydrogen by a novel, 2-step, water-splitting thermochemical cycle. Energy 1995; 20(4): 325-330.

Wang C.Y., Gu W.B., Liaw B.Y., Miro-macroscopic coupled modeling of batteries and fuel cells – I. Model development. Journal of the Electrochemical Society 1998; 145(10): 3407-3417.

Yildiz B, Kazimi MS, Efficiency of hydrogen production systems using alternative nuclear energy technologies. International Journal of Hydrogen Energy 2006; 31(1): 77-92.