Optimal Sizing of Hybrid Renewable Energy System via Flower Pollination Algorithm

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Abstract: - Hybrid renewable energy systems are required by off-grid settlements. Optimal sizing of such the systems can be considered as one of the constrained optimization problems. This paper presents the intelligent method based on the modern optimization for optimal sizing the hybrid renewable energy system by using the flower pollination algorithm (FPA) in order to minimize total net present cost and meet the load demand. The FPA is one of the most powerful population-based metaheuristic optimization search techniques. It mimics the pollination behavior of the flowering plant in nature. Due to its random number with Lévy distribution, the FPA can efficiently find the optimal solutions of wide-range optimization problems. In this work, the FPA is applied for optimal sizing of the hybrid renewable energy system. The considered hybrid renewable energy system is an off-grid type consisting of diesel generators, solar photovoltaic modules, hydro systems, wind turbines and battery sets. Daily load demands are randomly set to perform the effectiveness of the FPA. Results obtained by the FPA will be compared with those obtained by the genetic algorithm (GA). From experimental results, it was found that the FPA can significantly provide an optimal sizing of the given hybrid renewable energy system superior to the GA within faster computational time consumed.

Key-Words: - Optimal Sizing, Hybrid Renewable Energy System, Flower Pollination Algorithm, Optimization

1 Introduction

In off-grid locations, the power supply is usually utilized by diesel or petrol generators which are often only available at night or at certain number of hours. Alternative energy supple of such the locations is such as solar energy via photovoltaic (PV) panels, wind and hydro turbines. A combination of various sources of renewable energy is defined as the hybrid renewable energy system [1],[2]. The advantages of such the hybrid system are each other complementation, better capacity utilization, load factor improvement and exploitation, and safer maintenance and replacement costs. However, the main disadvantage of the hybrid system is the high cost [1-4].

Sizing of the hybrid renewable energy system problem can be considered as one of the constrained optimization problems in order to optimal combine components and sizing together to minimize total cost and not-oversized load demand. Following the literatures, sizing of the hybrid renewable energy optimization problems can be effectively solved by metaheuristic optimization search techniques, for examples, genetic algorithm (GA) [5-10], particle swarm optimization (PSO) [11-13], evolutionary algorithm (EA) [14-16], ant colony optimization (ACO) [17],[18] and cuckoo search (CS) [19],[20].

Among those population-based metaheuristic optimization techniques, the flower pollination algorithm (FPA) proposed by Yang in 2012 [21] is one of the newest and most powerful optimizers. The FPA algorithm was developed based on the behaviour of pollination of flowering plant in nature. In the FPA algorithm, the random number with Lévy flight distribution is conducted for efficiently movement by pollinators in order to generate the feasible solution within the particular search space. From literature reviews, the performance evaluation of the FPA against many standard test functions was proposed [21],[22]. Moreover, the FPA was successfully applied to solve many real-world optimization problems, for examples, pressure vessels design [21], disc break design [22], electrical power system [23], image processing [24], wireless sensor networking [25], structural engineering [26], control system design [27], and travelling transportation problem [28]. The state-of-the-art and its applications of the FPA have been reviewed and reported [29],[30].

In this paper, the FPA is applied for optimal sizing the hybrid renewable energy system based on the modern optimization in order to minimize total net present cost and meet the load demand. The remainder of this paper is presented as follows. The problem formulation of the hybrid renewable energy system is formulated in Section 2. The FPA algorithm is briefly reviewed in Section 3. Results and discussions are provided in Section 4. Conclusions and future studies are followed in Section 5.

2 Problem Formulation

In this work, a stand-alone hybrid renewable energy system for off-grid locations, consisting of diesel generators, solar PV modules, hydro systems and wind turbines with batteries and inverters, is considered as shown in Fig. 1.Profile of daily load demands is arbitrary set to be constant for all year as depicted in Fig. 2 [5],[31]. The power from renewable sources and batteries are formulated as follows [5],[32],[33].

Power supplied by the hydro power is stated in (1), where P_h is hydro turbine power output, η_h is efficiency of hydro turbine, ρ_{water} is density of water, g is gravitational acceleration, H is effective head and Q is flow rate.

$$P_h = \eta_h \rho_{water} gHQ \tag{1}$$

Power utilized by the wind power is expressed in (2), where P_w is wind turbine power output, η_w is efficiency of wind turbine, η_g is efficiency of generator, ρ_{air} is density of air, C is power coefficient of wind turbine, A is wind turbine swept area and V_r is wind velocity.

$$P_w = \frac{1}{2}\eta_w \eta_g \rho_{air} CAV_r^{\ 3} \tag{2}$$

Power obtained by the solar PV is demonstrated in (3), where P_s is solar PV power output, η_{pv} is conversion efficiency of PV, N_{pvp} is number of PV panels in parallel connection, N_{pvs} is number of PV panels in series connection, V_{pv} is voltage of PV panels and I_{pv} is current of PV panels.

$$P_s = \eta_{pv} N_{pvp} N_{pvs} V_{pv} I_{pv} \tag{3}$$

Total renewable power from hydro power, wind power and PV is then formulated in (4), where P_{re_total} is total renewable power, N_h is number of hydro power systems, N_w is number of wind power systems and N_s is number of solar PV power systems.

$$P_{re\_total} = \sum_{h=1}^{N_h} P_h + \sum_{w=1}^{N_W} P_w + \sum_{s=1}^{N_S} P_s \tag{4}$$

For batteries and inverters, power for battery discharging is stated in (5), while that for charging is performed in (6), where P_b is battery power at time interval, P_{bh} is total battery power, σ is self discharge factor, P_{bl} is load demand at time interval,

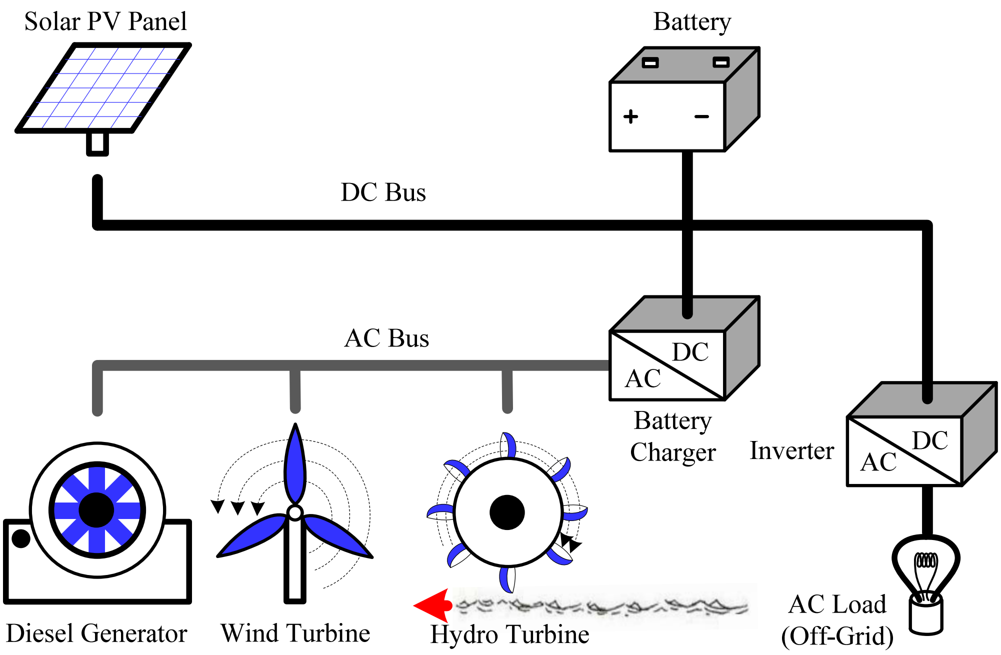

Fig. 1 Hybrid Renewable Energy System (Modified from [5]).

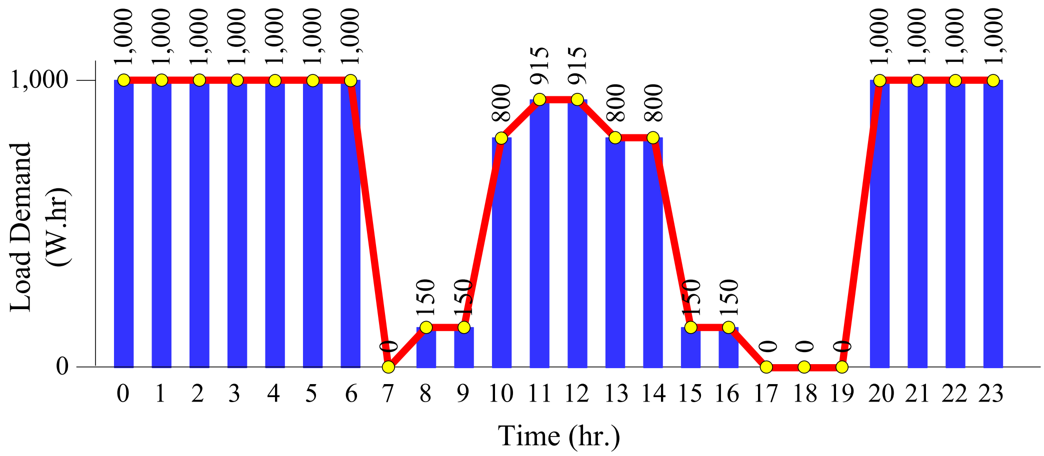

Fig. 2 Profile of Daily Load Demands (Modified from [5]).

η_{bi} is inverter efficiency and η_{bb} is battery charging efficiency.

$$P_b(t) = P_b(t-1)(1-\sigma) - \left(\frac{P_{bh}(t)}{\eta_{bi}} - P_{bl}(t) \right) \quad (5)$$

$$P_b(t) = P_b(t-1)(1-\sigma) + \left(P_{bh}(t) - \frac{P_{bl}(t)}{\eta_{bi}} \right) \eta_{bb} \quad (6)$$

The net present cost (C_{np}) can be formulated as follows. The annualized cost (C_a) of a component consists of annualized capital cost (C_{acap}), annualized replacement cost (C_{arep}), annual O&M cost (C_{ao}) and annual fuel cost for generator (C_{afg}). The operation cost can be calculated hourly on daily basis as expressed in (7), where N_g is number of generators and N_b is number of batteries.

$$\left.\begin{aligned} &\sum_{h=1}^{N_h} (C_h + C_{oh} + C_{reph}) \\ &\quad + \sum_{w=1}^{N_w} (C_w + C_{ow} + C_{repw}) \\ &\quad\quad + \sum_{s=1}^{N_s} (C_s + C_{os} + C_{reps}) \\ &\quad\quad\quad + \sum_{g=1}^{N_g} (C_g + C_{og} + C_{repg} + C_{fg}) \\ &\quad\quad\quad\quad + \sum_{b=1}^{N_b} (C_b + C_{ob} + C_{repb}) \end{aligned}\right\} \quad (7)$$

For example, in case of operating cost of hydro power, it can be calculated yearly as stated in (8).

$$C_{op} = \sum_{1}^{365} \left(\sum_{1}^{24} C_{oh}(t) \right) \quad (8)$$

Thus, C_{np} of each component is performed by (9), where CRF is capital recovering factor as shown in (10) [5],[33].

$$C_{np} = \frac{C_a}{CRF} \quad (9)$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (10)$$

Then, C_{acap} can be calculated by (11), where C_{cap} is capital cost and CRF_{proj} is project capital recovering factor.

$$C_{acap} = C_{cap} CRF_{proj} \quad (11)$$

In addition, the annualized replacement cost C_{arep} is formulated based on its salvage value at the end of the project, if any, and the cost of replacement itself as expressed by following relations, where C_{rep} is replacement cost, f_{rep} is replacement factor, SFF_{comp} is sinking fund factor of component, S_a is salvage value, SFF_{proj} is sinking fund factor of project,

$$C_{arep} = C_{rep} f_{rep} SFF_{comp} - S_a SFF_{proj} \quad (12)$$

…where,

$$f_{arep} = \begin{cases} CRF_{proj} / CRF_{rep}, & R_{rep} > 0 \\ 0, & R_{rep} = 0 \end{cases} \quad (13)$$

$$R_{rep} = R_{comp} I\left(\frac{R_{proj}}{R_{comp}}\right) \quad (14)$$

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (15)$$

$$S_a = C_{rep}\left(\frac{R_{rem}}{R_{comp}}\right) \quad (16)$$

$$SFF = \frac{i}{(1+i)^N} \quad (17)$$

From (13) – (17), f_{arep} is annualized replacement factor, CRF_{rep} is replacement capital recovering factor, R_{rep} is replacement years, R_{comp} is component years, I is annual interest rate, R_{proj} is replacement projects, R_{rem} is remaining years and S_a is salvage value.

The proposed hybrid renewable energy system considered in this work consists of hydro turbine, wind turbine and solar PV panels. Diesel generator, battery and inverter are included as the part of back-up and storage system. The proposed system is assumed to have an estimated lifetime of 25 years and fixed annual interest rate of 4.00%. Related data of the considered hybrid renewable energy system are detailed as follows [5],[31].

- ***Hydro Turbine:*** The initial capital cost for the hydro turbine is 2,625 US$ including initial civil works. Its replacement cost is 2,500 US$. The hydro turbine is expected to last 25 years. The water flow rate is assumed to be constant all year at 24 L/s. This turbine has a nominal power of 1 kW (P_{h_max}) and average output of 0.959 kW.
- ***Wind Turbine:*** The initial capital cost for the wind turbine is 5,125 US$ and its replacement cost is 5,000 US$. The wind turbine has a capacity of 0.6kW (P_{w_max}). Annual operation and maintenance cost is 125 US$. Its hub and anemometer is located at 15 meter height. The turbine is expected to last the project. The monthly wind speed (m/s) is reasonably assumed as depicted in Fig. 3.

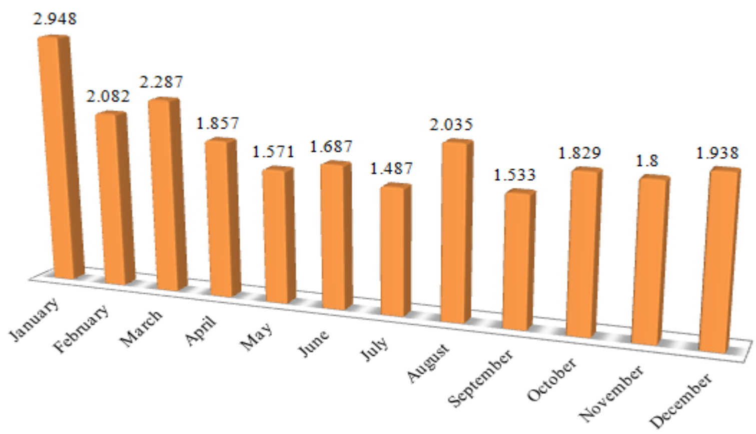

Fig. 3 Monthly Wind Speed (m/s).

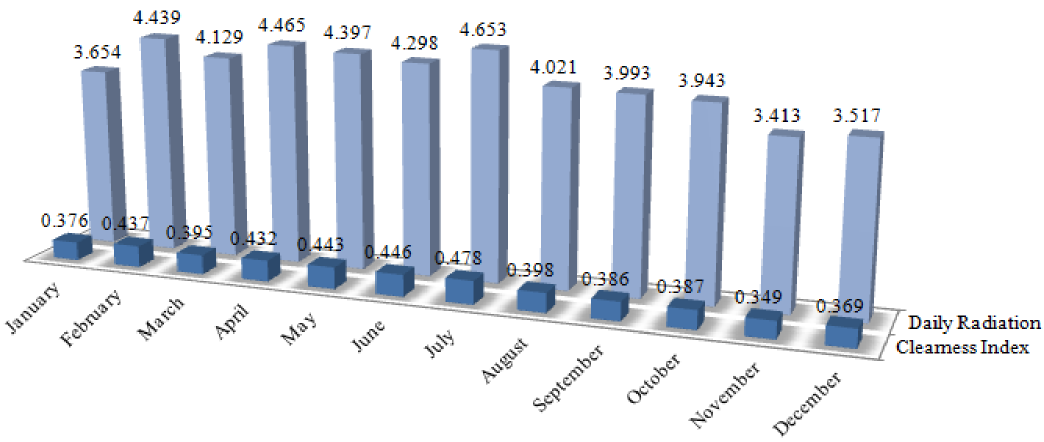

Fig. 4 Monthly Clearness Index and Daily Radiation (kWh/m^2).

- ***Solar PV Panel:*** The initial capital cost for the PV panels is 2,937.50 US$ and its replacement cost for each panel is 468.75 US$. In this work, there are six PV panels with each has a capacity of 75 W (P_{s_max}). The lifetime of the panels will last the project. Monthly clearness index and daily radiation (kWh/m^2) are depicted in Fig 4.
- ***Diesel Generator:*** The initial capital cost for diesel generator is 2,125 US$ and its replacement cost is 2,000 US$. The operation and maintenance cost is 0.025 US$/hr. The lifetime of this generator is estimated at 15,000 operating hours. Diesel is priced at 0.495 US$/L and the generator has a capacity of 1 kW (P_{g_max}).
- ***Back-up and Storage System:*** The initial capital cost for twelve batteries is 5,125 US$ and its replacement cost is 5,000 US$. The operation and maintenance cost is 6.25 US$ for the total cost annually. The valve regulated lead acid battery is rate at 2 V and has a capacity 500 Ah. or 1 kW/hr (P_{b_max}).

The objective function f and the associated constrained function are performed in (18) and (19), where C_h, C_w, C_s, C_g and C_b are the total costs of hydro turbine, wind turbine, solar PV panels, diesel generator and batteries in back-up system including capital (purchase and installation costs), operation, replacement and maintenance costs of each component, $P_{total,hr}$ is total power optimized in each hour and $P_{D,hr}$ is power load demand in each hour.

$$\left.\begin{aligned}\textbf{Min}\ & f(N_h, N_w, N_s, N_g, N_b) \\ & = C_{np} \\ & = C_h N_h + C_w N_w + C_s N_s \\ & \qquad + C_g N_g + C_b N_b\end{aligned}\right\} \tag{18}$$

$$\left.\begin{aligned}&\textbf{Subject to} \\ & P_{total,hr} \ge P_{D,hr},\ hr = 0,1,2,\ldots,23, \\ & 0 \le P_h \le P_{h\_\max},\ N_h = 0,1,2,\ldots, \\ & 0 \le P_w \le P_{w\_\max},\ N_w = 0,1,2,\ldots, \\ & 0 \le P_s \le P_{s\_\max},\ N_s = 0,1,2,\ldots, \\ & 0 \le P_g \le P_{g\_\max},\ N_g = 0,1,2,\ldots, \\ & 0 \le P_b \le P_{b\_\max},\ N_b = 0,1,2,\ldots\end{aligned}\right\} \tag{19}$$

3 Flower Pollination Algorithm

In this Section, the FPA algorithm is briefly described. In nature of flowering plants, the objective of the flower pollination is the survival of the fittest and optimal reproduction. Pollination in flowering plants can take two major forms, i.e. biotic and abiotic [34]. About 90% of flowering plants belong to biotic pollination. Pollen is transferred by a pollinator such as bees, birds, insects and animals. About 10% remaining of pollination takes abiotic such as wind and diffusion in water. Pollination can be achieved by self-pollination or cross-pollination as visualized in Fig. 5 [35],[36]. Self-pollination is the fertilization of one flower from pollen of the same flower (Autogamy) or different flowers of the same plant (Geitonogamy). They occur when a flower contains both male and female gametes. Self-pollination usually occurs at short distance without pollinators. It is regarded as the local pollination. Cross-pollination, Allogamy, occurs when pollen grains are moved to a flower from another plant. The process happens with the help of biotic or abiotic agents as pollinators. Biotic, cross-pollination may occur at long distance with biotic pollinators. It is regarded as the global pollination. Bees and birds as biotic pollinators behave Lévy flight behaviour [37] with jump or fly distance steps obeying a Lévy distribution. The FPA algorithm proposed by Yang [21] can be summarized by the pseudo code as visualized in Fig. 6.

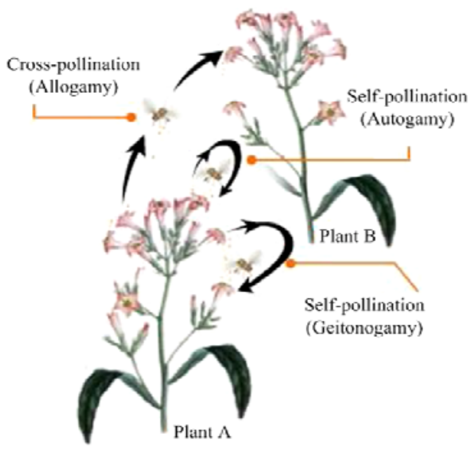

Fig. 5 Flower Pollination in Nature [35],[36].

In FPA algorithms, a solution $\boldsymbol{x}_i$ is equivalent to a flower and/or a pollen gamete. For global pollination, flower pollens are carried by pollinators. With Lévy flight, pollens can travel over a long distance as expressed in (16), where $\boldsymbol{g}^*$ is the current best solution found among all solutions at the current generation/iteration t, and L stands for the Lévy flight that can be approximated by (19), while $\Gamma(\lambda)$ is the standard gamma function as given in (20). The local pollination can be represented by (21), where $\boldsymbol{x}_j$ and $\boldsymbol{x}_k$ are pollens from the different flowers of the same plant species, while ε stands for random walk by using uniform distribution, where $\varepsilon \in [0,1]$. Flower pollination activities can occur at all scales, both local and global pollination. In this case, a switch probability or proximity probability p is used to switch between global pollination and local pollination. From Yang's recommendations [21], the number of pollens $n = 25$, proximity probability $p = 0.8$ and $\lambda = 1.5$ works better for most applications. Therefore, these recommendations are then conducted in this work.

```
- Objective f(x), x = (x1, x2,..., xd)
- Initialize a population of n flowers/pollen gametes
  with random solutions
- Find the best solution g* in the initial population
- Define a switch probability p ∈ [0, 1]
while (t < MaxGeneration)
    for i = 1 : n (all n flowers in the population)
        if rand < p,
            - Draw vector L via Lévy flight
            - Activate global pollination
        else
            - Draw ε from uniform distribution in [0,1]
            - Randomly choose j and k solutions
            - Invoke local pollination
        end if
        - Evaluate new solutions
        - If new solutions are better, update solutions
    end for
    - Find the current best solution g*
end while
```

Fig. 6 Pseudo Code of FPA Algorithms [21].

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + L(\boldsymbol{x}_i^t - \boldsymbol{g}^*) \tag{18}$$

$$L \approx \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}} \tag{19}$$

$$\Gamma(\lambda) = \int_0^\infty x^{\lambda-1}e^{-x}dx \tag{20}$$

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \varepsilon(\boldsymbol{x}_j^t - \boldsymbol{x}_k^t) \tag{21}$$

In this work, the FPA is conducted for optimal sizing the hybrid renewable energy system to minimize total net present cost (C_{np}) and meet the load demands. The FPA algorithms will randomly select a set of vector for sizing of such the hybrid system. The power derived from these components is compared to the daily load demands. If the power generated by the system able to meet the load demands, C_{np} will be then calculated. The FPA algorithm in Fig. 4 is then applied for optimal sizing the hybrid renewable energy system as follows:

Step 0 Define the objective function $f(N_h, N_w, N_s, N_g$ and $N_b)$ and the associated constrained function from (18) and (19). Initialize a population of n flowers with random solutions. Find the initial best solution $\boldsymbol{g}^*$ (N_h, N_w, N_s, N_g and N_b) among initialize population via the objective function f. Also, define $p = 0.8$, *MaxGeneration* (as termination criteria: TC) and $Gen = 1$.

Step 1 If rand $< p$ (cross/global pollination), draw L from (19)-(20) and generate the new solutions (N_h, N_w, N_s, N_g and N_b) via (18). Otherwise (self/local pollination), draw $\varepsilon \in [0,1]$ and generate the new solutions (N_h, N_w, N_s, N_g and N_b) via (21).

Step 2 Evaluate all new solutions via the objective function f and the constrained function from (18) and (19). Find the current best solution $\boldsymbol{x}$ (N_h, N_w, N_s, N_g and N_b).

Step 3 If $f(\boldsymbol{x}) < f(\boldsymbol{g}^*)$, update solution $\boldsymbol{g}^* = \boldsymbol{x}$, and update $Gen = Gen + 1$.

Step 4 If $Gen < MaxGeneration$, go back to Step 1. Otherwise, terminate the search process and report the current best solution $\boldsymbol{g}^*$ (N_h, N_w, N_s, N_g and N_b).

4 Results and Discussions

To apply the FPA for optimal sizing of the proposed hybrid renewable energy system, the FPA algorithm was coded by MATLAB version 2018b run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM. The searching parameters of FPA are set according to Yang's recommendations [21], i.e. $n = 25$, $p = 0.8$ and $\lambda = 1.5$. The maximum generation *MaxGeneration* = 500 is then set as the TC. 50 trials are conducted to find the optimal sizing of the hybrid renewable energy system. For a fair comparison with GA [38],[39], the searching parameters of GA are set as follows: number of population = 25, crossover rate = 80% and mutation rate = 5%. The GA algorithm was also coded by MATLAB version 2018b run on the same platform. After the search process stopped, the convergent rates of the objective function value in (18) proceeded by the GA and FPA over 50 trials are depicted in Fig. 7 and Fig 8. It was found that the GA shows lower convergent rates with averagely computational time of 264 seconds, while the FPA shows higher convergent rates with averagely computational time of 52 seconds.

The optimal sizing of the given hybrid renewable energy system obtained by GA and FPA are summarized by the six solutions (combinations of hydro turbine (H), wind turbine (W), solar PV panels (S), diesel generator (G), battery (B) and inverter (I)) giving least total net present cost (C_{np}) as details in Table 1 and Table 2, where C_e is cost of energy.

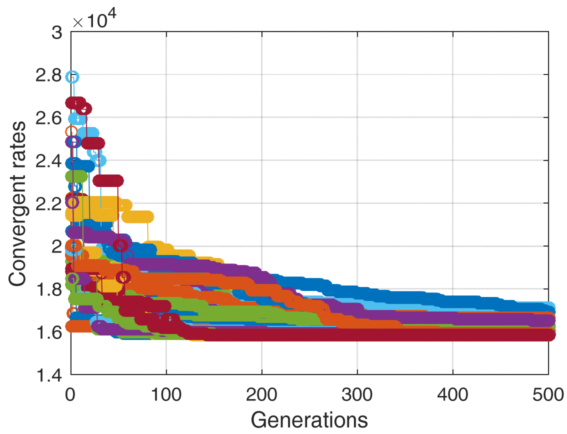

Fig. 7 Convergent Rates of Objective Function over 50 Trials Proceeded by GA.

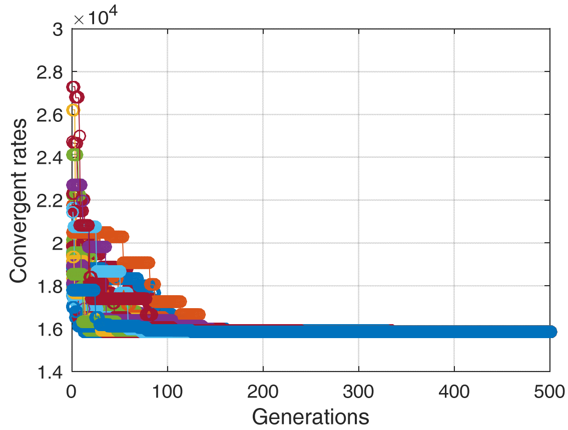

Fig. 8 Convergent Rates of Objective Function over 50 Trials Proceeded by FPA.

From Table 1 and Table 2, both GA and FPA can provide the optimal sizing of the given hybrid renewable energy system. The best solution (combination) consists of one hydro turbine, one battery set and one inverter. It was shown that the use of hydro turbine in this hybrid renewable energy system is an important part. For overall six solutions (combinations), however, the FPA can provide more optimal sizing of such the system than the GA.

As optimized results, wind turbine is not included in most cases because it may not consistent in this case. Meanwhile, solar energy is another one that is not included in many cases. It is because the high costs of battery and inverter lead to at least half of the total cost of the system.

Table 1 Optimal Sizing of Hybrid Renewable Energy System Obtained by GA

Solutions (Combinations)	Components (Numbers)	C_{np} (US$)	C_e (US$/kWhr)
1.	H(1) + B(1) + I(1)	15,971.75	0.1770
2.	S(1) + G(1) + B(1) + I(1)	17,365.25	0.1925
3.	H(1) + G(1)	18,311.75	0.2028
4.	H(1) + W(1) + S(1) + G(1) + B(1)	23,690.00	0.2625
5.	H(1) + W(1) + G(1) + I(1)	24,928.00	0.2763
6.	H(1) + W(1) + S(1) + G(1) + B(1) + I(1)	25,083.50	0.2780

Table 2 Optimal Sizing of Hybrid Renewable Energy System Obtained by FPA

Solutions (Combinations)	Components (Numbers)	C_{np} (US$)	C_e (US$/kWhr)
1.	H(1) + B(1) + I(1)	15,971.75	0.1770
2.	H(1) + S(1) + B(1) + I(1)	16,538.00	0.1833
3.	H(1) + G(1) + B(1) + I(1)	17,365.25	0.1925
4.	H(1) + S(1) + G(1) + B(1) + I(1)	17,931.50	0.1988
5.	H(1) + G(1)	18,311.75	0.2028
6.	H(1) + W(1) + G(1)	22,129.75	0.2453

5 Conclusions

Optimal sizing of the hybrid renewable energy system for off-grid settlements by the FPA has been proposed in this paper. As one of the constrained optimization problems, the given hybrid renewable energy systems, consisting of diesel generators, solar PV modules, hydro systems, wind turbines, batteries and inverters, has been conducted in order to minimize its total net present cost and meet the daily load demands. As results by comparison with the GA, it was found that both GA and FPA could provide the optimal sizing of the given hybrid renewable energy system. However, for overall solutions (combinations), the FPA could provide more optimal sizing of such the system than the GA within faster computational search time consumed.

For the future research, the time-dependent data of each component installed will be included, the multi-objective optimization of hybrid renewable energy system will be studies and the mixed off-grid and on-grid hybrid renewable energy systems will be investigated via some selected elite metaheuristic optimizers based on modern optimization context.

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