OPTIMAL SIZING OF A STAND-ALONE HYBRID POWER SYSTEM USING FIREFLY ALGORITHM

[1]PEYMAN NAZARIAN, [2]MOHAMMAD JAFAR HADIDIAN-MOGHADDAM

[1]Department of Electrical Engineering, Zanjan Branch, Islamic Azad University, Zanjan, Iran.
[2]Department of Electrical Engineering, Zanjan Science and Research Branch, Islamic Azad University, Zanjan, Iran.
E-mail: pay_naz@yahoo.com, hadidian2009@gmail.com

Abstract- Optimal design of hybrid power systems (HPSs) is necessary to meet both the profitability of renewable-energy resources operations and the electricity demand. The major objective of this study is to develop an effective method for optimizing size of HPSs. A new meta-heuristic nature-inspired algorithm, called firefly algorithm is used to achieve this objective. A general formulation of this algorithm is presented together with an analytical and mathematical modeling to solve the size optimization problem. The results are compared with those obtained by alternative techniques proposed in the literature in order to show that the proposed algorithm is capable of yielding better optimal solutions.

Keywords- Hybrid Power System, Firefly Algorithm, Wind Turbine System, Size Optimization, and Battery Bank System.

I. INTRODUCTION

The conventional energy resources such as oil and natural gas have been existence all over the world as the major source of energy for many years. However, they are the main cause of global warming throughout the world. On the other hand, the demand for clean, sustainable and reliable energies throughout the world is continuously increasing because of economic and technical issues. Therefore, there is today a trend towards the use of innovative kinds of energy resources such as wind and sun powers. It is because of the fact that energies generated by solar panels and wind turbines reduce the greenhouse-gas emissions and also provide the efficient power system. Moreover, such renewable resources offer numerous economic benefits for the power system by reducing the electricity generation cost in off-the-grid remote places such as the hybrid photovoltaic (PV)-wind power system.

Size optimization of the hybrid generation system plays an important role in minimizing the total annual cost and supplying annual load demand. To date, a considerable amount of literature has been published on the optimal design of PV and wind power generating systems. The main goal of these studies is to develop the cost-optimally design and energy management of the hybrid generation power system. Generally, four different approaches for size optimization of the hybrid generation system are employed, including hybrid, heuristic, analytical and probabilistic methods. Analytical and probabilistic approaches are quite simple. However, the need for high computational time is the main drawback of these methods. Moreover, they may find local solutions. Heuristic methods are one of the most widely used groups of methodologies in the optimal design of the hybrid PV-wind energy system because of their acceptable computational time. Nonetheless, in order to enhance the performance of the optimization techniques, the hybrid approaches are used in combination with such approaches.

The major objective of this study is to find the optimum size of a PV- wind hybrid generation system to minimize the total annual cost and supplying annual load demand. The main aim of this paper is to find the optimum number of solar panels, wind turbines and batteries. To cope with this challenge, the Firefly Algorithm (FA) which inspired by the flashing behavior of fireflies is employed. High convergence rate, independent performance of the algorithm and robustness are the main reasons behind choosing this meta-heuristic algorithm.

This paper is organized as follows. System component characteristic is described in Section 2. Optimization formulation is presented in Section 3. The FA is reviewed in Section 4. Simulation results are given in Section 5. Some conclusions are drawn in section 6.

II. SYSTEM COMPONENT CHARACTERISTIC

Wind turbines and photovoltaic arrays are widely used in HPS applications, for economic, environmental and technical reasons. The structure of used HPS is shown in Fig 1, which is composed of photovoltaic arrays, wind turbines and battery storage systems along with an inverter to convert DC power to AC power [9, 10]. The wind turbine and photovoltaic arrays are considered as the main source of power generation units in the HPS. Storage units are also employed to provide a functionality similar to a synchronous generator by absorbing temporary mismatches between power generation and demand. In other words, due to seasonal and periodical variations, the HPS should be used battery storage systems in combination of solar and wind resources. Dynamic models of the main components are described using MATLAB/Simulink in the following subsections.

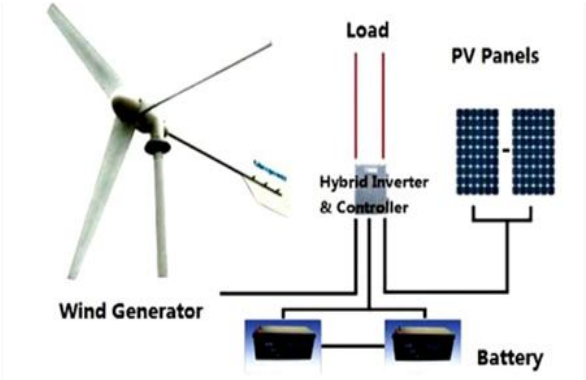


Fig 1: Structure of HPS.

A. Photovoltaic System Model

By considering the amount of radiated solar power on the surface of each PV panel, hourly power output from the PV system can be obtained as:

$$P_{PV}(t) = \eta_{pv} . A_{pv} . G(t) \quad (1)$$

Where, η_{PV} denotes the PV generator efficiency, A_{PV} is the area of PV array (m2) and $G(t)$ is the total solar irradiance (W/m2). The PV generator efficiency can be given as:

$$\eta_{PV}(t) = \eta_r . \eta_{pc} (1 - \beta (T_c - T_{cref})) \quad (2)$$

where η_r is the reference module efficiency, η_{Pc} is the power conditioning efficiency which is equal to 1 if a perfect maximum power tracker (MPPT) is used. μ is the generator efficiency temperature coefficient, it is assumed to be a constant and for silicon cells the range of μ is 0.004– 0.006 per (0C), $\theta_{Cell,ref}$ is the reference cell temperature (0C) and θ_{Cell} is the cell temperature (0C). According to above-mentioned equations, the total power generated by PV generators can be obtained as:

$$P_{PV,T}(t) = N_{PV} . P_{PV}(t) \quad (3)$$

Where N_{PV} is the number of solar panels.

B. Wind Turbine System Model

The wind speed at hub height and speed characteristics of the turbine are key components in calculation of the power output of the wind turbine generator at a particular site. Hence, Power output of a wind energy conversion system P_{WG} can be approximated as follows:

$$P_{WG} = \begin{cases} 0 & ; v_W \le v_{cutin}, v_W \ge v_{cutout} \\ P_{WG,\max} \times \left(\dfrac{v_W - v_{cutin}}{v_{rated} - v_{cutin}} \right)^m & ; v_{cutin} \le v_W \le v_{rated} \\ P_{WG,\max} + \dfrac{P_{furl} - P_{WG,\max}}{v_{cutout} - v_{rated}} \times (v_W - v_{rated}) & ; v_{rated} \le v_W \le v_{furl} \end{cases} \quad (4)$$

Where, v_{cutin}, v_{cutout}, and v_{rated} are the cut-in, cut-out, and rated speed of turbine (m/s), respectively. Also, P_{WGmax} is the maximum output power of turbine (kW), and P_{furl} is the output power at cut-out speed. According to above-mentioned equations, the total power generated by wind generators can be obtained as:

$$P_{WG,T}(t) = N_{WG} . P_{WG}(t) \quad (5)$$

C. Battery bank system model

At any hour, the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t. During the charging process, when the total output of PV and wind generators is greater than the load demand, the available battery bank energy at hour t can be described by:

$$E^T_{Batt}(t) = E^T_{Batt}(t-1) + \left[\left(E^T_{PV}(t) + E^T_{WG}(t) \right) - \frac{E_L(t)}{\eta_{inv}} \right] \quad (6)$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank energy at hour t can be expressed as:

$$E^T_{Batt}(t) = E^T_{Batt}(t-1) - \left[\frac{E_L(t)}{\eta_{inv}} - \left(E^T_{PV}(t) + E^T_{WG}(t) \right) \right] \quad (7)$$

Where $E^T_{Batt}(t)$ and $E^T_{Batt}(t-1)$ are the available battery bank energy at hour t and t-1, respectively; η_{inv} is the battery efficiency, which set equal to 1, and $E_L(t)$ is the load demand at hour t. At any hour, the storage capacity is subject to the following constraints:

$$E^T_{Batt,\min}(t) \le E^T_{Batt}(t) \le E^T_{Batt,\max}(t) \quad (8)$$

Where $E^T_{Batt,max}$ and $E^T_{Batt,min}$ are the maximum and minimum allowable storage energy. The minimum allowable storage energy can be obtained as:

$$E^T_{Batt,\min} = (1 - DOD) . E^T_{Batt,\max} \quad (9)$$

Where, DOD (%) represents the maximum permissible depth of battery discharge. The number of batteries N_{Batt} is determined by the following function:

$$N_{Batt} = Roundup \left[\frac{S_{Req}}{\eta \times S_{Batt}} \right] \quad (10)$$

Where Roundup (.) is a function which returns a number rounded up to an integer number; S_{req} is required storage capacity; η is usage% of rated capacity, which ensures battery's life span; and S_{Bat} is rated capacity of each battery. S_{req}can be written as:

$$S_{Req} = E^{T}_{Batt,\max} - E^{T}_{Batt,\min} \quad (11)$$

D. Generated Power of Renewable Energyresources

Basically, wind turbines and PV arrays are the main source of electric energy in the HPS. The total generated power through these small power generation units can be calculated by the following equations:

$$P_{ren}(t) = P_{PV,T}(t) + P_{WG,T}(t) = N_{PV}.P_{PV}(t) + N_{WG}.P_{WG}(t) \quad (12)$$

Where, N_{WG} and N_{PV} are the total number of installed wind turbines and PV arrays, respectively. The generated power by these two units can be either injected to loads using inverter or to battery units.

III. OPTIMIZATION FORMULATION

In this paper, minimizing the total annual cost (AC) considering reliability indices is the main aim of the size optimization problem. It contains the capital cost (C^{Cap}) and the total maintenance cost (C^{Main}). Therefore, the total annual cost can be obtained as:

$$AC = C^{Cap} + C^{Main} \quad (13)$$

The maintenance cost is considered over the lifetime of a project, whereas the capital cost is regarded from the start of a project. Therefore, it is impossible to compare these costs at different times. Discount factors are employed to convert a momentary value at one time to an equitant value at another time. In order to convert the initial capital cost to annul capital cost the capital recovery factor can be defined as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (14)$$

Where i is annual interest rate (6%); and n is the life span of the system (20 years). Hence, total annual capital cost of the PV-wind hybrid power system can be rewritten as:

$$C^{Cap} = CRF.\left[N_{PV}.C_{PV} + N_{WG}.C_{WG} + \left(\frac{n}{LS_{Batt}}\right).N_{Batt}.C_{Batt}\right]$$
$$C_{PV} = P_P + P_{if}$$
$$C_{WT} = T_P + T_{if} \quad (15)$$

where N_{PV} is the number of solar panels, N_{WG} is the number of wind turbines, C_{PV} is the capital cost of solar panel, P_P is unit cost of solar panel ($350), P_{if} is panel installation fee ($175), C_{WG} is the capital cost of wind turbine, T_p is unit cost of wind turbine($20000), T_{if} is wind turbine installation fee ($5000), N_{Batt} is the number of batteries, C_{Batt} is unit cost of battery and LS_{Batt} is battery's life span. For the annual maintenance cost the following equation is used:

$$C^{Main} = \left(C_{PV,main}.\sum_{t=1}^{T} P_{PV,T}(t).\Delta t + C_{WG,main}.\sum_{t=1}^{T} P_{WG,T}(t).\Delta t\right) \times 365 \quad (16)$$

Where, $C_{PV,main}$ is the maintenance costof the solar panel per kWh, $C_{WG,main}$ is the maintenance cost of the wind turbine per kWh and Δt denotes the time between the samples.

IV. FIREFLY ALGORITHM

The FA is a meta-heuristic algorithm, which operates based on the flashing patterns and behavior of fireflies. It is suggested by Xin-She Yang at Cambridge University in 2008. Basically, it is formulated based on the following idealized rules: fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex; the attractiveness is proportional to the brightness, and they both decrease as their distance increases. Thus for any two flashing fireflies, the less bright one will move towards the brighter one. If there is no brighter one than a particular firefly, it will move randomly; the brightness of a firefly is determined by the landscape of the objective function. Based on these three idealized rules, the pseudo-code of the FA can be summarized according to Fig 2. In this algorithm, the differences in light intensity play a key role in forming the objective function. Indeed, it aids the fireflies to move towards brighter and more attractive locations in order to find optimal solutions. All fireflies are characterized by their light intensity associated with the objective function. Each firefly has its attractiveness β described by monotonically decreasing function of the distance r between two any fireflies:

$$\beta(r) = \beta_0 e^{-\gamma r^m}, \quad (m \geq 1) \quad (17)$$

Where β_0 denotes the maximum attractiveness (at r = 0) and γ is the light absorption coefficient, which controls the decrease of the light intensity. The distance between two fireflies i and j at positions x_i and x_j can be defined as follows:

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} \left(x_{i,k} - x_{j,k}\right)^2} \quad (18)$$

Firefly algorithm
Initialize algorithm parameters:
MaxGen: the maximum number of generations
*Objective function of f(**x**), where **x**=(x1,.....,xd)T*
*Generate initial population of fireflies or **x**i (i=1, 2,..., n)*
*Define light intensity of **I**i at **x**i via f (**x**i)*
While *(t<MaxGen)*
For *i = 1 to n (all n fireflies);*
For *j=1 to n (all n fireflies)*
If *(Ij > Ii), move firefly i towards j;* **end if**
Attractiveness varies with distance r via Exp [-γr2];
Evaluate new solutions and update light intensity;
End for j;
End for i;
Rank the fireflies and find the current best;
End while;
Post process results and visualization;
End procedure;

Fig 2. Pseudo-code of the FA.

Where $x_{i,k}$ is the k-th component of the spatial coordinate x_i of i-th firefly and d denotes the number of dimensions. The movement of a firefly i is determined as:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}\left(x_j - x_i\right) + \alpha\left(rand - \frac{1}{2}\right) \quad (19)$$

Where the first term is the current position of a firefly i, the second term denotes a firefly's' attractiveness, and the last term is used for the random movement if there are not any brighter firefly (rand is a random number generator uniformly distributed in the range < 0, 1 >). For most cases $(0,1)\beta_0 = 1$. In practice the light absorption coefficient γ varies from 0.1 to 10. This parameter describes the variation of the attractiveness, and its value is responsible for the speed of theFA convergence.

V. SIMULATION RESULTS

Matlab environment is used to formulate the optimization problem. The parameters of the FA are adjusted as follows: n = 5, γ = 1, β_0 = 2, α = 0.2 and the maximum number of iterations is considered equal 40. Figures 3-5 show annual average hourly demand, annual power generated by each wind turbine and annual power generated by each solar panel, respectively. Fig 6 also illustrates the convergence process of FA, which shows the minimum value of the total annual cost during the iteration. It can be observed that after 24iterations, the FA converges to the optimal solution.

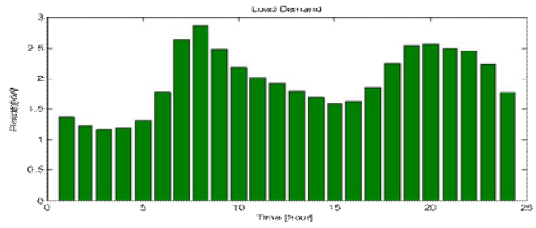


Fig 3: Average hourly electrical demand in a day.

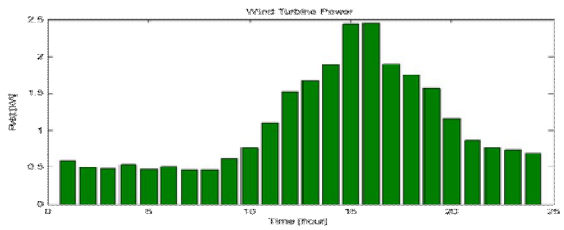


Fig 4: Average hourly power generated by a windturbine in a day.

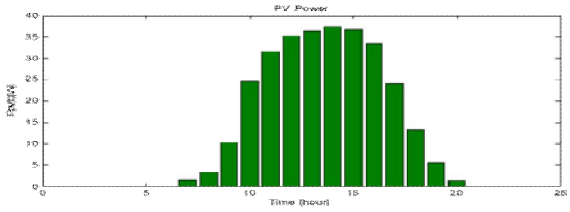


Fig 5: Average hourly power generated by a solar panel in a day.

The optimization of the HPS is done with the aim of minimizing the annual cost of power generation and considering the power balance constraint. The optimal capacity of the HPS is achieved for three different states, including by wind turbines resource, by solar panels and finally by the HPS.

Table 1 shows the optimal solution when the proposed algorithm is implemented without resource limitation constraints. As can be seen, in this simulation, the algorithms chose wind turbine only because the unit cost by wind turbines is cheaper than that by solar panels. Therefore, in this part, FA tries to use wind turbines to supply the load. As seen, the optimal solution vector $(N_{PV} = 0, N_{WG} = 2, N_{Batt} = 9)$ is calculated with the optimal cost of $5404. The results are also competed with those obtained by alternative techniques proposed in the [9] and [10]. According to this Table, the proposed algorithm shows better optimal solution.

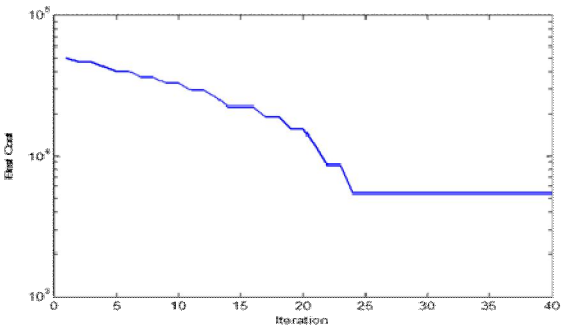


Fig 6: Convergence of FA to find the optimum size.

Table 1: The optimal solution when the proposed algorithm is implemented without resource limitation constraints.

	FA	[9]	[10]
N_{PV}	0	0	0
N_{WG}	2	2	2
N_{Batt}	9	11	10
AC ($)	5404	5652.66	5652.3

In the next step, in order to utilize some solar panels, the following constraints can be considered to the formulation:

$N_{WG} = 1 (20)$
$N_{WG} = 0 (21)$

Table 2, depicts the simulation results based on equation (3). As can be observed, in this stage, the solar panels, wind turbines and batteries are provided the load demand. The proposed method is obtained 72solar panels, 1 wind turbine and 11 batteries. As can be seen from Table 2, the results of proposed method are close to the results of references. However, in the suggested method, the lower-cost is provided.

Table 2: The simulation results based on equation (20).

	FA	[9]	[10]
N_{PV}	72	72	72
N_{WG}	1	1	1
N_{Batt}	11	11	11
AC ($)	6518	6692.6	6692.28

Table 3 also depicts the simulation results based on equation (4). As can be seen, the solar panels and batteries are provided the load demand. The proposed method is obtained 159 solar panels and 16 batteries. As can be seen from this Table, the results of proposed method are close to the results of references [9, 10]. However, in the suggested method, the lower-cost is provided.

Table 3: The simulation results based on equation (21).

	FA	[9]	[10]
N_{PV}	159	160	160
N_{WG}	0	0	0
N_{Batt}	16	17	17
AC ($)	8550	8844	8843.463

CONCLUSION

The main aim of this paperis to develop a firefly search-based method to find the optimum size of a HPS. High convergence rate, independent performance of the algorithm and robustness are the major reasons behind choosing this algorithm. The simulation results show that FA not only produces promising results but also finds the optimum solution less than other applied methods. It can be concluded that the FA cloud be an efficient candidate for optimizing the size of HPS.

REFERENCES

[1] YiyunGuo, Yufeng Lin, and Mingjie Sun, “The Impact of Integrating Distributed Generations on the Losses in the Smart Grid”, IEEE Power and Energy Society General Meeting, pp. 1-6, 2011.

[2] Miveh, M. R., Rahmat, M. F., Mustafa, M. W .A new per-phase control scheme for three-phase four-leg grid-connected inverters. ELECTRONICS WORLD, 2014, 120(1939), 30-36.

[3] R. Swisher, C.R. De Azua, J. Clendenin, “Strong Wind on the Horizon: Wind Power Comes of Age”, Proceedings of the IEEE, vol. 89, no.12, Dec 2001, pp. 1757-1764.

[4] K. Ro, and S. Rahman, “Two-loop controller for maximizing performance of a grid-connected photovoltaic-fuel cell hybrid power plant”, IEEE Trans Energy Conversion 1998; 13(3); pp. 276-281.

[5] 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.

[6] Luna-Rubio et al. Optimal sizing of renewable hybrids energy systems: a review of methodologies. Solar Energy 2012, 86, 1077–1088.

[7] Erken, O., Erken, B.Y., Ozerdem, B. Break-even analysis and size optimization of a PV/wind hybrid energy conversion system with battery storage – a case study. Applied Energy, 2009 86, 1043–1054.

[8] A. KashefiKaviani, H.R Baghaee, G.H. Riahy, “Design and Optimal Sizing of a Photovoltaic/Wind-generator System Using Particle Swarm Optimization”, Proceedings of the 22nd Power System Conference (PSC), Tehran, Iran, December 19-21 2007.

[9] AlirezaAskarzadeh," Developing a discrete harmony search algorithm for size optimization of wind–photovoltaic hybrid energy system", Solar Energy 98 (2013) 190–195.

[10] Zong Woo Geem," Size optimization for a hybrid photovoltaic–wind energy system", International Journal of Electrical Power and Energy Systems 42 (2012) 448–451.

[11] AbdelhamidKaabeche, MaïoufBelhamel, RachidIbtiouen, Techno-economic valuation and optimization of integrated photovoltaic/wind energy conversion system, Solar Energy, Volume 85, Issue 10, October 2011, Pages 2407-2420.

[12] Yang X-S.Firefly algorithms for multimodal optimization. In: Stochastic algorithms: foundations and applications, SAGA 2009. Lecture notes in computer sciences, vol. 5792; 2009. p. 169–78.

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