Optimization of Stand-alone Hybrid PV/Wind/Fuel-Cell System Considering Reliability Indices Using Cuckoo Optimization and Firefly Algorithm

Mehdi Rezaei[1], Mahmood Ghanbari[2]*

Abstract – In this paper, a hybrid system based on wind turbines, solar arrays and fuel cells is designed optimally in the view of economical and technical aspects. The objective of the hybrid system optimization is to minimize the system net peresent cost(NPC) while considering the reliability as a constraint. The economical designing aspect is defined as equivalent loss factor (ELF) of reliability. The NPC consist of capital, operation and maintenance, replacement and, especially, loss of load costs. The data of load, solar radiation and definitive wind speed are from the North West of Iran. It is assumed that between the system components, i.e., wind turbine, photovoltaic array and inverter, there is a forced outage probability. The cuckoo optimization (COA) and firefly algorithms(FA) are applied to optimize the hybrid system components and the results are compared with the last studies. The results show that the COA method is superior to the FA and the last studies, with respect to the economical and technical aspects and convergence speed. They also show that complete consideration of the components availability and the availability of inverter increases the generation costs of the system, but improves the system reliability indices, too.

Keywords: Solar/wind/fuel cell hybrid system, Equivalent loss factor, Net present cost, Cuckoo optimization algorithm, Firefly algorithm

I. Introduction

Application of renewable energies has grown substantially over the past decade. Many industrialized countries provide much of their required energy from renewable energy sources [1]. In a hybrid system, by combining two or more sources, the predictability of generation is increased [2-5]; that is, these resources cover their deficiencies to some extent. Fuel cells and batteries can be noted as the storage systems that combined with solar arrays and wind turbines, they are able to compensate for their power oscillations. In solar-wind hybrid systems optimization, the optimal sizing of system component is very important in the design process. Different systems are already used in a hybrid system to generate power. Several studies have been done in the field of optimization of hybrid power generation system. In [6], a hybrid system consisted of solar arrays, fuel cell and SMES is used to supply the load. In [7], the units sizing and analysis of hybrid cost of wind/solar/fuel cell has been considered. The performance and sizing of solar array/wind turbine is studied in [8] and the sizing of a wind turbine driven diesel generator optimized in [9].In [10], a method has been proposed to determine the size of the solar-wind system with battery storage. In [11], authors determine optimal sizing of the system component subject to minimal cost and desired load reliability. In [12], effect of some parameters of size determination such as, sizing factor, which represents the ratio of the energy generated by system to the energy demand in a solar-wind system with battery storage, has been analyzed. In [13], optimal design of a solar-wind hybrid system is presented. In [14], a model for for solar-wind hybrid system is introduced. In [15], a Genetic Algorithm (GA) is used to find angle of the solar panel installation and thus, maximum achievable energy from the sun. In [16], a hybrid diesel/wind/photovoltaic generation systems, which supplies a power load highly distant from the source, is introduced, considering the benefits of renewable energy from an economic standpoint. In [17], minimization of the power generation cost of solar-wind-fuel cell hybrid system is studied considering the reliability indices and constraints. In [18], the optimization of solar-wind-fuel cell system with the objective of system cost minimization and reliability as constraint is proposed using particle swarm algorithm (PSO) and the harmony search algorithm (HS) and finally,

---

2* **Corresponding Author** :Department of Electrical Engineering, Gorgan Branch, Islamic Azad University, Gorgan, Iran; E-Mail: ghanbari@gorganiau.ac.ir
1-Department of Electrical Engineering, Golestan Science and Research Branch, Islamic Azad University, Gorgan, Iran
E-Mail: mehdi_rezaei@gorganiau.ac.ir

Received 2018.01.22 ; Accepted 2018.12.10

in[19], using evolutionary differential algorithm the sizing of solar-wind-fuel cell system considering the cost and reliability indices optimized.

In this paper, we aim to use and analyze effectiveness of the cuckoo optimization algorithm (COA) and firefly algorithm(FA) for optimization of a Stand-alone Hybrid Photo-Voltaic/Wind/Fuel-Cell (PV/WG/FC) System. The rest of the paper is as follows. In section 2, mathematical modeling of hybrid PV/WG/FC system and its components are presented. In section 3, the ratio of the reliability to the system cost, reliability indices and formulation of the expected generated energy by the system is evaluated. In section 4, the optimization problem's structure including objective function and constraints is detailed along with analysis of COA. Lastly, section 5 and 6, respectively, illustrates the simulation results and concludes the paper.

II. Hybrid System Modeling

In this paper, a hybrid system consisting of solar arrays, wind turbines and fuel cells [17-19] is designed to supply a stand-alone load. The fuel cells are used as a storage system to compensate for power oscillations resulted from the solar array and wind turbines and, in turn, which provide continuous supply to the load. Fuel cell includes an electrol yzer and a hydrogen storage tank. The scenario of this study consider the following system component: solar arrays, wind turbines, electrolyzer, hydrogen storage tank, fuel cell and inverter. The hybrid system includes both DC and AC buses. This is shown in Fig. 1.

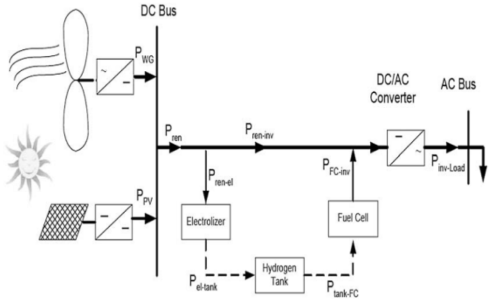

Fig. 1: Hybrid solar-wind-fuel cell system [17-19]

In hybrid system of Figure 1, when the total energy generated by renewable sources is equal to the load demand, we assume that the whole power generated by the solar arrays and wind turbines is delivered to the load through the inverter. In conditions that the total energy generated by renewable sources is larger than the load demand, the excess power is injected into electrolyzer in order to produce the hydrogen, and in turn, store the excess the leftover. Accordingly, when the total energy generated by renewable sources is less than the load demand, the load power shortage can be compensated by fuel cell. If the fuel cell is not able to compensate for the power shortage, a percentage of the load is disconnected or lost.

A. Solar Array System Modeling

The power generated by the solar array, in terms of the intensity of radiation emitted by the array surface, is obtained as [17-19]:

$$P_{PV} = \frac{G}{1000} \times P_{PV,rated} \times \eta_{PV,conv} \tag{1}$$

$$G(t,\theta_{PV}) = G_V(t) \times \cos(\theta_{PV}) + G_H(t) \times \sin(\theta_{PV}) \tag{2}$$

In (1) and (2), P_{PV} represents the output power of the solar array, G, the radiation power perpendicular to the array surface [volt/m2] in the tth time step, $P_{PV,rated}$, the rated power of each array obtained for $G = 1000\, W/m^2$, and $\eta_{PV,conv}$, the efficiency of DC/DC converter between each array and DC bus. $G_H(t)$ and $G_V(t)$, respectively, represent the horizontal and vertical solar radiation intensities. In order to achieve maximum output power of the solar array, here, we assumed a solar tracking system actively, follows the sun trajectory. The output voltage of the system is equal to 48 V and connected to the DC bus.

B. Wind Turbine

The turbine used here is BWC Excel-R / 48 [20]. The output voltage is equal to 48 volts DC and the corresponding output power as a function of wind speed is [17-19]:

$$P_{WG} = \begin{cases} 0 & ; v_W \le v_{cut\,in}, v_W \ge v_{cut\,out} \\ P_{WG,\max} \times \left(\dfrac{v_W - v_{cut\,in}}{v_{rated} - v_{cut\,in}} \right)^m & ; v_{cut\,in} \le v_W \le v_{rated} \\ P_{WG,\max} + \\ \dfrac{P_{furl} - P_{WG,\max}}{v_{cut\,out} - v_{rated}} \times \left(v_W - v_{rated} \right); v_{rated} \le v_W \le v_{furl} & \end{cases} \tag{3}$$

where, P_{WG} is the output power of the wind turbine, v_W, the wind speed, $v_{cut\,in}$, the down cut speed, v_{atat} the, high cut speed [m/s], $P_{WG,\max}$, the maximum turbine output power [KW] and P_{furl}, the output power in high cut speed. Since we have sample data of wind speed at 40m height, the wind speed at 15m height can be calculated as [17-19]:

$$v_W^h = v_W^{ref} \times \left(\frac{h}{h_{ref}} \right)^{\alpha} \quad (4)$$

where, v_W^h is the wind speed in height h, v_W^{ref} is the wind speed at reference height h_{ref} in terms of [m/s] and α is a number between0.14-0.25 [21].

C. Total generation power of renewable sources

The total generation power is sum of the energies produced by solar arrays and wind turbines. Assuming the number of solar arrays and wind turbines, respectively, are N_{PV} and N_{WG}, the power generated by all renewable units delivered to the DC bus is calculated [17-19]:

$$P_{ren} = N_{WG} .P_{WG} + N_{PV} .P_{PV} \quad (5)$$

Pulling out of the renewable units might be occurred due to reasons such as maintenance service or failure; this effect must be accounted for in reliability calculation of the hybrid system. If n_{PV}^{fail} be the number of solar array and n_{WG}^{fail}, the number of wind turbines pulled out from the system, the total power generated by renewable units can be obtained as [17-19]:

$$P_{ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right) = \left(N_{WG} - n_{WG}^{fail}\right) \times P_{WG} + \left(N_{PV} - n_{PV}^{fail}\right) \times P_{PV} \quad (6)$$

D. Electrolyzer

Electrolyzer is a device that produces hydrogen and oxygen from decomposition of water by electrolysis process. The electrolyzer output power can be obtained by [17-19]:

$$P_{el-tank} = P_{ren-el} \times \eta_{el} \quad (7)$$

where, η_{el} is the electrolyzer efficiency and P_{ren-el}, the power injected by renewable sources into electrolyzer.

E. Hydrogen Storage Tank

The task of this tank is storage of hydrogen received from pressurized electrolyzer. At each time step t, the energy stored in the tank is:

$$E_{tank}(t) = E_{tank}(t-1) + P_{el-tank}(t) \times \Delta t - P_{tank-FC}(t) \times \Delta t \times \eta_{storage} \quad (8)$$

in which, Δt is length of each time step equal to one hour and $\eta_{storage}$, the storage system efficiency. Then, mass of hydrogen stored in the tank is calculated from:

$$m_{storage}(t) = \frac{E_{storage}(t)}{HHV_{H_2}} \quad (9)$$

where HHV_{H_2} Indicates high heating value of hydrogen equal to 39.7 kWh per Kg [22].The tank energy is constraint to be within its minimum and maximum values:

$$E_{\tan k,\min} \le E_{\tan k}(t) \le E_{\tan k,\max} \quad (10)$$

F. Fuel Cell

The fuel cell generates the electrical energy out of hydrogen. In this study, polymer membrane fuel cell is used because of its high reliability. The polymer membrane fuel cell has fast dynamic response in range of 1 to 3 seconds. Its output power is obtained as [17-19]:

$$P_{FC-inv} = P_{tank-FC} \times \eta_{FC} \quad (11)$$

Here, η_{FC} is the fuel cell efficiency.

G. Inverter

The inverter converts the DC power to AC power which is then transferred to the load. The relationship between input and output power of the inverter is:

$$P_{inv-load} = \left(P_{FC-inv} + P_{ren-inv}\right) \times \eta_{inv} \quad (12)$$

where, η_{inv} indicates inverter efficiency.

III. Evaluation of Reliability/cost

The studied system is simulated for one year with one hour time steps; the ratio of reliability to cost is,then, derived accordingly. With the economic factors given, the results are derived for 20 year useful life span. In this study, we assumed that the load growth, the uncertainly of load/solar radiation, and wind speed are all negligible.

A. Reliability Indices

In this section, a number of reliability indices used in literatures are presented to evaluate reliability of the power system delivery [23-26]. The considered indices are: Loss of Load Expected (LOLE), Loss of Energy Expected (LOEE), Expected Energy not Supplied (EENS), Loss of Power Supply Probability (LPSP) and Equivalent Loss Factor (ELF).

$$LOLE = \sum_{t=1}^{N} E\left[LOL\left(t\right)\right] \tag{13}$$

In (13), $E\left[LOL\ (t)\right]$ indicates expected loss of load in time step t and can be calculated from the following:

$$E\left[LOL\right] = \sum_{s \in S} T_s \times P_s \tag{14}$$

here, T_s is the time length of each possible loss of load, P_s, the probability of being in state s and S, set of all possible states of the system under study.

$$LOEE = EENS = \sum_{t=1}^{N} E\left[LOE\left(t\right)\right] \tag{15}$$

where, $E\left[LOE(t)\right]$, the expectation of loss of load in time t , is obtained as follows:

$$E\left[LOE\right] = \sum_{s \in S} Q_s \times P_s \tag{16}$$

in which, Q_s is the amount of lost load per kilowatt-hour in S state. The probability of lost power supply is also obtained as:

$$LPSP = \frac{LOEE}{\sum_{t=1}^{N} D\left(t\right)} \tag{17}$$

where, $D(t)$ indicates the required load power per KWh in time t. finally, The Equivalent Loss Factor is calculated as:

$$ELF = \frac{1}{N}\sum_{t=1}^{N}\frac{Q\left(t\right)}{D\left(t\right)} \tag{18}$$

B. Expectation Calculation of the Renewable Energy

The expected value of the solar arrays and wind turbines output power is used to calculate averages of reliability indices:

$$E\left[P_{ren}\right] = \sum_{s \in S} P_{ren}\left(s\right) \times f_p\left(s\right) \tag{19}$$

in which, $f_p\left(s\right)$ indicates being in the position S and $P_{ren}\left(s\right)$, the power injected into DC bus generated by solar and wind renewable units. Since power is delivered to the load through the inverter, so the probability of the inverter be out of service should be considered. The probability of the solar-wind-inverter units' exits is obtained as [17-19]:

$$f_{hybridsystem}\left(n_{WG}^{fail}, n_{PV}^{fail}, n_{inv}^{fail}\right) = f_{ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right) \times A_{inv}^{N_{inv}-n_{inv}^{fail}} \times \left(1 - A_{inv}\right)^{n_{inv}^{fail}} \tag{20}$$

where A_{inv} is the inverter availability. Combining (6) with the exits probabilities of solar-wind units, the expected energy generated by the renewable units will be [17-19]:

$$E\left[P_{ren}\right] = \sum_{n_{WG}^{fail}}^{N_{WG}} \sum_{n_{PV}^{fail}}^{N_{PV}} \left\{P_{ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right) \times P_p\left(n_{WG}^{fail}, n_{PV}^{fail}\right)\right\} \tag{21}$$

Considering the availability of units, then, the energy generated by renewable sources is calculated as [17-19]:

$$E\left[P_{ren}\right] = N_{PV} \times P_{PV} \times A_{PV} + N_{WT} \times P_{WT} \times A_{WT} \tag{22}$$

in which, A_{PV} and A_{WT}, indicate the solar and wind availability, respectively. The availability of components is defined as [17]:

$$A_{com} = \frac{\mu_{com}}{\mu_{com} + \lambda_{com}} \tag{23}$$

where, in (23), μ_{com} and λ_{com}, are the rates of the maintenance and component failure.

IV. Optimization Problem

The objective of this paper is the optimal sizing of system component including the number of wind turbines, solar arrays, angle of installation of solar arrays, electrolyzer capacitance, hydrogen tank, fuel cell and inverter with minimizing the system energy generation costs.

A. Objective Function

Net present cost of the ith component of hybrid system can be obtained as follows [17-19]:

$$NPC_i = N_i \times \left(CC_i + RC_i \times K + O\,\&\,MC_i \times PWA\right) \quad (24)$$

where, N represents the number of unit or size of component per kWh or kg, CC, the initial investment cost in dollars per unit, RC, the cost of each replacement in terms of dollars per unit, O & MC, annual maintenance cost in dollars per unit per year and R , the 20 year project life span. The real interest, ir, is related to the nominal interest ir-nominal and the annual inflation rate (f) as:

$$ir = \frac{ir_{no\min al} - f}{1+f} \quad (25)$$

In (24), PWA represents the present value factor of annual payments and K, a constant. Their relation is:

$$PWA\,(ir,R) = \frac{(1+ir)^R - 1}{ir\,(1+ir)^R} \quad (26)$$

$$K_i = \sum_{n=1}^{y_i} \frac{1}{(1+ir)^{n.L_i}} \quad (27)$$

here, y represents the number of replacements and L, life time span of the components. Net present value of the lost load is calculated as:

$$NPC_{loss} = LOEE \times C_{loss} \times PWA \quad (28)$$

in which, C_{loss} represents the cost of lost load for each KWh in terms of dollar per KWh. Therefore, the objective function of the optimization problem can be expressed as:

$$J = \min_X \left\{ \sum_i NPC_i + NPC_{loss} \right\} \quad (29)$$

in which, i, indicates the component and X, a vector with seven optimization problem variables including: number of wind turbine, solar arrays, angle of installation of solar array, electrolyzer capacitance, hydrogen tank, fuel cell and inverter.

B. Problem Constraints

To solve (29), first, the following constraints should be taken into account:

$$E\left[ELF\right] \le ELF_{\max} \quad (30)$$

$$0 \le N_i \quad (31)$$

$$0 \le \theta_{PV} \le \pi/2 \quad (32)$$

$$E_{tank}\,(0) \le E_{tank}\,(8760) \quad (33)$$

here, θ_{PV} represents the angle of installation of solar arrays. Constraint (31) shows that the number of solar arrays must be a positive integer. Constraint (32) indicates that the angle of solar arrays toward sun must be between zero and 90 degrees. Constraint (33) shows that at the start of the program,the tank energy should be higher than that of the initiation time.

C. Optimization Methods

In this section, the optimization problem is formulated for designing a Stand-alone hybrid PV/Wind/FC system,considering reliability indices, is presented.Then, FA, COA, and their roles in problem solving are described.

C.1 Firefly Algorithm and Implementation

FA method is an evolutionary optimization method introduced by Mr. Yang in 2007. The main idea behind it is the optical connection between firefly worms. It is considered as a subset of swarm intelligence algorithms [27]. The attractiveness of a firefly depends strongly on its light. The objective function is the same the intensity of a firefly light. So we can write [27]:

$$I_i = F(x_i) \quad (34)$$

As the brightness of a firefly diminishes, its attractiveness decreases. The light intensity as a function of distance, in the simplest form, varies as [27]:

$$I_{ij} = I_0 e^{-\gamma r_{ij}} \quad (35)$$

where, rij is the distance between two variables and calculated as:

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (36)$$

and γ is the absorption coefficient of light and I0 is the intensity of light at zero distance. Typically, the value is selected from 0.1 to 10.In (36), d is the number of variables to be designed. The attractiveness of a worm is dependent on the light intensity of the worm whichcan be calculated according to the following [27]:

$$B_{ij} = B_0 e^{-\gamma r_{ij}} \qquad (37)$$

here, B0 is the amount of attractiveness at zero distance, usually considered in articles to be one. If a worm has a lower brightness relative to its adjacent worm, it moves toward it according to [27].

$$x_i^{new} = x_i + B_0 e^{-\gamma r_{ij}} + \alpha(rand - \frac{1}{2}) \qquad (38)$$

where, α is a coefficient of the FA algorithm, which is assumed to be 0.1 here, and rand, a random number between zero and one. A FA works through the following steps:

Step 1: After determining the parameters of the FA (including the number of firefly worms (n), B0, α, γ and the total number of algorithmic repetitions), input data including economic and technical design and load data, solar radiation and the wind speed are applied.

Step 2: The primary population of the firefly is determined randomly from a set of decision variables.

Step 3: The system equipment constraints are evaluated via objective function and the best set of variables is determined.

Step 4: Update the population (based on the firefly algorithm) and randomly select variables.

Step 5: Specify the target function for the updated variables of Step 4. If a better value is achieved, the objective function is replaced by that of step 3.

Step 6: The convergence condition is inspected. If convergence conditions are satisfied, go to step 7, otherwise go to step 2.

Step 7: Stop the algorithm and print the results (extract optimization variables)

Here, the maximum iteration and population of the algorithm are assumed to be 200 and 70, respectively.

C.2 COA and Implementation

COA is one of the newest and most powerful evolutionary optimization methods. In COA,the design variable array is called "habitat[28]:

$$Habitat = \left[X_1, X_2, \ldots, X_{N\,\mathrm{var}}\right] \qquad (39)$$

whereNvarshows number of design variables indicating the current positions of cuckoos, for which, the profit function f_p is[28]:

$$\mathrm{Pr}ofit = f_p(habitat) = f_p(X_1, X_2, \ldots, X_{N\,\mathrm{var}}) \qquad (40)$$

Since COA is a maximization algorithm, the cost function must be multiplied by minus one. To start the optimization algorithm, a habitat matrix is produced. The Eggs Laying Radius (ELR), which is proportional to the current number of eggs, is defined as [28]:

$$ELR = \alpha \times \frac{number\ of current\ cuckoo's\ \ eggs}{total\ \ number\ \ of\ \ eggs} \times \left(Var_{hi} - Var_{low}\right) \qquad (41)$$

where α is a control parameter to limit the maximum value of ELR. For s Cuckoo with new eggs in next habitats, ELR must be recalculated. Cuckoos migrate tonew and best positions according [28]:

$$X_{NextHabitat} = X_{currenttHabitat} + F(X_{Goalpo\,\mathrm{int}} - X_{currentHabitatt}) \qquad (42)$$

After a few iterations, all the cuckoos arrive to an optimum point with maximal similarity to the host bird's eggs and also with highest food sources. This site will have the greatest overall benefit where minimal number of eggs will be destroyed. The main steps of COA can be expressed as follows:

Step 1: Determine the cuckoo's current habitatrandomly.

Step 2: Assign some number of eggs to each cuckoo.

Step 3: Determine ELR for each cuckoo.

Step 4: Cuckoos lay eggs within the nest of hosts in their egg laying radius.

Step 5: some of eggs identified by the host, are destroyed.

Step 6: Eggs not identified by the hosts will grow.

Step 7: Evaluate the new cuckoo's habitat.

Step 8: Determine the maximum number of cuckoos with one or more places to live and eliminate those that are in the wrong habitats.

Step 9: Cluster the cuckoos using the K-means method and specify best group of cuckoos as the objective habitat.

Step 10: Move Cuckoo's population toward the target habitat.

Step 11: If stopping condition is satisfied, stop, otherwise go to step 2.

In this paper, to solve our optimization problem using COA, the maximum number of iterations and population sizeare assumed to be 200 and 70, respectively.

V. Simulation results

A. The System Data

The system data consists of annual radiation and wind information for one of the areas in North West of Iran, extracted with accuracy of one sample per hour [17-19].Annual wind speed at 15m height and horizontal and vertical radiations, are shown, respectively, in figs. 2 to 5. Within the simulation, we used the annual load curve of IEEE standard load with a peak 50kW [17-19] (fig. 5).Values of for system components are given in table 1. Scenarios assumed for the studied system include: loss of load cost, load peak, load template, ELF, Real interest rate and system life, all given in Table 2. According to table. 2, here, the loss of load cost is considered 5.6 US$/kWh [17-19].

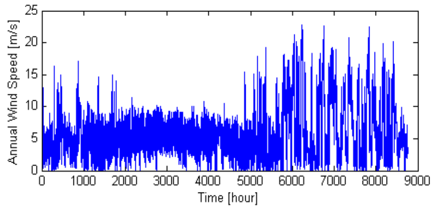

Fig. 2 The annual wind speed at the height of 15 meters in a year

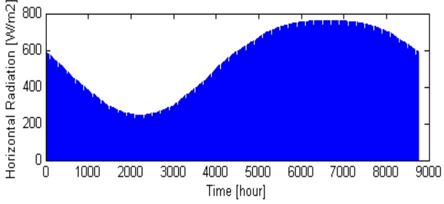

Fig.3 Horizontal solar radiation intensity on the array surface in a year.

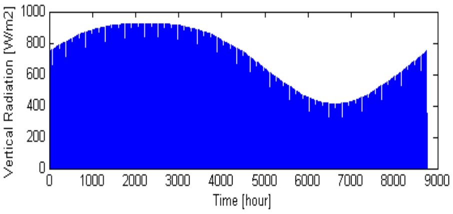

Fig.4 Vertical solar radiation intensity on the array surface in a year.

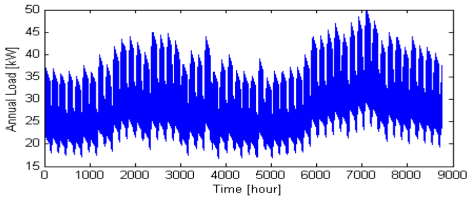

Fig.5 the IEEE annual load curve with a peak of 50 kW

B. The Simulation Results of the Base State

In this section, results of optimization of the hybrid system characterized in table. 1 using FA and COA are shown. The simulation is done in a computer with Pentium IV, CPU 3.2 GHz and 512 MB RAM. Table 3 indicates agreement of our results using COA with those presented in [18-19], in which authors used the HS and the evolutionary differential algorithm methods. The results of the optimization including the system cost and reliability indices are presented in table. 4. From our results, in comparison with other researches, it is clear that COA performs better than FA. Apart from the system cost, the reliability indices obtained by COA are better than that of FA in LOEE, LPSP and LOLE.The generated power of wind turbines and Photo-Voltaic array susing COA is illustrated in fig. 6. The hydrogen energy storage in the tank and LOEE and ELF reliability indices, respectively, are depicted in fig. 7and fig. 8.

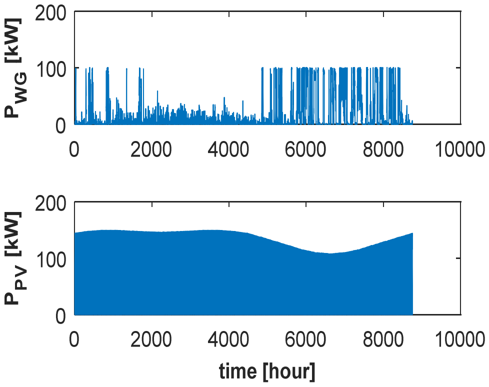

Fig. 6 The generated power by wind turbines and PV arrays

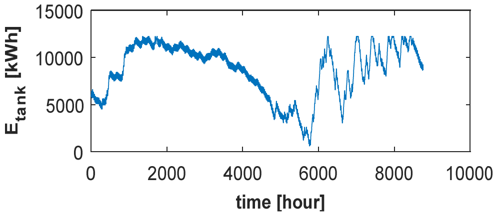

Fig.7 The hydrogen energy storage in the tank

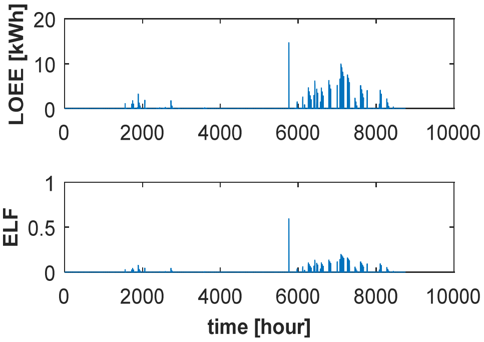

Fig.8 The LOEE and ELF reliability indices curves

C. The Sensitivity Analysis

In this section, impact of PV and WT availability and inverter efficiency, on the economical and technical design variables, using COA is evaluated.

C.1 Impact of Complete Availability of PV and WG

For complete availability (100 %) of components (solar and wind), results are shown in tables 5 and 6. According to table 6, considering the complete availability of PV and WG, the system costs have been reduced and the reliability indices are improved.

C.2 Impact of Inverter Efficiency

According to table 1, at the base mode, efficiency of the inverter is equal to 90%;here, however, the availability of inverter is considered to be 100%. The results obtained from optimization including the optimal sizing of system components are shown in table. 7;thecorresponding system costs and reliability indices are presented in table 8. The results show that the NPC is declined from 2.69 M$ to 2.59M$. Also, reliability indices are improved considerably in 100% inverter efficiency compared to 90%.

VI. Conclusion

In this paper, a method based on cuckoo optimization and firefly algorithm is presented to determine the optimal sizing of wind/solar/fuel-cell hybrid system considering economical and technical design aspects. The hybrid PV/WG/FC system is designed and optimized using the cuckoo optimization and firefly algorithms with the objective of net present cost minimization including the investment, maintenance and replacement costs and those related to the cost of load not supplied during 20 years of the system lifespan. Results of simulation illustrated superior performance of COA as compared with other methods. We observed improvements of the system reliability indices at the price of slightly increased costs. Also, via sensitivity analysis, impacts of the complete components' availability and 100% inverter efficiency on the optimization problem have been evaluated. The results show that, compared to the base case, the system costs are decreased and the reliability indices are improved.

Table 1 The rated parameters of the studied system component [17-19]

Device	*Investment Cost)US$/unit(*	*Replacement Cost)US$/unit(*	*Maintenance andRepair Cost)US$/unit-yr(*	*Efficiency)%(*	*Lifetime)Year(*
Wind Turbine	19400	15000	75	-	20
PV Array	7000	6000	20	-	20
Electrolyzer	2000	1500	25	75	20
Hydrogen Tank	1300	1200	15	95	20
Fuel Cell	3000	2500	175	50	5
ConverterDC/AC	800	750	8	90	15

Table 2 The assumed conditions for studied system [17-19]

System Lifetime	*Real Interest Rate*	ELF_{max}	*Load Pattern*	*Peak Load*	*Load Curtailment Cost*
20 Years	6%	0.01	IEEE RTS	kW50	**5.6 US$/kWh**

Table 3 The optimal sizing of hybrid PV/WG/FC system (base case)

Parameter	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}	N_{WG}
FA	34.09	46.83	41.71	123.11	111.60	209	10
COA	33.40	47.66	39.86	176.75	104.93	196	9
PSO/HS [18]	33.12	45.72	43.42	143.24	119.44	223	8
DE [19]	34.1	46.7	43.4	144.2	119.4	224	**8**

Table 4 The amounts of cost and reliability indices of hybrid system (base case)

Parameter	$LOLE$)hr/yr(	$LPSP$	$LOEE$)MWh/yr(	ELF	)MUS$(NPC_{loss}	$\sum_i NPC_i$)MUS$(
FA	295.32	0.0088	2.34	0.0081	0.153	2.7
COA	227.39	0.0049	1.31	0.0043	0.084	2.63
PSO/HS [18]	335.85	0.0092	2.34	0.0067	0.143	2.634
DE [19]	336	0.009	2.4	0.008	0.15	**2.7**

Table 5 The optimal sizing of hybrid PV/WG/FC system (complete availability of PV and WG) by COA

Parameter	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}	N_{WG}
FA (APV=AWG=0.96)	34.09	46.83	41.71	123.11	111.60	209	10
FA (APV=AWG=1)	34.40	46.55	41.67	173.29	110.87	201	**9**

Table 6 Amounts of hybrid system costs and reliability indices (complete availability of PV and WG)

Parameter	$LOLE$ $)hr/yr($	$LPSP$	$LOEE$ $)MWh/yr($	ELF	$)MUS\$($ NPC_{loss}	$\sum_i NPC_i$ $)MUS\$($
FA (APV=AWG=0.96)	295.32	0.0088	2.34	0.0081	0.153	2.69
FA (APV=AWG=1)	264.35	0.0060	1.62	0.0054	0.104	**2.65**

Table 7 The optimal sizing of hybrid PV/WG/FC system (Inverter Efficiency)

Parameters	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}	N_{WG}
FA ($\eta_{inv} = 0.9$)	34.09	46.83	41.71	123.11	111.60	209	10
FA ($\eta_{inv} = 1$)	32.10	46.85	39.58	170.81	104.04	191	**10**

Table 8 The amounts of cost and reliability indices of hybrid system (Inverter Efficiency)

Parameters	$LOLE$ $)hr/yr($	$LPSP$	$LOEE$ $)MWh/yr($	ELF	$)MUS\$($ NPC_{loss}	$\sum_i NPC_i$ $)MUS\$($
FA (0.9)	295.32	0.0088	2.34	0.0081	0.153	2.69
FA (1)	255.36	0.0058	1.54	0.0051	0.099	**2.59**

References

[1] A. M. Borbely, "Distributed generation: the power paradigm for the new millennium; 2001.

[2] Z. Yuedong, W. Hua, Z. Jianguo, "Modeling and control of hybrid UPS system with backup PEM fuel cell/battery.Int J Electr Power Energy Syst, 43(2012):1322–31.

[3] A. Billinton, "Reliability study of power systems", 2nd ed., New York: Plenum press; 1994.

[4] L. Hedstrom, C. Wallmork, P. Alvafors, "Description and modeling of the solar hydrogen – biogas-fuel cell system in glashusett", J Power Sources, 2004.

[5] R. Dufo-López, J. L. Bernal-Agustín, "Multi-objective design of PV– wind–diesel–hydrogen–battery systems", Renew Energy, 33(2008):2559–72.

[6]T. Monai, I. Takano, H. Nishikawa, Y. Sawada, "Response characteristics and operation methods of new type dispersed power supply system using photovoltaic, fuel cell and SMES", IEEE Power Engineering Society Summer Meeting, 2002, pp.1231-1236.

[7] D.B. Nelson, M.H. Nehrir, C. Wang, "Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation system", Renewable Energy,31(2006):1641-1656.

[8]S. Kim, J. Song, G. Yu, “Load sharing operation of a 14kW photovoltaic/wind hybrid power system”, IEEE Photovoltaic Specialists Conference,1997, pp. 1325-1328.

[9]R.S. Garcia, D. Weisser, “A Wind–diesel system with hydrogen storage: joint optimization of design and dispatch”, Renewable Energy, 31 (2006): 2296-2320.

[10] H. Yang, W. Zhou, L. Lu, Z. Fang,” Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm”, Solar Energy, 82 (2008): 354–367.

[11] Fatih O. Hocaoğlu, Ömer N. Gerek, Mehmet Kurban, “A novel hybrid (wind–photovoltaic) system sizing procedure”, Solar Energy, 83 (2009): 2019–2028.

[12] Ángel A. Bayod-Rújula, Marta E. Haro-Larrodé, Amaya Martínez-Gracia, “Sizing criteria of hybrid photovoltaic–wind systems with battery storage and self-consumption considering interaction with the grid”, Solar Energy, 98 (2009): 582–591.

[13] AlirezaAskarzadeh,” A discrete chaotic harmony search -based simulated annealing algorithm for optimum design of PV/wind hybrid system”, Solar Energy, 97 (2013): 93–101.

[14] S. Subhadarshi, V. Ajjarapu “MW resource assessment model for hybrid energy conversion system with wind and solar resources” IEEE Transaction on sustainable energy , 2(4)(2011).

[15] E.Koutroulis."Design optimization of desalination systems power supplies by PV and WG energy source with GA.", Solar Energy,75 (2003): 187-198.

[16] Sonia Leva□, Dario Zaninelli “Hybrid renewable energy-fuel cell system: Design and performance evaluation” Electirical Power System Research, 79(2009): 36-324.

[17] A.KashefiKaviani, G.H. Riahy, SH.M. Kouhsari, "Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages", Renewable Energy, 34 (2009): 2380–2390.

[18] S. Dehghan, B. Kiani, A. Kazemi, A. Parizad,” Optimal sizing of a hybrid wind/PV plant considering reliability indices”, World Academy of Science, Engineering and Technology, 56(2009).

[19] S. Abedi, H. Gharavi Ahangar, M. Nick, S. H. Hosseinian," Economic and reliable design of a hybrid PV-wind-fuel cell energy system using differential evolutionary algorithm", 19th Iranian Conference on Electrical Engineering (ICEE), 2011.

[20] M. J. Khan,M. T. Iqbal, "Pre-feasibility study of stand-alone hybrid energy systems for applications in new found land. Renewable Energy,30(2005):835–854.

[21] H. Yang, W. Zhou, L. Lu,Z. Fang, "Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm", Sol Energy, 82(2008):354–367.

[22] K. Strunz, EK. Brock," Stochastic energy source access management: infra- structure-integrative modular plant for sustainable hydrogen-electric co- generation. Int J Hydrogen Energy, 31(2006):1129–41.

[23] D. Xu, L. Kang, L. Chang, B. Cao," Optimal sizing of standalone hybrid wind/PV power systems using genetic algorithms", In: Canadian conference on electrical and computer engineering, 2005, 1–4 May , pp. 1722–1725.

[24] RS. Garcia, D. Weisser," A wind–diesel system with hydrogen storage: joint optimization of design and dispatch", Renewable Energy, 31 (2006): 2296–320.

[25] R. Billinton, "Evaluation of different operating strategies in small stand- alone power systems", IEEE Trans Energy Convers., 20(3)(2005): 654–60.

[26] R. Karki, R. Billinton, "Reliability/cost implications of PV and wind energy utilization in small isolated power systems", IEEE Trans Energy Convers., 16(4)(2001): 368–73.

[27] X. S. Yang, "Firefly algorithm, stochastic test functions and design optimization", International Journal of Bio-Inspired Computation, 2(2)(2010): 78-84.

[28] R. Rajabioun, "Cuckoo optimization algorithm", Applied soft computing, 11(8)(2011): 5508-5518.