Australian Journal of Basic and Applied Sciences, 6(10): 249-256, 2012
ISSN 1991-8178

Optimal Sizing Method of Solar-Hydrogen Hybrid Energy System for Stand-alone Application Using Fuzzy Based Particle Swarm Optimization Algorithm

Halimeh Rashidi, Saeed Niazi, Jamshid Khorshidi

Mechanical Engineering Department, University of Hormozgan Bandar-Abbas, Iran

Abstract: This paper focuses on the optimal design of a solar-hydrogen hybrid based standalone energy system such that the optimized system provides reliable supply with minimum cost during the 20-years system life. From the design stand point, optimization of the size of a hybrid system is important which can lead to a good relation between cost and system's performance. In this paper two different configurations for fuel cell and photovoltaic hybrid system, including fuel cell-electrolyser unit for producing energy using hydrogen, and combination of battery with fuel cell- electrolyser unit is developed. The two configurations are optimized using Fuzzy based Particle Swarm Optimization Algorithm (FPSO) and the optimum configuration is selected considering efficiency and related costs.

Key words: standalone power system, PV panel, Fuel cell, electrolyser, battery, Fuzzy logic, PSO algorithm

INTRODUCTION

In recent years, the energy consumption is steadily increasing, at the same time the necessary tools for energy production are also faced with many problems. Now days, fossil plants are used to produce electricity, however, this option has many disadvantages such as high operating cost, air pollution, low efficiency and etc. Using renewable energy, particularly solar energy because of no limitation, reliability, simple technology, intermittent nature of energy sources and environmentally friendly, has a special place among the other energy. Although renewable energy have major advantages among other traditional methods of energy production, but due to the dependency of this resource to the weather conditions, its output energy may fluctuate a lot and not be consistent with the required energy. To overcome this issue and ensure availability of sustainable and uninterrupted electrical energy, it is necessary to store energy in large scale and for long period of time to. Energy storage is used for increasing reliability of the system and improving power quality. Battery pack is one of the popular options in energy storage (*Boquan, et al. 2008*). Stability of battery pack depends on some factors such as: response time of battery, discharge rate, life time and battery life cycle cost. Batteries can be used for daily storage but for seasonal storage, batteries are not practical because of the low storage capacity. Therefore, using only the batteries as storage system may endanger sustainability of supplying electrical energy. As fuel cells can convert hydrogen energy to electrical energy, storing energy in the form of hydrogen is another solution for both daily and seasonal storage of electrical energy. Hydrogen tanks are less costly than batteries and despite longer life, they need less maintenance. Therefore combination of fuel cell and electrolyser is a reasonable choice for energy storage (*Kaviani, et al., 2008*). Since the fuel cells are more efficient at low load profile, using the combination of battery with fuel cell- electrolyser as backup and storage system not only increases efficiency and life time of fuel cell, but also it provides a suitable and uninterrupted power supply. Fig 1(a) and 1(b) show the two configurations considered in this paper. The configuration in Fig. 1(a) consists of PV Panels, combination of battery and electrolyser as storage unit a Fuel cell fed by hydrogen (H2) from electrolyser to supply the system during critical periods and nights. The operation of this configuration is such that in the early morning when there is no solar energy available, the batteries supply the required power and when the battery SOC (state of charge) is lower than the allowable fractional state, the fuel cell works until PV panel is able to supply required power alone. At this time fuel cell becomes off and the battery can be recharged. When the battery SOC reaches its nominal value, the battery charging is stopped and the electrolyser is activated. With the excess load of PV panel, hydrogen will be provided by electrolyser and this activity will continue. The second configuration which is shown in fig 1(b) doesn't use batteries as storage system and only uses electrolyser supplied by PV for producing hydrogen from water electrolysis. The produced hydrogen is then stored in hydrogen tank and feeds the FC. The operation of this configuration is such that in the early hours of the day when there is not enough radiation (*Chaparro, et al., 2005*) to PV panels and enough energy, the fuel cell provides the required energy. When the panel can provide user load alone, fuel cell gets off and the excess load will be transferred to electrolyser and PV panel continues to operate and fills up the hydrogen tank.

Corresponding Author: Mechanical Engineering Department, University of Hormozgan, Bandar-Abbas, Iran

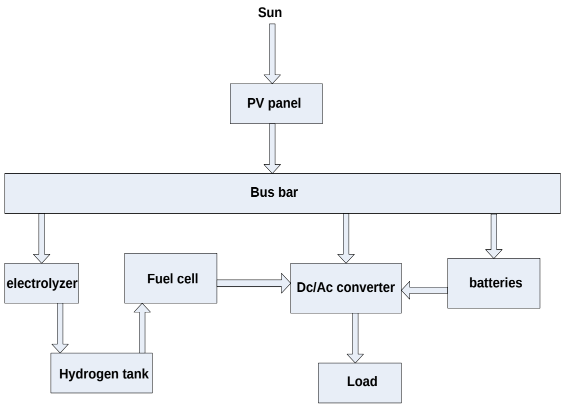

Fig. 1(a): Schematic of standalone power system consist of PV panel and combination of battery and fuel cell-electrolyser and hydrogen tank.

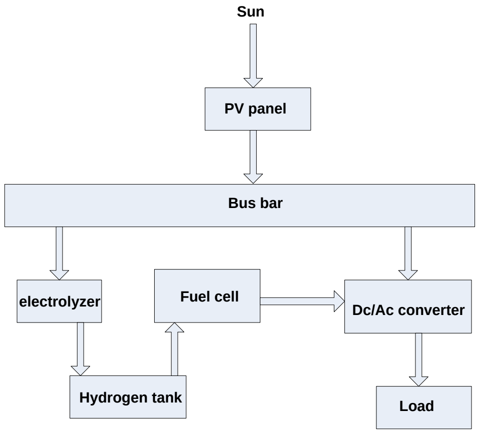

Fig. 1(b): Schematic of stand-alone power system consist of PV panel and fuel cell- electrolyser and hydrogen tank.

System Configuration:

Before sizing the system by PSO algorithm for minimization of generation cost for necessary power load, it is required to evaluate the load profile and solar power availability.

The first step in designing is determining the load profile that system should supply. The chosen daily profile is shown in figure (2).

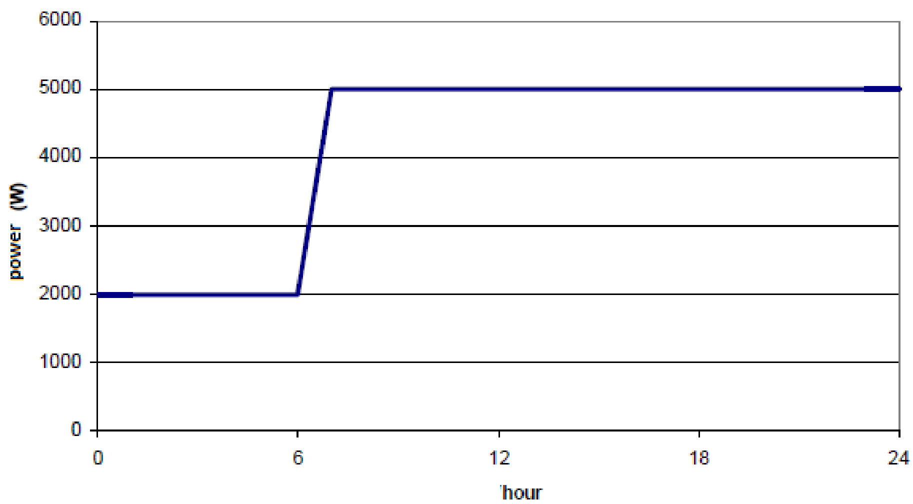

Fig. 2: Load profile on daily period.

As shown in fig (2) the required load is 5kw for hours between" 6 to 24" and for the rest of day the required load is 2kw. Therefore the required annual energy is 37.23Mwh. The second step in designing is related to the solar radiation. Obviously, the solar power is directly related to weather conditions. Figure (3) shows the variations of daily average radiation on the surface area 1 m^2over a year.

The last step is related to identifying the components of system and evaluating the role of each component in the system performance.

Description if the System Components:

A hybrid solar–Hydrogen energy system consists of Photovoltaic Panels, Fuel cell, battery bank, converter, electrolyser and other accessory devices and cables. In order to predict the hybrid system performance, individual components need to be modeled first and then their mix can be evaluated to meet the load demand.

Photovoltaic Panels:

Most of the commercial solar panels are made from silicon and according to the quality of the cells; the efficiency of the panels for converting energy from solar power into direct current can be in the range of 5% to 20% *(Lagorsea, et al. 2008)*. The performance of PV panels is noticeably affected by cell temperature. As the cell temperature increasing for a constant radiation, reduces the power output of PV panels. The decrease in output power is about 7% per degree centigrade increasing of cell temperature *(Agbossou, et al., 2004)*. PV power output can be calculated from the equation (1).

$$P_{PV} = \eta_{PV} . A_{PV} . Insulation \qquad (1)$$

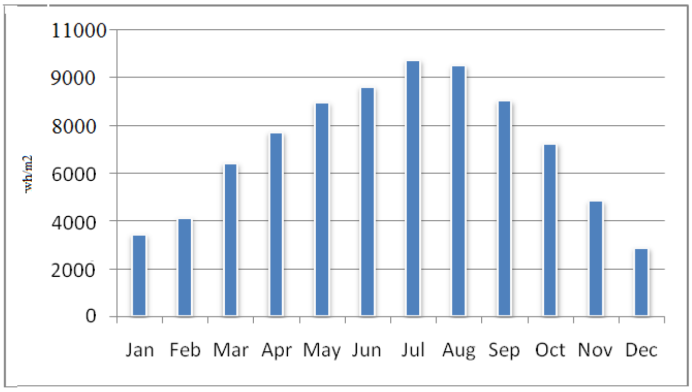

Fig. 3: Daily average insolation (wh/m^2).

Where *Insulation (t)* is the insulation data at time t (W/m^2), A_{PV} is PV surface (m^2), and η_{PV} is the overall efficiency of the PV panel. On the PV models, the effect of temperature on the surface is neglected.
Technical properties of PV panel are shown in Table (1).

Table 1: PV panel technical properties.

Photovoltaic Panels	
Maximum Power	130 Watt
Nominal cell temperature	47 $^\circ C$
I_{sc}	6.47 A
V_{oc}	19.9 V
V_{max}	15.5 V
I_{max}	5.94 A
Module unit	0.946 m^2

Fuel Cell:

The fuel cells supply the required load when there is not enough solar radiation. Fuel cells use hydrogen as fuel under normal temperature conditions (from 30 to 200°C and can work with a pressure of 1 atm). The fuel cell power can be calculated according to the maximum load required. Stack electrical efficiency for commercial fuel cell is about 40%, nominal power is 500w and operating temperature of fuel cell is 40℃. Life time of fuel cell is about 5000 hours of fuel cell performances.

Battery:

The chosen battery in standalone power system is regular lead acid battery; the efficiency of this technology is about 90%, and their life time is 5 years. In standalone power system batteries are used for daily storage to assist the fuel cell in the peak hours. The battery input power can be positive or negative depending on the charge or discharge mode. The state of charge (SOC) is obtained from the battery power and efficiency

$$Soc_{bat} = \int \left(P_{Bat,charge} \times \eta_{Bat} - P_{Bat,discharge}\right)dt \tag{2}$$

The battery stack has a maximum and a minimum allowable fractional state of charges (SOC_{max} and SOC_{min}) set to 0.8 and 0.4 because of the safety and efficiency reasons (*Zhou , et al., 2009*):
The battery power is obtained from the equations (3) and (4):

$$P_{Bat} = P_{PV} + P_{FC} - P_{load} \quad (SOC < SOC_{min}) \tag{3}$$

$$P_{Bat} = P_{PV} - P_{load} \quad (SOC > SOC_{min}) \tag{4}$$

Electrolyser:

For this system, PEM electrolyser is used, PEM electrolysers have lesser parasitic losses and higher efficiency compare to alkaline electrolysers which also decreases the cost of hydrogen production (*Pedrazzi, et al., 2010*).

The electrolyser power when battery is charged ($SOC = SOC_{max}$), can be obtained from equation (5)

$$P_{electrolyzer} = P_{PV} - P_{load} \tag{5}$$

Electrolyser SOC is determined with difference between amount of hydrogen produced by electrolyser and hydrogen consumed by fuel cell i.e.:

$$Soc_{electrolyzer} = \int \left(P_{electrolyzer} \times \eta_{electrolyzer}\right)dt - \int \left(\frac{P_{FC}}{\eta_{FC}}\right)dt \tag{6}$$

The average efficiency of electrolyser is about 70%, electrolyser nominal power for 50 ℃ cell temperature is 25kw and for 80 ℃ cells temperature is 33Kw and peak power is 1200W (*Konstantinos, et al. 2004*). PEM electrolyser life time is 10 years and Over 20 years in system performance needs to be replaced once.

Optimization of the System:

In order to efficiently and economically utilize the solar-hydrogen hybrid Energy System, an optimum design sizing method is necessary. Various optimization techniques such as the genetic algorithm, ant colony optimization, and simulated annealing method have been recommended by researchers. In this paper, one optimal sizing model based on fuzzy PSO for a stand-alone hybrid solar-hydrogen system is developed. The optimization procedure aims to find the configuration that yields the best compromise between the two considered objectives: efficiency and total cost. This configurations can be obtained by an optimization technique such as FPSO, which it is generally robust in finding global optimal solution s, especially in multi-objective optimization problems, where the location of the global optimum is a difficult task.

PSO Algorithm:

Particle Swarm Optimization (PSO) is an approach to problems whose solutions can be represented as a point in an n-dimensional solution space. In this approach a number of *particles* are randomly set into motion through this space. At each iteration, each particle keeps track of previous best position and the best particle in the swarm. The previous best value is the best solution it has achieved so far. This value is called *pbest*. Another "best" value that is tracked by the PSO is the global best value, obtained so far by any particle in the population. This best value is called *gbest* .The new velocity and position of each particle are dynamically updated by the following equations (*Hong, et al., 2009*):

$$v_{id}(t+1) = \omega v_{id}(t) + c_1 r_1 (pbest - x_{id}(t)) + c_2 r_2 (gbest - x_{id}(t))$$
$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \tag{7}$$

Where the acceleration coefficients c_1 and c_2 are two positive constants; ω is an inertia weight and r_1, r_2 is a uniformly generated random number from the range [0, 1] which is generated every time for each iteration. Proper control of global exploration and local exploitation is crucial in finding the optimum solution efficiently to PSO algorithm. Equation (7) shows that, when calculating the new velocity for a particle, the previous velocity of the particle (v_{id}), their own best location that the particles have discovered previously (x_{id}) and the global best location $gbest$ all contribute some influence on the outcome of velocity update. The global best location is identified, based on its fitness, as the best particle among the population. All particles are then accelerated towards the global best particle as well as in the directions of their own best solutions that have been visited previously. While approaching the current best particle from different directions in the search space, all particles may encounter by chance even better particles en route, and the global best solution will eventually emerge (*Fei, et al., 2009*). The inertia weight ω is critical for the convergence behavior of PSO. A suitable value for the inertia weight usually provides balance between global and local exploration abilities and consequently results in a better optimum solution. To balance between global and local exploration abilities, inertia weight is adjusted dynamically to control the process of algorithm. Due to the lack of knowledge of the searching process, it is very difficult to design a mathematical model to adapt this parameter dynamically. Hence the fuzzy adaptive PSO is proposed to design a fuzzy system, which dynamically adapts the inertia weight for the optimal sizing method of solar-hydrogen hybrid energy system. The Mamdani type fuzzy rule is used to formulate the conditional statements that comprise fuzzy logic. The fuzzy control strategy is used to map the outputs from the given inputs. The AND operator is used to combine the membership values for each fired rule to generate the membership values for the fuzzy sets of output variables in the consequent part of the rule. Method of centroid (center-of-sums) is used to obtain a deterministic control action. To obtain a better inertia weight under the fuzzy environment the variables selected as input to the fuzzy system are the current best performance evaluation and current inertia weight, whereas output variable is the change in the inertia weight. Typical inertia weight value is $0.3 < \omega < 1$. Both positive and negative corrections are required for the inertia weight. Therefore, a range of -0.1 to 0.1 has been chosen for the inertia weight correction.

$$\omega(t+1) = \omega(t) + \Delta\omega \tag{8}$$

All the memberships of input are presented in three linguistic values; S, M and L for Small, Medium and Large, respectively in Table 1. Output variable is presented in three fuzzy sets of linguistic values; N (Negative), Z(Zero), and P(Positive) with associated membership functions. In this paper the acceleration coefficients c_1 and c_2 are $c_1 = c_2 = 2$.

Objective Function:

The aim of this study is to achieve a standalone power system optimization with PSO algorithm; algorithm output includes the number of required components such as the number of PV panels, fuel cells and battery capacity. The number of components should be optimized so that the system required load can be supplied with high reliability.

For sizing optimization, in addition to minimizing components generation and maintenance costs, it is so important to store enough energy in the hydrogen tank and batteries to use in critical periods (*Lai, et al., 2009*).

The function that must be optimized is the system performance and system costs in 20 years which includes capital cost and also maintenance and operation costs.

This function is defined as a summation of system component cost such as PV panels cost (f_{PV}), battery cost (f_{BAT}), FC cost (f_{FC}) and electrolyser cost ($f_{electrolyser}$).

$$f(x) = f_{PV} + f_{BAT} + f_{FC} + f_{electrolyser} \quad \begin{Bmatrix} f_i = N_i \times \left[C_i (Y_i + 1) + M_i (20 - Y_i + 1) \right] \\ i = BAT, PV, FC, ELECTROLYZER, Conductor \end{Bmatrix} \tag{9}$$

Where N_i is the number/size of the system component; C_i is the capital cost, M_i is operation and maintenance cost and Y_i the number of replacement in the system life time (*Mousavi, et al., 2007*).
The proposed system optimization parameter should be within certain range

$$X = \lfloor N_{PV}, N_{BAT}, N_{FC}, N_{electrolyzer} \rfloor$$
$$N_{PV}, N_{BAT}, N_{FC}, N_{electrolyzer} > 0 \tag{10}$$

System shown in fig 1(b) does not use battery therefore in the objective function $f_{BAT} = 0$. To achieve the high reliability in the system it is necessary the supply load by system being greater than the load required, i.e. $P_{Supply} \geq P_{demand}$. In the critical period and also early morning hours, the required load is supplied by batteries and fuel cell, therefore battery energy at the end of the day (in normal condition) should be equal or greater than the battery energy at the beginning of the day.

$$P_{bat,min} \leq P_{bat} \leq P_{bat,max}$$
$$P_{H_2,first} \leq P_{H_2,end} \tag{11}$$

The cost of system components can be seen in Table (2).

Table 2: System components cost.

components	Life time	Capital cost ($)	Replacement and maintenance cost ($/year)
PV panel	20 (years)	4.84 ($/w$_{peak}$)	3
Fuel cell	5000 hours	8($/W)	6 ($/W)
electrolyser	10 years	30($/W)	15($/W)
Battery	5 years	20 ($/kwh)	0
DC/AC convertor	5 years	2410 ($)	25

Simulation Results:

The following optimization model is a simulation tool to obtain the optimum size or optimal configuration of a hybrid solar–hydrogen system by using a FPSO algorithm. An initial swarm of 10 chromosomes, comprising the 1st generation, is generated randomly and the constraints described by inequalities (10)–(11) are evaluated for each chromosome. If any of the initial population chromosomes violates the problem constraints then it is replaced by a new chromosome, which is generated randomly and fulfills these constraints. With the optimization of configurations shown in figure 4(a) and 4(b), the cost are estimated and presented in Table (3). The second configuration shown in figure 4(b) is more costly than configuration shown in figure 4(a), because this configuration uses only the hydrogen storage for critical periods, because of lower efficiency of hydrogen storage compare to combination of hydrogen and batteries storage, the second configuration need more PV panels to produce more energy for maintaining high reliability. Furthermore the fuel cell is also more powerful to supply required power when there is not enough radiation and this causes decreasing the fuel cell life time, therefore the fuel cell cost also increases. Figure 5 represents the convergence properties of the FPSO in the process of searching for the minimization of objective function. It is clear from the Figure 5 that the proposed method can avoid the shortcoming of premature convergence and can obtain higher quality solution with better computation efficiency and convergence property. The CPU execution time of proposed algorithm and comparing the execution time obtained from FPSO algorithm is about 23 seconds.

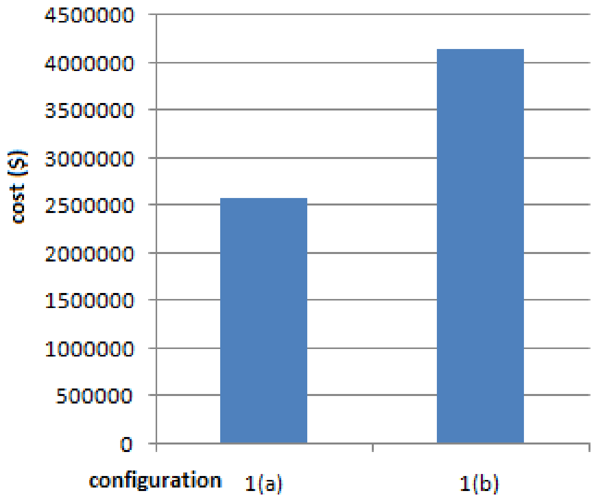

Fig. 4: Cost comparison of two configurations.

Table 3: Details of optimization.

Configuration	System 1(a)	System 1(b)
PV panels number	235	380
Battery capacity	90 Kwh	0
Hydrogen tank volume	35 m^3	40 m^3
Fuel cell operation hours	10.2	15.4
Total cost ($)	2589580	4171458
Global efficiency (%)	Up to 50%	Below 50%

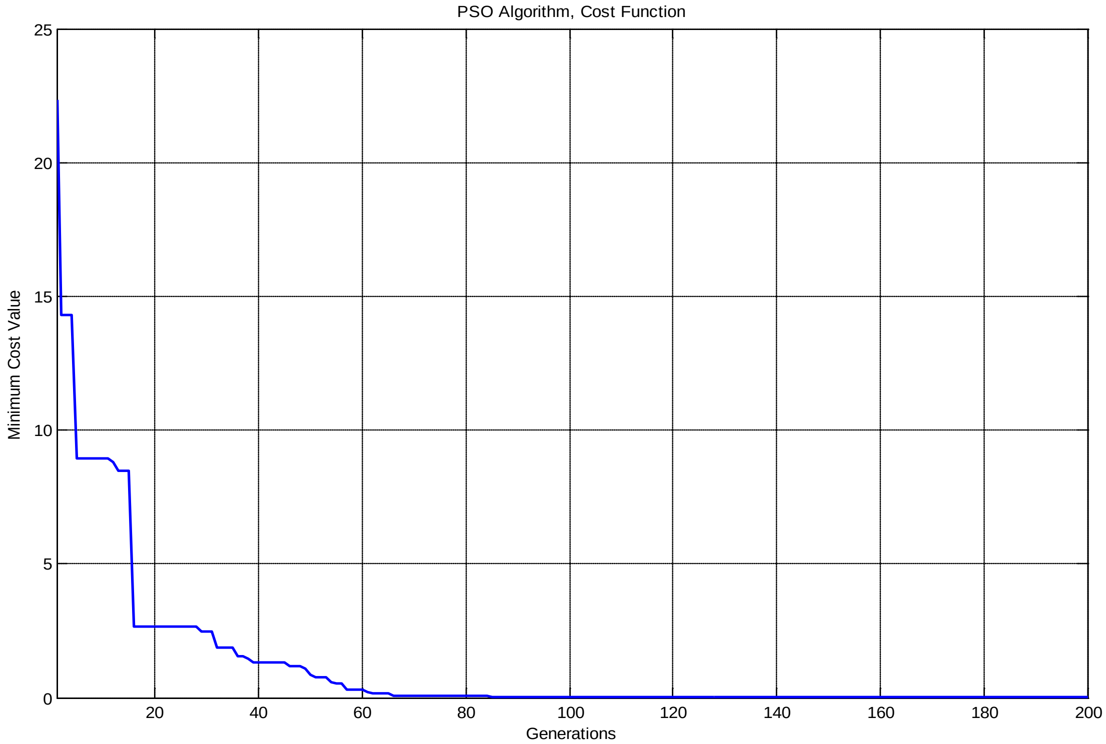

Fig. 5: Convergence behaviors of FPSO Algorithm.

Conclusion:

The main goal of this paper is choosing the best configuration of standalone power system with appropriate economic justification and high reliability, therefore FPSO algorithm was used to optimize two different configurations of fuel cell and photovoltaic hybrid system. Two proposed configurations were optimized and the optimization results were compared; finally the best configuration of system was selected. This configuration includes PV panels, fuel cell, electrolyser, hydrogen tank and batteries for storage energy. Because the fuel cells are more efficient at low load profile, using the combination of battery with fuel cell- electrolyser as backup and storage system not only increases efficiency and life time of fuel cell, but also provides a suitable and uninterrupted power supply, using battery the hydrogen tank volume will reduce also. Increasing battery stack size caused reduced the number of PV panels to supply required load. Therefore the best configuration of standalone power system is combination of fuel cell-electrolyser and battery as storage system.

REFERENCES

Boquan Zhang, Yimin Yang, and Lu Gan, 2008. "Dynamic Control of Wind/Photovoltaic Hybrid Power Systems Based on an Advanced Particle Swarm Optimization" *Proc. Int. Conf. on Industrial Technology*, pp: 1-6.

Chaparro, A.M., J. Soler, M.J. Escudero, E.M.L. de Ceballos, U. Wittstadt, L. Daza, 2005. "Date results and operational experience with a solar hydrogen system", *Journal of Power Sources*, 144: 165-169.

Dimitris Ipsakisa, Spyros Voutetakis, Panos Seferlis, Fotis Stergiopoulos, and Costas Elmasides, 2008. "Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage" *ELSEVIER. International journal of hydrogen energy*, 10-15.

Fei, S.W., M.J. Wang, Y.B. Miao, J. Tu and C.L. Liu, 2009. “Particle swarm optimization based support vector machine for forecasting dissolved gases content,” Power Transform. Oil Energy Conversion Manag, 50: 1604-1609.

Hong, W.C., 2009. “Chaotic particle swarm optimization algorithm in a support vector regression electric load forecasting model,” *Energy Conversion Manag.*, 50: 105-117.

Je´re´my Lagorsea, Marcelo G. Simoesb, Abdellatif Miraouia, Philippe Costergc, 2008. “Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications”, *International Journal Of Hydrogen Energy*, 33: 2871-2879.

Kashefi Kaviani, A., G.H. Riahy and SH.M. Kouhsari, 2008. “Optimal Design of a Reliable Hydrogen-based Stand-alone Wind/PV Generation System” *Proc. Int. Conf. on Optimization of Electrical and Electronic Equipment*, pp: 413-418.

Kodjo Agbossou, Mohanlal Kolhe, Jean Hamelin, and Tapan K. Bose, 2004. “Performance of a Stand-Alone Renewable Energy System Based on Energy Storage as Hydrogen” *IEEE Trans. on Energy Conversion*, 19(3).

Konstantinos E. Parsopoulos and Michael N. Vrahatis, 2004. "On the Computation of All Global Minimizers Through Particle Swarm Optimization", *IEEE Transactions On Evolutionary Computation*, 8(3).

Lai, C., C.H. Wu and M. Tsai, 2009. Feature selection using particle swarm optimization with application in spam filtering, *International Journal of Innovative Computing, Information and Control*, 5(2): 423-432.

Mattei, M., G. Notton, C. Cristofari, M. Muselli, P. Poggi, 2005. “Calculation of a polycrystalline PV module temperature using a simple method of energy balance”, Renewable Energy, 31: 553-567.

Mousavi Badejani, M., M.A.S. Masoum and M. Kalanta, 2007. “Optimal Design and Modeling of Stand-Alone Hybrid PV-Wind Systems” *Proc. Int. Conf. on Power Engineering*. Australasia, pp: 1-6.

Pedrazzi, S., G. Sini, P. Tartarini, 2010. “Complete modeling and software implementation of a virtual solar hydrogen hybrid system”, Energy Conversion and Management, 51: 122-129.

Tao Zhou, and Bruno Francois, 2009. “Modeling and control design of hydrogen production process for an active hydrogen/wind hybrid power system” *ELSEVIER”. International journal of hydrogen energy*, 34: 21-30.