



OPTIMUM CONFIGURATION OF FUEL CELL-B PV/WIND HYBRID SYSTEM USING A HYBRID METAHEURISTIC TECHNIQUE

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Abstract

Because of their low impact on environment, PV/wind hybrid systems which use fuel cells (FCs) as the energy storage device are one of the most promising renewable energy sources. In such systems, optimum configuration (sizing) plays an important role for decreasing the system cost. In this paper, PV/wind/FC system is modeled and a hybrid metaheuristic technique based on chaotic search (CS), harmony search (HS) and simulated annealing (SA) is employed to find the optimum configuration. Optimum configuration is found for PV/FC, wind/FC, and PV/wind/FC systems and the results are compared.

Keywords: Hybrid systems; PV/wind/fuel cell; Optimum configuration.

1. Introduction

Because of the irregular nature of wind and solar energies, energy storage is needed in Photovoltaic-wind hybrid systems. Traditionally, deep-cycle lead acid batteries are used for energy storage. However, environmental concerns related to using these batteries limit the application of Photovoltaic-wind-battery hybrid systems.

As an alternative, fuel cells (FCs) in combination with an electrolyser (for hydrogen production) and hydrogen storage tanks are being considered for energy storage. Using PV/wind/FC energy source leads to a non-polluting dependable energy source and decreases the total maintenance cost Fig. 1 shows the arrangements of PV/wind/FC system.

Considering economic aspects, optimum sizing of a PV/wind/full cell hybrid system is necessary. Finding optimum size means to determine number of wind turbines, photovoltaic panels and hydrogen tanks with the aim of minimizing the total annual cost of the system so that the load demand is satisfied. Then the decision variables (number of wind turbines, PV panels and hydrogen tanks) are discrete, optimum sizing of such system belongs to combinatorial optimization problems. Combinatorial optimization is a branch of optimization which is concerned with the optimization of functions with discrete decision variables. To optimally size the PV/wind/FC hybrid system, an optimization algorithm suitable for combinatorial problems should be used. This paper formulates a PV/wind/FC energy source for optimum sizing and studies the application of a recently hybrid method proposed by the authors.

Recently, study of stand-alone hybrid systems based on renewable sources and hydrogen power have attracted significant attention [1-12]. Though various aspects of hydrogen-based systems have been careful in the literature, an informative model and efficient optimization tool for optimal sizing is rarely found. To efficiently and economically use the energy sources integrated in the hybrid system,

an appropriate sizing methodology is necessary. For a PV/wind/FC hybrid system, optimum sizing means the determination of number of wind turbines, PV panels and hydrogen tanks to satisfy the load demand and minimize the total annual cost. If the hybrid systems are optimally designed, they can be cost-effective and reliable.

Optimal sizing of hybrid systems is a very difficult task which necessitates the improvement of mathematical models for the components and using optimization techniques. In this paper, for cost analysis, a mathematical model is introduced for each system's component and then, a discrete chaotic harmony search-based simulated annealing (DCHSSA)-based optimization technique is used to optimally size the system components (number of wind turbines, PV panels and hydrogen tanks) in order to satisfy the load in the most cost-effective way.

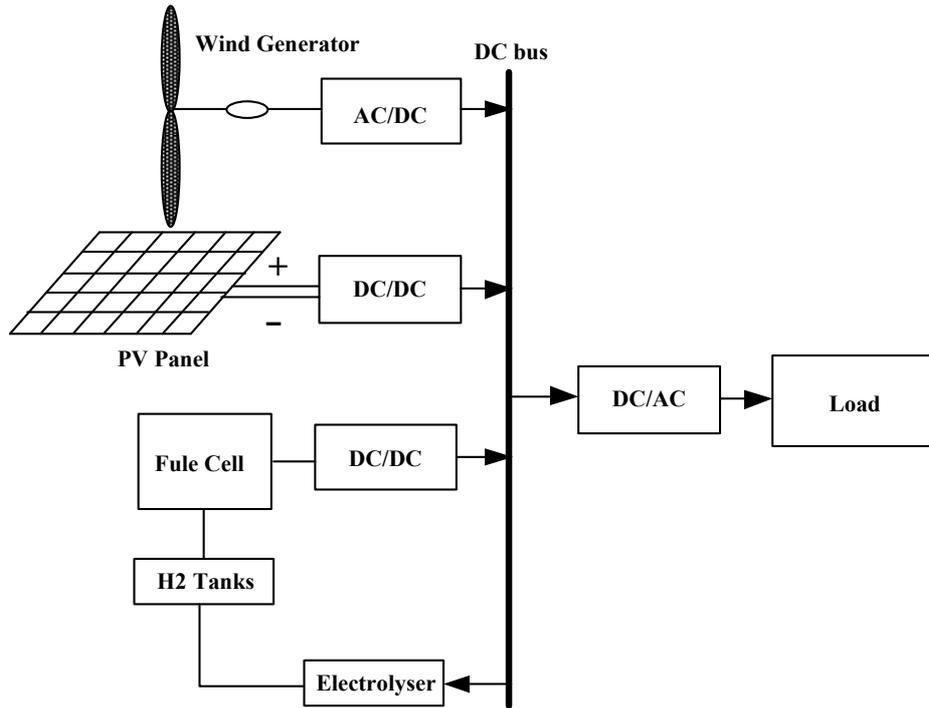


Figure 1: Schematic of the.PV/wind/FC-based hybrid system.

2. Sizing formulation

2.1. Modeling the system components

2.1.1. PV system

The output power of each PV system (p_{PV}) at time t can be obtained from the solar radiation by the following formula:

$$p_{PV}(t) = I(t) \times A \times \eta_{PV} \quad (1)$$

where I is the solar radiation, A denotes the PV area and η_{PV} is the overall efficiency of PV panels and DC/DC converter. It is assumed that the PV panels have maximum power point tracking (MPPT) system. Also, temperature effects on the PV panels are ignored. If the number of PV systems is N_{PV} , the overall produced power is $P_{PV}(t) = N_{PV} \times p_{PV}(t)$.

2.1.2. Wind turbine (WT)

For a wind turbine, if the wind speed exceeds the cut-in value, the wind turbine generator starts generating. If the wind speed exceeds the rated speed of the wind turbine, it generates constant output power, and if the wind speed exceeds the cut-out value, the wind turbine generator stops running to protect the generator. The produced power of each wind turbine (p_{WT}) at time t is obtained as follows:

$$p_{WT}(t) = \begin{cases} 0 & v(t) \leq v_{cut-in} \quad or \quad v(t) \geq v_{cut-out} \\ P_r \frac{v(t) - v_{cut-in}}{v_r - v_{cut-out}} & v_{cut-in} < v(t) < v_r \\ P_r & v_r < v(t) < v_{cut-out} \end{cases} \quad (2)$$

where v is the wind speed, P_r is the rated power of the wind turbine, and v_{cut-in} , $v_{cut-out}$ and v_r are cut-in, cut-out, and rated speed of the wind turbine, respectively. If the number of wind turbines is N_{Wind} , the overall produced power is $P_{WT}(t) = N_{Wind} \times p_{WT}(t)$.

2.1.3. FC/electrolyser

In the PV/wind/FC-based hybrid system, the storage system works as follows:

In this paper, a charging efficiency for electrolyser and a discharging efficiency for FC are used in calculating the efficiency of the storage system.

If the power generated from the wind/PV system is greater than the load demand at time t , the electrolyser will be used to fill the hydrogen tanks. The amount of hydrogen stored in the tanks is obtained by the following equation.

$$E_{Stor}(t) = E_{Stor}(t-1) + \left[(E_{PV}(t) + E_{WT}(t)) - \frac{E_{Load}(t)}{\eta_{Inv}} \right] \times \eta_{Elect} \quad (3)$$

where $E_{Stor}(t)$ and $E_{Stor}(t-1)$ are the energy stored in the hydrogen tanks at hours t and $t-1$, respectively, η_{Inv} is the efficiency of the inverter, and η_{Elect} is the efficiency of the electrolyser.

When the load demand is greater than the energy generated by the wind/PV system, the FC is used to supply the load. In this case, the amount of hydrogen in the tanks at hour t is obtained by

$$E_{Stor}(t) = E_{Stor}(t-1) - \left[\frac{E_{Load}(t)}{\eta_{Inv}} - (E_{PV}(t) + E_{WT}(t)) \right] / \eta_{FC} \quad (4)$$

where η_{FC} is the overall efficiency of the FC and its corresponding DC/DC converter.

2.2. Cost modeling

2.2.1. Objective function

The objective function of the optimum design problem is the minimization of the total annual cost (C_T). The total annual cost consists of the annual capital cost (C_{Cpt}) and the annual maintenance cost (C_{Mtn}). To optimally design the hybrid generation system, the optimization problem, defined by Eq. (5), should be solved using an optimization technique.

$$\text{Minimize } C_T = C_{Cpt} + C_{Mtn} \quad (5)$$

Maintenance cost occurs during the project life while capital cost occurs at the beginning of a project.

In order to convert the initial capital cost to the annual capital cost, capital recovery factor (CRF), defined by Eq. (6) is used.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

where i is the interest rate and n denotes the life span of the system.

Some components of PV/wind/FC system need to be replaced several times over the project life time. In this paper, the lifetime of FC/electrolyser is assumed to be 5 years. By using the single payment present worth factor, we have

$$C_{FC/Elect} = (P_{FC/Elect} + P_{FC/Elect}^{ins}) \times \left(1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}} \right) \quad (7)$$

where $C_{FC/Elect}$ is the present worth of FC/electrolyser system, $P_{FC/Elect}$ is FC/electrolyser price and $P_{FC/Elect}^{ins}$ denotes FC/electrolyser installation fee.

In the same way, the lifetime of converter/inverter is assumed to be 10 years. By using the single payment present worth factor, we have

$$C_{Conv/Inv} = P_{Conv/Inv} \times \left(1 + \frac{1}{(1+i)^{10}} \right) \quad (8)$$

where $C_{Conv/Inv}$ is the present worth of converter/inverter components and $P_{Conv/Inv}$ is the converter/inverter price.

By breaking up the capital cost of PV/wind/FC system into the annual costs of wind turbine, PV panel, FC/electrolyser and converter/inverter, Eq. (9) is obtained.

$$C_{Cpt} = \frac{i(1+i)^n}{(1+i)^n - 1} [N_{Wind} \times C_{Wind} + N_{PV} \times C_{PV} + N_{Tank} \times C_{Tank} + C_{FC/Elect} + N_{Conv/Inv} \times C_{Conv/Inv}] \quad (9)$$

where C_{Wind} is unit cost of wind turbine, C_{PV} is unit cost of PV panel, N_{Tank} is the number of storage tanks, C_{Tank} is unit cost of hydrogen storage tank and $N_{Conv/Inv}$ is the number of converter/inverter systems.

For obtaining the annual maintenance cost of the system components, the following equation is used:

$$C_{Mnt} = N_{PV} \times C_{Mnt}^{PV} + N_{Wind} \times C_{Mnt}^{Wind} + C_{Mnt}^{FC} + C_{Mnt}^{Elect} \quad (10)$$

where C_{Mnt}^{PV} , C_{Mnt}^{Wind} , C_{Mnt}^{FC} and C_{Mnt}^{Elect} are the annual maintenance costs of PV, wind turbine, fuel cell and electrolyser systems, respectively. The maintenance costs of hydrogen tank and converter/inverter systems are neglected.

2.2.2. Constraints

For PV/wind/FC systems, the following constraints should be satisfied:

$$N_{Wind} = Integer, \quad 0 \leq N_{Wind} \leq N_{Wind}^{max} \quad (11)$$

$$N_{PV} = Integer, \quad 0 \leq N_{PV} \leq N_{PV}^{max} \quad (12)$$

where N_{Wind}^{max} and N_{PV}^{max} are the maximum available number of wind turbines and PV panels, respectively.

In PV/wind/FC system, in addition to Eqs. (11) and (12), the following equations should be satisfied:

$$N_{Tank} = Integer, \quad 0 \leq N_{Tank} \leq N_{Tank}^{max} \quad (13)$$

$$E_{Stor}^{min} \leq E_{Stor} \leq E_{Stor}^{max} \quad (14)$$

where N_{Tank}^{max} is maximum number of hydrogen tanks and E_{Stor}^{min} (assumed to be 0 in this study) and E_{Stor}^{max} denote the minimum and maximum storage capacity of the hydrogen tanks, respectively.

3. Methodology

3.1. Discrete simulated annealing algorithm (DSA)

The name and inspiration of SA originates from annealing in metallurgy, a process involving heating and controlled cooling of a metal to increase the size of its crystals and reduce its defects. SA starts its search by a large enough temperature (T) to search a broad region of the space and terminates it by a small temperature to move downhill according to the steepest descent heuristic. In SA, as the iterations progress, the temperature is gradually reduced.

The SA used in this study is same as that proposed in [13] which is a discrete SA (DSA). At any iteration ($iter$), the current solution is $x(iter)$ and the corresponding objective function value is defined by $f(x(iter))$. The probability of the next solution, $x(iter + 1)$, being at x_{new} (a random solution near-by $x(iter)$) depends both on the difference between the corresponding fitness values, $\Delta F = f(x_{new}) - f(x(iter))$, and also on the temperature. As a result, the position of the next solution is determined as follows:

$$x(iter + 1) = \begin{cases} x_{new} & \text{if } \exp(-\Delta F/T) > r \\ x(iter) & \text{o. w.} \end{cases} \quad (15)$$

where r is a uniform random number in $[0, 1]$.

As can be seen, if $\Delta F \leq 0$, x_{new} is always accepted. There is a probability of selecting x_{new} as $x(iter + 1)$ even though the function value at x_{new} is worse than that at $x(iter)$. This probability depends on ΔF and T values. The process of producing new solutions continues until maximum number of iterations, $iter_{max}$, is met. In DSA, x_{new} and T change by the following formulas during the iterations:

$$x_{new} = x(iter) + WF \quad (16)$$

$$T(iter+1) = s \times T(iter) \quad (17)$$

where WF is a vector with the elements randomly distributed between $[-wf \ wf]$ and s is the step size. The algorithm is started by an initial temperature (T_0).

3.2. Discrete harmony search (DHS)

HS is a heuristic algorithm which attempts to mimic the musicians' improvisation process. The HS used in this study is same as that proposed in [14, 15] which is a discrete HS (DHS). The key parameters which play important role in the convergence of the HS algorithm are harmony memory considering rate ($HMCR$), pitch adjusting rate (PAR), and bandwidth of generation (b_w). These parameters can be potentially useful in adjusting convergence rate of the algorithm to the optimal solution. The $HMCR$ varying between 0 and 1 is the rate of choosing one value from the HM . PAR and b_w are defined as follows:

$$PAR(t) = PAR_{min} + \frac{PAR_{max} - PAR_{min}}{iter_{max}} \times iter \quad (18)$$

$$b_w(t) = b_{w_{max}} \exp(c \times iter) \quad (19)$$

$$c = \frac{\text{Ln}\left(\frac{b_{w_{min}}}{b_{w_{max}}}\right)}{iter_{max}} \quad (20)$$

where PAR_{max} and PAR_{min} are the maximum and minimum pitch adjusting rates, respectively, and $b_{w_{max}}$, $b_{w_{min}}$ are the maximum and minimum bandwidths, respectively. In HS, a new harmony is produced by the following pseudocode:

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for k=1:3
  if  $r_1 > HMCR$ 
 $x_{new}(k)$ =a feasible random integer number;
  else
 $x_{new}(k)$ =the value corresponding to a random selected harmony from HM;
  if  $r_2 < PAR$ 
 $x_{new}(k)$ =  $x_{new}(k) + r_w$ ;
  end
end
end
end

```

where x_{new} is the improvised harmony and r_1 as well as r_2 are uniformly distributed random numbers between 0 and 1. The parameter r_w is obtained as follows:

$$r_w = \begin{cases} 1 & r_3 < 0.5 \\ -1 & otherwise \end{cases} \quad (21)$$

where r_3 is a uniformly distributed random number between 0 and 1.

3.4. Discrete chaotic harmony search-based simulated annealing (DCHSSA)

Chaotic variables can go through every state in a certain area according to their regularity without repetition. Due to the ergodic and dynamic properties of chaos variables, chaos search (CS) has been applied to the area of optimization. To improve the search power of the proposed algorithm, the chaotic search is combined with DHSSA. In DCHSSA, Logistic function as a well-known chaotic sequence is used as follows:

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for k=1:3
  if  $r_1 > HMCR$ 
     $x_{new}(k)$ =a feasible random integer number by chaotic sequence;
  else
     $x_{new}(k)$ = $x(iter, k)$ ;
    if  $r_2 < PAR$ 
       $x_{new}(k)$ =  $x_{new}(k)$ + $r_w$ ;
    end
  end
end
end

```

4. Results

The experimental data used here for wind speed and solar insolation is obtained from Rafsanjan, Iran. Figs. 2 show the average hourly insolation and wind speed profiles and the corresponding produced powers. The parameters related to the components have been given in Table 1. Fig. 3 indicates the average hourly load demand considered in this paper.

Recently, two efficient metaheuristic-based optimization techniques have been proposed by the author for optimal sizing of the hybrid systems [16] In order to optimally size the components of PV/wind/FC systems, the optimization method proposed in [13] is used which is based on a discrete chaotic harmony search-based simulated annealing (DCHSSA). MATLAB environment is used to implement the proposed methodology. Parameter setting of DCHSSA is as follows: $iter_{max} = 1000$; $HMCR = 0.9$; $PAR_{max} = 1$; $PAR_{min} = 0.1$; $s = 0.97$; $T_0 = 100$. DCHSSA tries to find the optimum number of PV panels, wind turbines and hydrogen tanks in PV/wind/FC-based hybrid system. In this study, the minimum and maximum bounds of the decision variables are set to 0 and 200, respectively. At initial moment, it is assumed that the charge of hydrogen tank is 30 % of its nominal capacity.

Table 2 summarizes in detail the results of optimum sizing for different hybrid systems: PV/wind/FC, PV/FC and wind/FC. This table shows the optimum number and total annual cost. Among the PV/wind/FC, PV/FC and wind/FC, it is clear that economically the PV/wind/FC-based hybrid system is a better choice for providing power. The total annual costs for PV/wind/FC, PV/FC and wind/FC systems are found 18798 \$, 46744.8 \$ and 20364.8 \$, respectively. For the PV/wind/FC system, it is found that the optimum number of PV panels, wind turbines and hydrogen tanks is 10, 9 and 26, respectively. For PV/FC and wind/FC systems, the optimum numbers of hydrogen tanks are 184 and 36, respectively, which are greater than that of the PV/wind/FC system. Fig. 4 illustrates the convergence process of DCHSSA during the minimization of the hybrid systems cost.

From the results, it is clear that economically hybrid PV/wind/FC system is a better candidate for energy production because it has the minimal total annual cost. It is important to mention the advantages of FC/Electrolyser storage system. FC/Electrolyser storage system is environmentally

friendly, has a small footprint and hydrogen can be shipped to the site if storage is low. Moreover, with improvement in the efficiency of both FC and electrolyser, FC/electrolyser storage system can be economically better.

Table 1. Component parameters.

i	5%
n	20 years
Wind turbine	
P_r	1 kW
v_{cut-in}	2.5 m/s
$v_{cut-out}$	13 m/s
v_r	11 m/s
C_{Wind}	3200 \$
C_{Mnt}^{Wind}	100 \$
PV panel	
P_r	120 W
C_{PV}	614 \$
C_{Mnt}^{PV}	0 \$
A	1.07 m ²
Efficiency	12%
Fuel cell	
Rated power	3 kW
η_{FC}	50%
Life span	5 years
C_{FC}	20000 \$
C_{Mnt}^{FC}	1400 \$
Electrolyser	
Rated power	3 kW
η_{Elect}	74%
Life span	rs□ 5 ye
C_{Elect}	20000%
C_{Mnt}^{Elect}	1400 \$
C_{Tank}	2000 \$
Nominal capacity of hydrogen tank	0.3 kWhr
Power converter/inverter	
Rated power	3 kW
η_{Inv}	95%
Life span	10 years
$C_{Conv/Inv}$	2000 \$

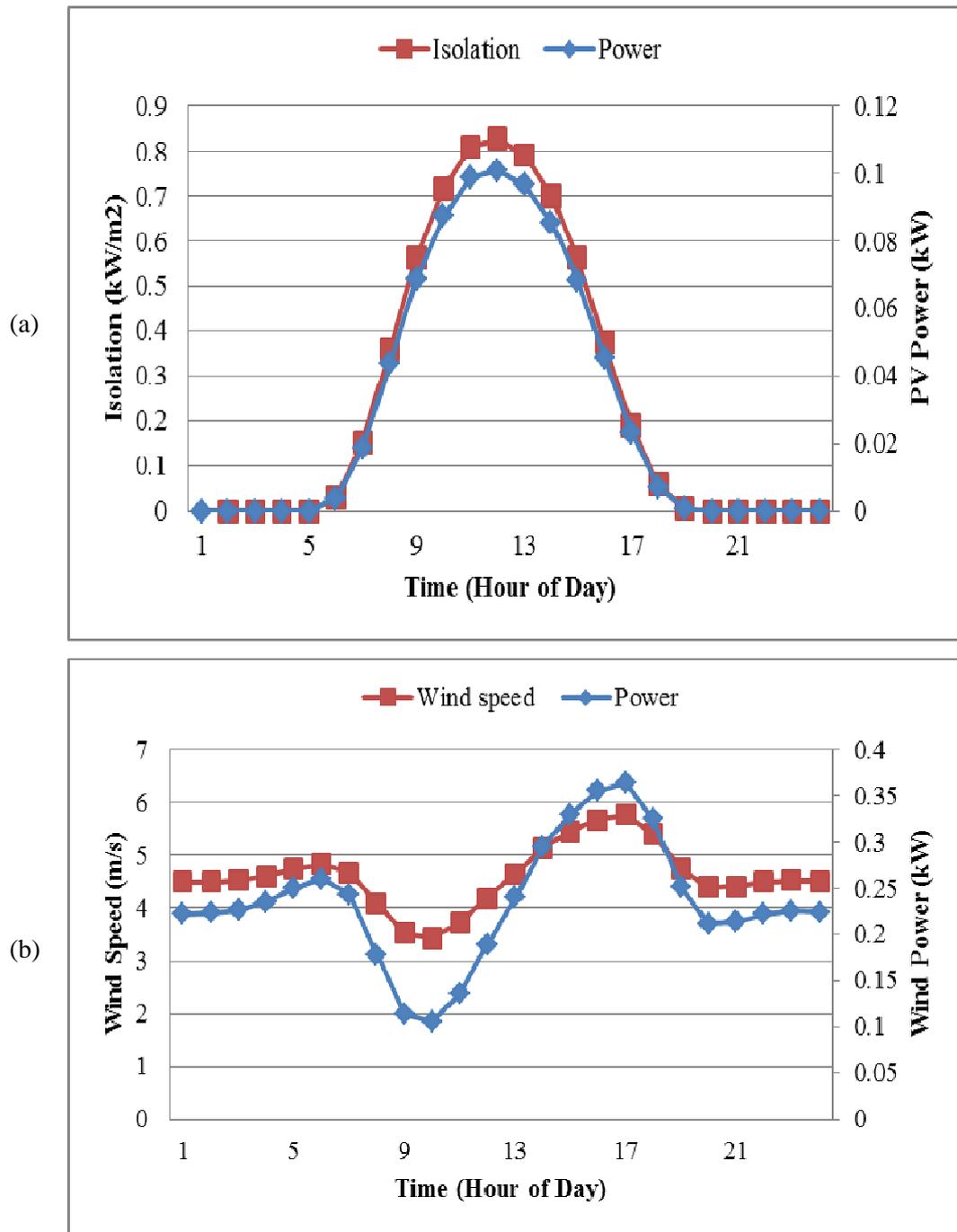


Figure 2: Average hourly profiles of (a) PV system, insolation and produced power and (b) Wind turbine, wind speed and produced power

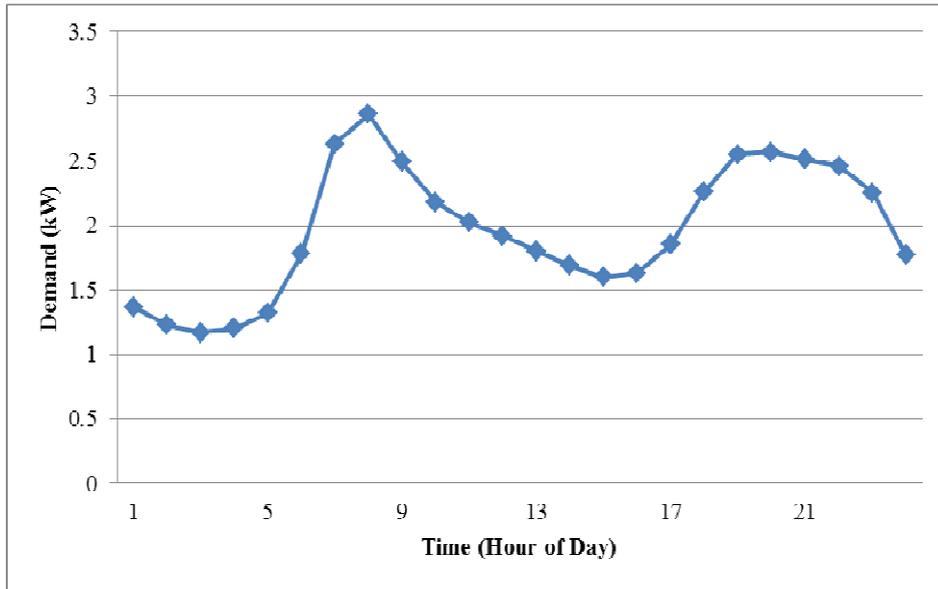


Figure 3: Average hourly load demand.

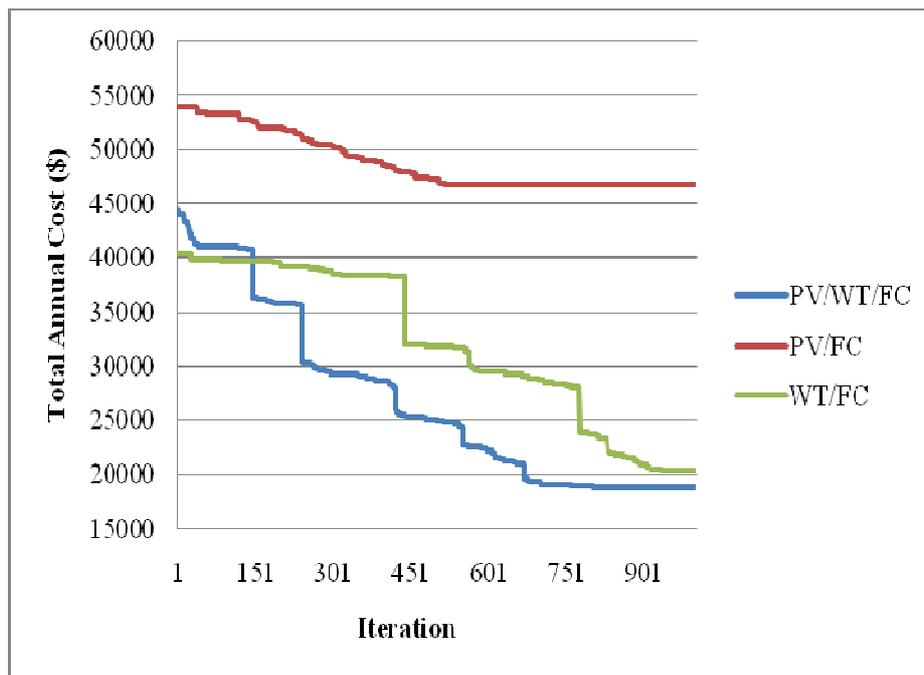


Figure 4: Convergence process of DCHSSA for finding the optimum size of the hybrid systems.

5. Conclusion

In this paper, a hybrid system based on PV, wind and fuel cell is mathematically formulated. Then, three decision variables, namely, number of wind turbines, PV panels and hydrogen tank are considered and found so that the system meets the load demand and includes the minimal cost. Moreover, the optimum configuration for PV/FC and wind/FC is found and compared with the

PV/wind/FC system in terms of the total annual cost. It is found that PV/wind/FC system has the minimal cost and so is the best choice for application. For finding the optimum configuration, a discrete metaheuristic technique is used which is based on chaotic search (CS), harmony search (HS) and simulated annealing (SA) algorithms. The proposed methodology has the advantage of escaping local optima by using stochastic search process.

Table 2. Summary of the results for the hybrid systems obtained by DCHSSA algorithm.

<i>PV/wind/FC-based hybrid system</i>				
N_{PV}	N_{Wind}	N_{Tank}	$N_{Conv/Inv}$	Total annual cost (\$)
10	9	26	4	18798
<i>PV/FC-based hybrid system</i>				
N_{PV}	N_{Wind}	N_{Tank}	$N_{Conv/Inv}$	Total annual cost (\$)
133	-	184	3	46744.8
<i>Wind/FC-based hybrid system</i>				
N_{PV}	N_{Wind}	N_{Tank}	$N_{Conv/Inv}$	Total annual cost (\$)
-	11	36	3	20364.8

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