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Application of Artificial intelligence techniques for optimum design of hybrid grid-independent PV/WT/battery power system

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ABSTRACT

The idea of this paper is behind the development of sizing optimization model based on a new optimization algorithm to optimize the size of different stand-alone hybrid photovoltaic (PV)/wind turbine (WT)/battery system components to electrify a remote location including ten residential buildings located in Rafsanjan, Kerman, Iran. Then, the optimal system is estimated based on various inconstant parameters related to the renewable energy system units: the number of batteries, occupied region by the turbine blades rotation, and occupied space by the group of solar panels. The solar radiation, ambient temperature, and wind velocity data are achieved from the website of renewable energy and energy efficiency organization of Iran. The ant lion optimizer is suggested to find the optimal values of the parameters for satisfying the electrical load demand in the most cost-effective way. The results obtained from the simulation illustrate that the off-grid PV/WT/battery hybrid power system is the more promising method to provide the electricity consumption of an urban location. To evaluate the performance of the proposed method, the simulation results are compared with other hybrid energy systems, which optimized by particle swarm optimization (PSO), harmony search (HS), firefly algorithm (FA), and differential evolutionary (DE) algorithm. The results obtained by the investigated algorithms show that the PV/WT/battery system that is optimized by the ALO method is more economical compared with PV/battery and WT/battery hybrid systems. Optimal sizing, Hybrid renewable energy, Photovoltaic system, Wind turbine, Battery storage, Ant lion optimizer.

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I. INTRODUCTION

The most accessible and vital renewable energy resources such as wind speed and solar insolation can be considered as Green energies; these energy resources can be combined to build a hybrid energy system with higher quality and reliability than individual resources [1-2]. Wind speed and solar irradiation are the essential resources in a hybrid renewable energy system. The energy storage devices like batteries, fuel cells (FC), and diesel generators can be used in a hybrid system to enhance efficiency and decrease the amount of dump load. When the wind speed or solar radiation decreases or a peak demand occurs, the existence of these storage units becomes necessary [3]. The design optimizing an adequate sizing of hybrid energy systems are essential to increase the performance and reliability, meet the external load demand, reduce the energy cost and net present cost (NPC), and minimize the greenhouse gas emissions [4]. Therefore, designing a hybrid energy system, which is economically and technically justified, requires the multi-objective optimization stages. In general, the sizing methodologies for the optimal designing of hybrid PV/WT generating systems can be divided into four categories, including probabilistic, analytical, iterative, and hybrid methods. The literature study indicates that these methods have been developed, as single-objective and multi-objective, in the form of numerical, analytical, and

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optimization means or through different commercial software. Among the hybrid systems that are still being investigated can be mentioned: PV-wind [5], PV-battery [6], PV-wind-diesel [7], PV-wind-diesel- battery [8], PV-wind-battery [9], PV-wind- biomass [10], etc. The effectiveness of heuristic algorithms has led to their application to optimization problems in different aspects of renewable energy. Although various aspects of PV/WT-based hybrid systems have been considered in the literature, an informative model and efficient optimization tool for optimal sizing are seldom found. To efficiently and economically use the energy sources integrated with the hybrid system, an appropriate sizing methodology is crucial. If the hybrid systems are optimally designed, they can be cost-effective and reliable. Kellogg et al. [11] addressed a simple method for the sizing optimization of a hybrid system. It has been used to estimate the optimal capacity of a hybrid renewable energy system, which consists of wind turbines and photovoltaic panels to electrify a remote area located in Montana. In [12], the authors introduced a metaheuristic algorithm, namely simulated annealing (SA), to find the optimal numbers of wind turbines, photovoltaic panels, and batteries for a hybrid energy system. The presented method is a knowledge base algorithm which uses a stochastic gradient search for the optimization procedure. Yahiaoui et al. were used as a heuristic procedure to find the optimal values in a hybrid off-grid PV/diesel/battery system [13]. The PSO algorithm was used to find the minimum values of the global capital cost of the system, loss of load probability (LLP), and CO2 emission concerning the system parameters. The optimal values show that the interest in using the PV and battery subsystems is more economical than other strategies. In [14], Kornelakis and Marinakis proposed a heuristic method, namely, the PSO algorithm for the optimal design of a grid-connected system consist of PV panels. The purpose was applied to find the various design parameters of the system, such as the number of PV panels to get the maximum net economic benefit during the system lifetime. In [15], the authors proposed a procedure, namely the hybrid big bang–big crunch (HBB–BC) algorithm, to find the minimal cost of the examined system. In order to show the performance of the proposed method, two other evolutionary algorithms, namely PSO and discrete harmony search was used for comparison. Mohammadi et al. [16] presented an optimal design of micro-grid in distribution systems with multiple distributed generation units under different market policies such as pool / hybrid electricity market, proposed micro-grid consist of various renewable energy sources like PV panel, wind turbine and a storage component such as battery bank. The PSO as a swarm algorithm is used to optimize the system to have the minimum total net present cost. In [17], the authors presented the modeling and optimization of a hybrid PV/wind generation system for electrification of remote rural communities in Rafsanjan, Iran, by the PSO algorithm-based Monte Carlo method. Their results proved that the Monte Carlo simulation method could provide a novel approach to tools already used in the field of optimization. Besides, the case study showed that the wind/battery option was the most reliable and economical.

A hybrid optimization algorithm has been proposed for the optimal sizing of a stand-alone hybrid solar and wind energy system based on three algorithms: chaotic search, harmony search, and simulated annealing [18]. However, in their research, they didn't consider a real meteorological data. Besides, the disadvantages of the application of their algorithm are that all of them have been stuck in the local minimum, and the proper use of them strongly depends on placing the correct initial value. Wind-irradiation-load typical scenarios generation method has been developed by Dongfeng Yang and et al. [19] for optimal sizing RE resources of micro-grid. The teaching-learning-based optimization (TLBO) method is used to find the best configuration of the micro-grid system. Albeit, the TLBO is an out-of-date method, and it may stick in the local optimal and can't find the best parameters and the most optimal and competent system in the optimization process. Jean-Laurent Duchaud and et al. [20] have been suggested an adaptable optimal sizing algorithm for hybrid power plant with storage. With the same formulation, it can model a wide range of Renewable Energy Systems, storages, and types of equipment with power-dependent efficiencies. The optimization problem is solved by a MOPSO algorithm to minimize the total annual cost of the examined systems while ensuring power supply. However, the optimization procedure is not a new method, and it is abolished. Furthermore, in such a problem, MOPSO can't find the best parameters to find the minimum cost of the system. Although in the presented study, the application of PSO has been examined. In this paper, a new sizing way based on MATLAB/Code is used to perform a technical optimization of the hybrid system ingredients. Selected hybrid renewable energy system integrating PV panel, wind turbine, and a storage component like a battery bank. Two inconstant parameters (total swept area by the rotating turbine blades and total area filled up by the group of PV panels) and one integer variable (total number of batteries) has been considered in optimally designing hybrid PV / WT / battery system and suggest a valid version of swarm and evolutionary algorithms which is the most recent nature-inspired algorithm (NIA), called ant lion optimizer, to optimal design an off-grid hybrid system to satisfy the load demand of a residual building located in two different location namely, Rafsanjan, Kerman. The effectiveness of the ALO algorithm in solving a complex problem is checked out, and its performance is compared to other well-known optimization algorithms. To highlight the proposed method performance, a real case study has been carried out, and the results are inspected.

The paper is organized as follows. The mathematical model of

hybrid system components and optimization framework are presented in Sections II. Modeling for the total annual cost is described in section III. Objective functions and constraints are introduced in Section IV. Brief overviews of the investigated algorithms addressed in section V. Numerical studies are carried out in a rural area include ten residual buildings in Section VI. Furthermore, the simulation results are discussed in this Section. Finally, the concluding remarks are provided in Section VII.

II. Optimization Framework and Mathematical Model of Hybrid System Components

Fig. 1 show the block diagram of the hybrid PV / WT / battery renewable energy system, including several energy sources: photovoltaic, wind turbine. An energy storage part is included several batteries. Wind turbines are connected to an inverter before connecting with electrical consumers, because of almost all of the electrical systems are uses AC power. The amount of energy produced at each time due to the optimization procedure should be considered. For this goal, a mathematical model of the hybrid system component is developed, and the energy produced by each of the power sources is determined. In the next sections, the modeling of each element in the hybrid system and the optimization framework are described in detail.

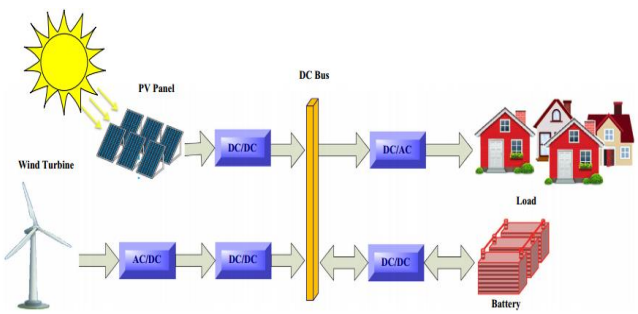


Fig. 1. The block diagram of the hybrid PV/WT/ battery system

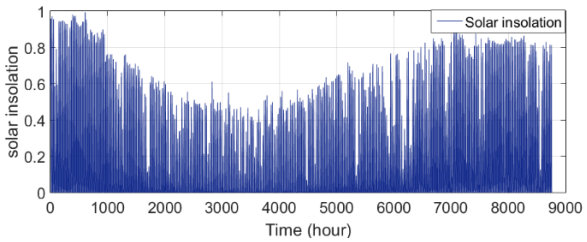
A. Modeling of Photovoltaic panel

The formula of the output power of each photovoltaic panel, with respect to the ambient temperature and solar radiation power, can be calculated as follows [21-25].

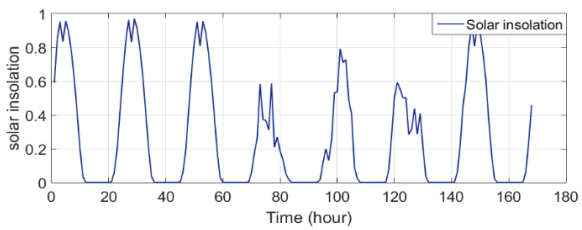
$$p_{out} = P_{N-pv} \times \frac{G}{G_{ref}}[1 + K_t\left((T_{amb} + (0.0256 \times G)) - T_{ref}\right)] \quad (1)$$

where P_{out} is the output power of photovoltaic panel, P_{N-pv} is rated power under reference conditions, G is solar radiation (W/m^2), G_{ref} is $1000\,W/m2$, T_{ref} is $25\,C$, K_t is $-3.7 \times 10^{-3}(1/C)$, and T_{amb}, is the ambient temperature. Figs. 2 and 3 shows the hourly experimental data of solar insolation data and the ambient temperature of one of the selected location, which is located in the northwest of Iran. If the number of PV panels is NO_{pv}, so the total produced power of all photovoltaic panels can be calculated by the following equation:

$$P_{PV}(T) = NO_{PV} \times P_{OUT}(T) \quad (2)$$

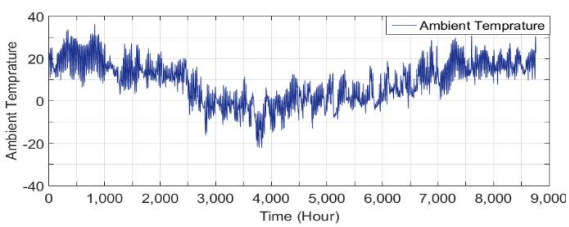


a

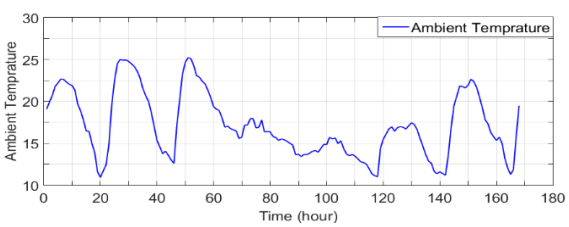


b

Fig. 2. Hourly experimental data of solar insolation: a) during one year and b) during the first week of the year



a



b

Fig. 3. Hourly experimental data of ambient temperature: a) during one year and b) during the first week of the year

B. Modeling of wind turbine generator

Selecting an acceptable model is very important for wind turbine power simulations. Three main factors determine the power output of a wind turbine, i.e., the power output curve of a chosen wind turbine, the wind speed distribution of a selected area where the wind turbine is installed, and the tower

height. Wind speed changes with altitude and the available wind data at different sites are typically measured at different height levels. The power-law equation of each wind turbine calculated by the following correlation [22]:

$$p_{WT}(t)=\begin{cases}0 & \text{if } v(t)\le V_{ci}\\ a.v^3(t)-b.P_r & \text{if } V_{ci}<v(t)<V_r\\ P_r & \text{if } V_r<v(t)<V_{co}\\ 0 & \text{if } v(t)\ge V_{co}\end{cases} \quad (3)$$

where v is the wind speed (m/s); V_{ci}, V_{co}, and V_r, are cut-in, cutout, rated speeds of the wind turbine, respectively; and P_r is the wind generator rated power (kW). The parameters a and b can be expressed as:

$$a=P_r/(V_r^3-V_{ci}^3) \quad (4)$$

$$b=V_{ci}^3/(V_r^3-V_{ci}^3) \quad (5)$$

The rated power P_{r-wt} is expressible as a function of the area swept by the wind turbine generator blades A_{WT}, the power coefficient C_P, the air density ρ_a, the reducer efficiency η_r and the mechanical efficiency of the wind turbine η_{WT}:

$$P_r=\frac{1}{2}.A_{WT}.C_P.\rho_a.\eta_r.\eta_{WT}.V_r^3 \quad (6)$$

Fig. 4 shows the hourly profile of wind speed for Rafsanjan station at the height of 10m respect to the ground. Attentive to the generated power by each wind turbine, the total produced power by wind turbines can be obtained by the following equation:

$$P_{wt}(t)=NO_{wt}\times p_{wt}(t) \quad (7)$$

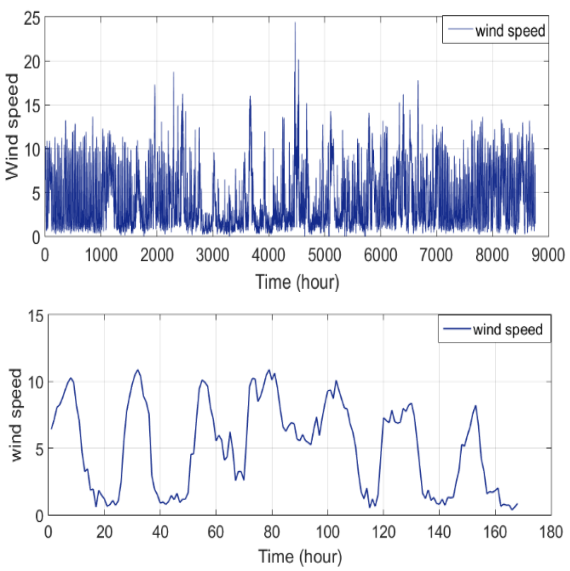


Fig. 4. Hourly experimental data of wind speed at the height of 10 meters: a) during one year and b) during the first week of the year

C. *Modeling of battery*

The battery bank is one of the most commonly used storage devices in renewable energy systems to save the balance of energy generated by power sources to supply the load demand. Because of the random treatment of photovoltaic panels and wind turbines, the storage capacity continuity changes in the hybrid system. In such an order, the state of charge (SOC) of the battery is the amount of energy stored in batteries [23-26]. When the total output power of PV panels and wind turbines is higher than the load demand, the battery bank is in a charging state. The amount of energy stored in the storage system at time t can be achieved by:

$$SOC(t)=SOC(t-1)\times(1-\sigma)+\left[(No_{PV}\times P_{PV}(t)\times\eta_{CON}+No_{WT}\times P_{WT}(t)\times\eta_{REC})-\frac{P_{Load}(t)}{\eta_{INV}}\right]\times\eta_{BA} \quad (8)$$

Where $SOC(t)$ and $SOC(t-1)$ are the amounts of energy stored in batteries at time t and $t-1$, respectively. r is the hourly self-discharge rate, η_{CON}, η_{REC} and η_{INV} illustrate the efficiency of the converter, rectifier, and inverter, respectively. $P_{Load}(t)$ is the load demand and $\eta_{BA}$is the charge efficiency of the battery bank. When the total output power of energy sources is less than the electrical load demand, the storage system is in discharging state. In this research, the discharge efficiency of the battery bank is assumed to be 1. Therefore, the amount of energy stored in the storage system at time t can be obtained by:

$$SOC(t)=SOC(t-1)\times(1-\sigma)-\frac{\left[\frac{P_{Load}(t)}{\eta_{INV}}-(No_{PV}\times P_{PV}(t)\times\eta_{CON}+No_{WT}\times P_{WT}(t)\times\eta_{REC})\right]}{\eta_{BA}} \quad (9)$$

For battery longevity, the state of charge $E_{Bat}(t)$ must be bounded by two different thresholds, an upper threshold noted $SOC_{Bat.max}$ which represents the nominal capacity of the battery bank C_n and a lower threshold called $SOC_{Bat.min}$ so that $SOC_{.min}\le SOC_{Bat}(t)\le SOC_{max}$ obtaining a battery bank requires knowledge of the relation between the number of battery units and battery capacity [23][27]. The following equation gives this relation:

$$C_n=\left(\frac{No_{batt}}{No_{batts}}\right)\times C_{batt}=No_{batp}C_{batt} \quad (10)$$

where N_{batt}: the total number of batteries, N_{batts}: the number of batteries connected in series, N_{battp}: Number of batteries connected in parallel, $C_{batt}[Ah]$: Capacity of a battery unit. The relation between the maximum and minimum state of charge is given by the following formula:

$$SOC_{min}=(1-DOD)SOC_{max} \quad (11)$$

With DOD: represents the Depth Of Discharge, which generally equals 80% of the nominal capacity [24]. The expression of the DC bus voltage depending on the voltage of a battery can be written as follows:

$$V_{bus}=\sum_{i=1}^{V_{batts}}N_{batt}V_{batt-i} \quad (12)$$

In which V_{batt} is the voltage of a single battery. In our case DC bus voltage $V_{bus}=24v$. Fig. 5 shows the operating strategy of the energy stored in the battery bank at each hour during the year. From the above-described situations, a

program is developed in MATLAB to size the components for each configuration, the flow diagram of the hybrid optimal sizing model is illustrated in Fig. 5.

Using the expanded program, all arrangements which satisfy the rate of $LPSP = 0$ are retained.

Afterward, the optimal configuration is predicted based on the minimum cost. In this paper, the temperature effects on the battery bank are ignored.

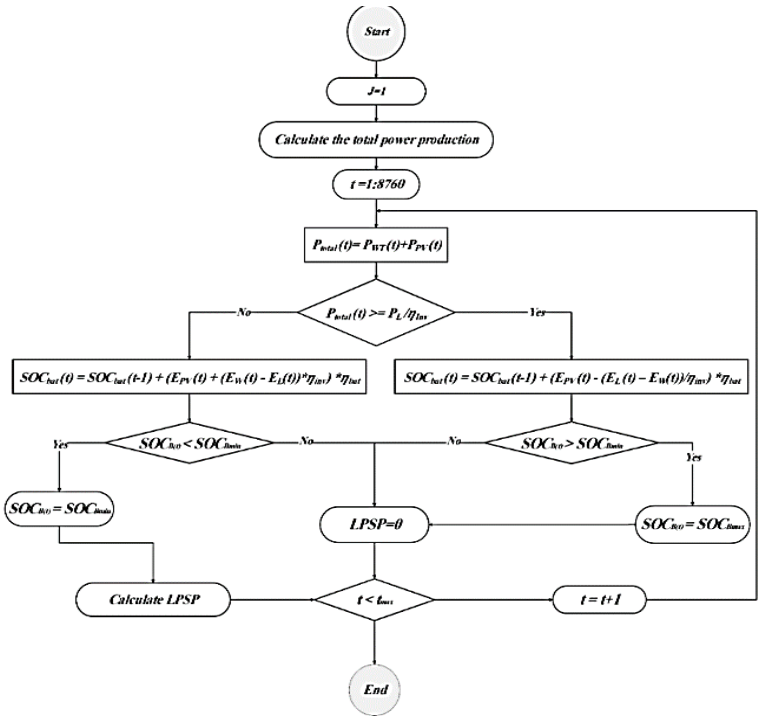


Fig. 5. Operation algorithm of SOC of the hybrid renewable energy system

III. MODELING FOR THE TOTAL ANNUAL COST

The total annual cost (TAC) is used in this paper for the cost analysis of the hybrid PV / WT / battery system. The TAC analysis includes finding the NPC of all costs of the hybrid system over the system lifetime. The following equation describes the TAC:

$$\mathrm{TAC} = \mathrm{CC_{npc}} + \mathrm{MC} \quad (13)$$

Where, CC is the annual capital cost, and MC is the yearly maintenance cost, the 'npc' illustrates the net present cost of each component. A capital cost expenditure occurs at the beginning of a project while maintenance costs occur over the project life. For converting the initial cost of the system to the annual capital cost, the capital recovery factor (CRF) is used, which is explained below:

$$\mathrm{CRF}(\mathrm{i_r}, \mathrm{n_p}) = \frac{\mathrm{A}}{\mathrm{P}} = \frac{\mathrm{i_r}(1+\mathrm{i_r})^{\mathrm{n_p}}}{(1+\mathrm{i_r})^{\mathrm{n_p}} - 1} \quad (14)$$

In this equation, $\mathrm{n_p}$ denotes the project lifetime and $\mathrm{i_r}$ is the real interest of the system.

A. TAC of PV array

The capital cost of PV panels can be calculated by considering the total area swept by PV panels by the following equation:

$$\mathrm{CC_{npv,PV}} = \mathrm{CRF}.\mathrm{A_{PV}}.\mathrm{C_{PV}} \quad (15)$$

where $\mathrm{A_{PV}}$ is the area equipped with photovoltaic panels, and $\mathrm{C_{PV}}$ is the cost of solar panels, which is included as the combination of each panel price and panel installation fee. The annual maintenance cost for PV panels can be explained as follows:

$$\mathrm{MC_{PV}} = \mathrm{A_{PV}}.\mathrm{C_{Mnt-PV}} \quad (16)$$

where $\mathrm{C_{Mnt-PV}}$ is the annual maintenance cost of each PV panel.

B. TAC of wind turbines

The capital cost of wind turbines can be calculated the same as the PV system by considering area swept by turbine blades for the hybrid system:

$$\mathrm{CC_{npv,WT}} = \mathrm{CRF}.\mathrm{A_{WT}}.\mathrm{C_{WT}} \quad (17)$$

$\mathrm{C_{wt}}$ is the cost of wind turbines, which is included as the combination of each wind turbine price and the installation fees, the annual maintenance cost can be defined as bellow:

$$\mathrm{MC_{WT}} = \mathrm{A_{WT}}.\mathrm{C_{Mnt-WT}} \quad (18)$$

C. TAC of batteries

The capital cost of No_{batt} batteries for the storage component can be obtained as follows:

$$CC_{npv,PV} = CRF.\, No_{batt}.\, c_{batt} \quad (19)$$

Where No_{batt} is the number of batteries, and c_{batt} is the unit cost of one battery.

D. TAC of converter/inverter

The formula for calculating the capital cost for $N_{Conv/Inv}$ converter/inverters for the hybrid PV/WT/battery system can be expressible as:

$$CC_{npv,Conv/Inv} = CRF.\, N_{Conv/Inv}.\, PW_{Conv/Inv} \quad (20)$$

By considering the lifetime of the inverter to be ten years, the present worth factor can be obtained by the following equation:

$$PW_{Conv/Inv} = C_{Conv/Inv} \frac{1}{(1+i_r)^k} \quad (21)$$

where $N_{Conv/Inv}$ denotes the number of converter/inverter components, $PW_{Conv/Inv}$ is the present worth of converter/inverter components, and $C_{Conv/Inv}$ is the converter/inverter cost.

IV. OBJECTIVE FUNCTION AND CONSTRAINTS

The objective function of the optimum design problem is the minimization of the system's total cost (TAC). That is, for the hybrid renewable energy system, the following function is minimized, and the following constraints are satisfied:

$$\text{Minimize LCC}\,(A_{WT}, A_{PV}, No_{batt}) = \sum_{m \in WT, PV, conv, inv, battery} CC_{npc,m} + MC_m + RC_m \quad (22)$$

$$A_{WT} \geq 0, A_{PV} \geq 0, No_{batt} \geq 0, LPSP^m \geq LPSP \quad (23)$$

In this study, the variables (A_{WT}, A_{PV}, and No_{batt}) are optimally obtained, where No_{batt} is an integer variable and A_{WT} and A_{PV} Are continuous variables. For having excellent reliability in hybrid energy systems, it is required to consider LPSP (loss of power supply probability), which is in the range of 0 and 1. The LPSP of 1 means the electrical load never be satisfied, and the LPSP of 0 means the electrical amount always be prepared. The expression of LPSP for a period of time (1year in this paper) can be calculated as follows:

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_{Load}(t)} \quad (24)$$

where $LPSP^m$ is the maximum admissible LPSP

V. Investigated metaheuristic algorithm

A. Particle swarm optimization

PSO is one of the most applicable evolutionary algorithms in the field of artificial intelligence for solving complicated problems. This metaheuristic algorithm was proposed for the first time by Kennedy and Ebrahat in 1995 [28]. This theory mainly inspects a particular location named the solution area, where each space has a feasibility degree for solving the complex problems. The particle swarm optimization moves each particle in every part of the solution area to estimate the optimal values concerning the distinctive and neighboring particles that have experience of the PSO due to the optimization procedure. So, particles entailed in optimization use the memory of the particles to adjust the particle fitness by treading on the heels of the treatment of the victorious particles in the swarm. The PSO starts with a stochastic particle for initializing particles, keep on by looking for optimal solutions within the past iterations, and then evaluating the particle quality according to the fitness function [29].

The basic PSO algorithm that defines the next position of the candidate solution is as follows:

$$V_i^{k+1} = WV_i^k + C_1\, r_1\, (P_{bi} - x_i^k) + C_2\, r_2\, (G_{bi} - x_i^k) \quad (25)$$

$$X_i^{k+1} = X_i^k + V_i^k \quad (26)$$

where I represents the optimization vector variable, k is the number of iterations, V_{ik} and X_{ik} are the respective velocity and position of the $i-th$ variable within k iterations, W is the inertia weight factor, C_1 is the cognitive coefficient of the individual particles, C_2 is the social coefficient of all the particles, and r_1 and r_2 are the randomly selected variables in the range [0, 1]. These random parameters mainly aim to maintain stochastic movement within the iterations.

B. Differential evolution algorithm

Another population-based optimization procedure is the differential evolutionary algorithm, which is practical to find the globally optimal values in complex problems. The method has much the same idea to GA and was addressed for the first time by Storn and Price [30]. Outstanding to its lack of complication, DE is one of the robust population-based optimization algorithms among other heuristic methods. Optimal values of the problem are obtained by generating new candidate solutions based on different sets of expressions for each of the various procedures while carrying on the population size.

C. Firefly algorithm

The firefly algorithm is a kind of heuristic algorithm, which is a particle-based method. The FA is inspired by brightening insects, and the mathematical equation defined in [31]. In FA method, we can suppose that brightness of a firefly determines its attractiveness which successively is related to the objective function. For a known environment with a constant light attractiveness coefficient γ, the light intensity I is changed according to the distance r,

$$I = I_0 e^{-\gamma r^2} \quad (27)$$

I_0 is the light intensity in the center. To realize better here is an example: if the firefly p has lower brightness than firefly q, the new position for firefly p is determined by the following

equation:

$$x_p^{t+1} = x_p^t + \beta(r)\left(x_p - x_q\right) + \alpha\varepsilon_i \quad (28)$$

Where the positions of two fireflies are denoted by X_p and X_q, respectively. r is the interval between these two fireflies is represented by r, the attractive level in mating is β, and α is a random movement factor and is a constant parameter in the range of [0, 1]. It is essential to mention that a considerable value of α makes it possible to search for the solution through an extensive search space; also, a smaller amount of α tends to facilitate the local search. The degree of attractiveness (β) in Eq. (29) the following equation can define:

$$\beta(r) = \beta_0 e^{-\gamma(x_{pq})^n}, \quad n \geq 1; \quad (29)$$

Where β_0 is the first attractiveness.

D. Harmony search (HS)

Harmony search is a knowledge-based method that attempts to mimic the musicians' improvisation process [32]. There are three parameters namely harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and bandwidth of generation (bw) that play a significant role in the convergence of the HS algorithm. These values can be potentially useful in modifying the convergence rate of the method to obtain the optimal solution in engineering problems. The HMCR is different between 0 and 1 is the rate of selecting one value from the HM. PAR and bw are introduced as follows:

$$\mathrm{PAR}(t) = \mathrm{PAR}_{\min} + \frac{\mathrm{PAR}_{\max} - \mathrm{PAR}_{\min}}{\mathrm{iter}_{\max}} \times \mathrm{iter} \quad (30)$$

$$bw(t) = bw_{max}\exp(c \times iter) \quad (31)$$

$$c = \frac{Ln(bw_{max}/bw_{max})}{iter_{max}} \quad (32)$$

where the maximum and minimum pitch adjusting rates are represented by $\mathrm{PAR}_{\max}$ and $\mathrm{PAR}_{\min}$, respectively, and $\mathrm{bw}_{\max}$, $\mathrm{bw}_{\min}$ are the maximum and minimum bandwidths, respectively.

E. Overview of the Ant Lion Optimization Algorithm

Mirjalili, in 2015 [33], introduced a novel nature-inspired algorithm called ant lion optimizer. The ALO algorithm imitates the hunting method of ant lions in a natural environment. An ant lion larva digs a cone-shaped hole in the sand by moving along a circular way and throwing out sands with its massive jaw [34]. After excavation of the trap, the larva hides underneath the bottom of the cone and waits for insects to be trapped in the pit. The border of the funnel is keen enough for insects to fall into the trap easily. Once the ant lion understands that a hunt is in the trap, it starts hunting it. Then, it is pulled under the soil and died. After eating the prey, ant lions throw the rest of the food outside the pit and get the pit ready for the next hunt [33].

Operators of the ALO algorithm

The ALO algorithm emulates the interaction between ant lions and ants in prison. To model such interactions, ants are required to move the search space, and ant lions are allowed to hunt them and become fitter using traps. Because of the random behavior of ants in nature for searching for food, a stochastic walk is selected for modeling the displacement of ants as follows [33]:

$$X(t) = \begin{bmatrix} 0, \mathrm{cums}(2r(t_1) - 1), \\ \mathrm{cums}(2r(t_2) - 1), \ldots, \mathrm{cums}(2r(t_n) - 1) \end{bmatrix} \quad (33)$$

Where cums denotes the cumulative sum and $r(t)$ is introduced as follows:

$$r(t) = \begin{cases} 1 \text{ if rand} > 0.5 \\ 0 \text{ if rand} \leq 0.5 \end{cases} \quad (34)$$

The bellow matrix illustrated the location of each ant and used during the optimization procedure:

$$M_{\mathrm{ant}} = \begin{bmatrix} \mathrm{ant}_{1,1} & \mathrm{ant}_{1,2} & \ldots & \mathrm{ant}_{1,d} \\ \mathrm{ant}_{2,1} & \mathrm{ant}_{2,2} & \ldots & \mathrm{ant}_{2,d} \\ & \vdots & & \\ \mathrm{ant}_{n,1} & \mathrm{ant}_{n,2} & \ldots & \mathrm{ant}_{n,d} \end{bmatrix} \quad (35)$$

The location of an ant refers to the parameter for each solution. For saving the position of each ant the Matrix of M_{ant} is considered. The fitness function is developed [33] due to the optimization problem, and the fitness value of each ant saves into the following matrix:

$$M_{\mathrm{oa}} = \begin{bmatrix} F_t([\,\mathrm{ant}_{1,1}, \mathrm{ant}_{1,2}, \ldots, \mathrm{ant}_{1,d}]) \\ F_t([\,\mathrm{ant}_{2,1}, \mathrm{ant}_{2,2}, \ldots, \mathrm{ant}_{2,d}]) \\ \vdots \\ F_t([\,\mathrm{ant}_{n,1}, \mathrm{ant}_{n,2}, \ldots, \mathrm{ant}_{n,d}]) \end{bmatrix} \quad (36)$$

Also, the ant lions are kept out of sight in the search area. The following matrices are used to save their positions.

$$M_{\mathrm{antlion}} = \begin{bmatrix} \mathrm{antlion}_{1,1} & \mathrm{antlion}_{1,2} & \ldots & \mathrm{antlion}_{1,d} \\ \mathrm{antlion}_{2,1} & \mathrm{antlion}_{2,2} & \ldots & \mathrm{antlion}_{2,d} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{antlion}_{n,1} & \mathrm{antlion}_{n,2} & \ldots & \mathrm{antlion}_{n,d} \end{bmatrix} \quad (37)$$

$$M_{\mathrm{oal}} = \begin{bmatrix} F_t([\,\mathrm{antlion}_{1,1}, \mathrm{antlion}_{1,2}, \ldots, \mathrm{antlion}_{1,d}]) \\ F_t([\,\mathrm{antlion}_{2,1}, \mathrm{antlion}_{2,2}, \ldots, \mathrm{antlion}_{2,d}]) \\ \vdots \\ F_t([\,\mathrm{antlion}_{n,1}, \mathrm{antlion}_{n,2}, \ldots, \mathrm{antlion}_{n,d}]) \end{bmatrix} \quad (38)$$

Random walks of ants

The position of each ant is change based on equation (33). The stochastic steps are normalized to be inside the searching contribution by the following equilibrium:

$$X_i^t = \frac{(X_i^t - A_i) \times (D_i - C_i^t)}{(D_i^t - A_i)} + C_i \quad (39)$$

Trapping in ant lion's pits

Random walks of ants are affected by ant lions' traps. The following equations are defined to model this suggestion:

$$C_i^t = \mathrm{Ant\ lion}_j^t + C^t \quad (40)$$

$$D_i^t = \mathrm{Ant\ lion}_j^t + D^t \quad (41)$$

Randomly walking of ants in a hypersphere introduced by the vector of C and D in equations (40-41)

Building trap

For modeling, the ant lion hunting ability uses a roulette wheel. Based on the fitness of each ant during the performance of the program, the ALO algorithm is required to utilize a roulette wheel operator. One selected antlion is assumed to have only one trapped ants. The fitter antlions to catch ants will have a high chance of using this mechanism. This is because of the fitter the antlion, the smaller probability of the trapped ant to escape from the pits. That is why it is crucial to determine the fitness of the antlion during optimization. Antlions can build traps relational to their fitness and ants are required to travel randomly based on the mechanism proposed so far. But, when antlions realize an ant is in a trap, they shoot sands outwards the center of the pit. This action slides down the trapped ant that is trying to escape.

Sliding ants towards ant lion

With the last instructions, a random movement is required for ants for building traps concerning their fitness. However, ant lions shoot sands outwards the center of the pit once they sense that an ant is in the trap. This behavior slides down the trapped ant that is trying to escape. To model this behavior, the radius of ant's random walk hypersphere is reduced adaptively. The following equations are introduced in this regard:

$$c^t = \frac{c^t}{I} \tag{42}$$

$$d^t = \frac{d^t}{I} \tag{43}$$

Catching prey and rebuilding the pit

The objective function is calculated in this step. If the ant has a better objective function than the selected ant lion, then it changes its position to the latest situation of the hunted ant to enhance its chance of catching the new one. The following equation is presented in this regard:

$$\text{Ant lion}_j^t = \text{Ant lion}_i^t \quad \text{if} \quad f(\text{Ant}_i^t) > f(\text{Ant lion}_j^t) \tag{44}$$

Elitism

It is necessary to keep the best solution acquired at each step of the optimization task. The best ant lion finished so far is maintained as the elite. Since the elite is the best ant lion, it should be capable of affecting the motions of all ants during iterations. Thus, it is assumed that every ant randomly walks around a selected ant lion by the roulette wheel and the elite simultaneously as follows:

$$\text{Ant}_i^t = \frac{r_a^t + r_e^t}{2} \tag{45}$$

Figure 6 shows the operation strategy of the ant lion optimizer algorithm as an optimization procedure.

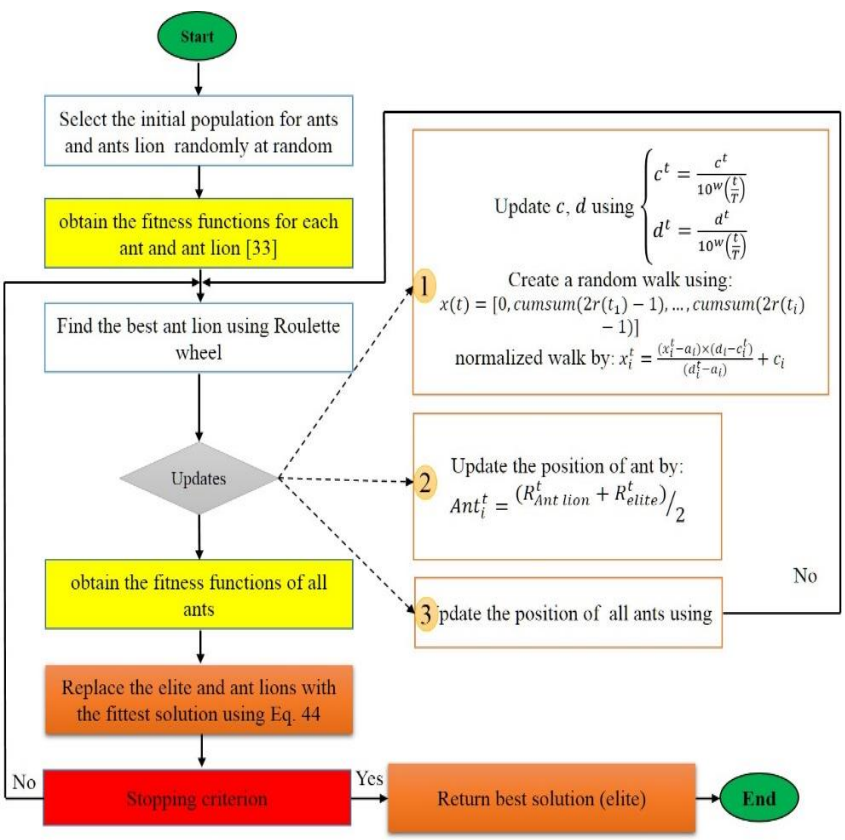


Fig. 6. Flowchart of the ALO

In the ALO algorithm, the matrix of ant and ant lions stochastically initialized by an objective function which is defined by Mirjalili [33]. In each iteration, the location of each ant has been updated by another stochastic function [33] in which the chosen antlions selected by the roulette wheel operator and the elite. The boundary of position updating is first defined proportional to the current number of iteration. The updating position is then accomplished by two random walks around the selected antlion and elite. The ants are evaluated by the fitness function after a stochastic walk of all of them.any of the ants become fitter than any other antlions, their positions are considered as the new positions for the antlions in the next iteration. The best antlion is compared to the best antlion during the optimization procedure and replaced if needed.

VI. RESULT AND DISCUSSION

The experimental meteorological data used is achieved for Rafsanjan, Kerman, Iran [35]. The hourly load profile of fifteen homes with a maximum demand of 27.92 kwh and the total annual electricity demand of 154024 kwh located in Rafsanjan, Kerman Iran, is shown in Fig. 7. Table I lists the technical data of system components. Table II shows the minimum, maximum and average of solar insolation, wind speed and load demand where used in this study. The MATLAB software is used to code and perform the suggested method. The evolutionary algorithm parameters are listed in Table III. Evolutionary algorithms search the optimal values of batteries, wind turbines, and photovoltaic panels in the hybrid power system to satisfy the maximum loss of power supply and find the minimal amount of the total annual cost of the system. This problem involves three different variables (No_{batt}, A_{pv}, and A_{wt}) where No_{batt} is an integer decision variable and A_{pv} and A_{wt} are continuous decision variables. Each of the heuristic algorithms is run 15 times and Max. (the maximum total annual cost which is found by the algorithms during 15 times run), Mean (the mean of total annual cost which is seen by the algorithms during 15 times run) and Min. (the minimum total annual cost which is found by the algorithms during 15 times run) indexes are reported. Assume that the state of charge of each battery is 20% of its nominal capacity in the initial condition.

TABLE I

Input Data For Simulation.

Component parameters		**Wind turbine**	
Interest rate (i)	5%	Nominal wind turbine power	1 kW
Project lifetime (n_p)	20 years	Cut-in wind speed	3 m/s
Photovoltaic panel		Cut out wind speed	20 m/s
Nominal PV power	120 W	Nominal wind speed	9 m/s
PV area	1.07 m^2	Annual maintenance cost	100 $/year
Annual maintenance cost	10 $/year	Power coefficient	0.59
PV panel cost	$ 614	Air density	1.225 kg/m^3
Replacement cost of PV	$ 608	Mechanical efficiency of wind turbine	85 %
PV efficiency	98%	Lifetime	20 years
PV lifetime	20 years	Wind turbine cost	$3200
Battery		Wind turbine replacement cost	$1730
Voltage	12 V	Wind turbine area	3.14 m^2
Battery cost	$ 130	**Power converter/inverter**	
Nominal capacity of a battery	200 A h	Rated power	3 kW
Battery efficiency	85%	Lifetime	10 years
Battery life time	5 years	Converter/inverter efficiency	95%
DOD	0.8	Converter/inverter cost	$ 2000
σ	0.0002	Converter/inverter maintenance cost	$ 12
		Converter/inverter replacement cost	$ 1500

TABLE II

Minimum, maximum and average of meteorological data and load demand

Index / Item	min	mean	max
Solar radiation ($^{Kw}/_{m^2}$)	0	0.17	0.99
Wind speed ($^{m}/_{s}$)	0	4.14	24.34
Load demand ($K\ wh$)	9.23	17.50	27.92

TABLE III

The Initial Parameter Of The Optimization Methods

ALO	No. of search agent		Maximum Iteration	
	150		1000	
PSO	C1	C2	No. of particles	Maximum Iteration
	2	2	150	1000
HS	HMCR	BW	PAR	Maximum Iteration
	0.9	$0.01 \leq bw \leq 1$	$0 \leq PAR \leq 1$	1000
FA	Betta	gamma	nPop	Maximum Iteration
	2	1	150	1000
DE	$Betta_{min}$	$Betta_{max}$	PCR	Maximum Iteration
	0.2	0.8	0.2	1000

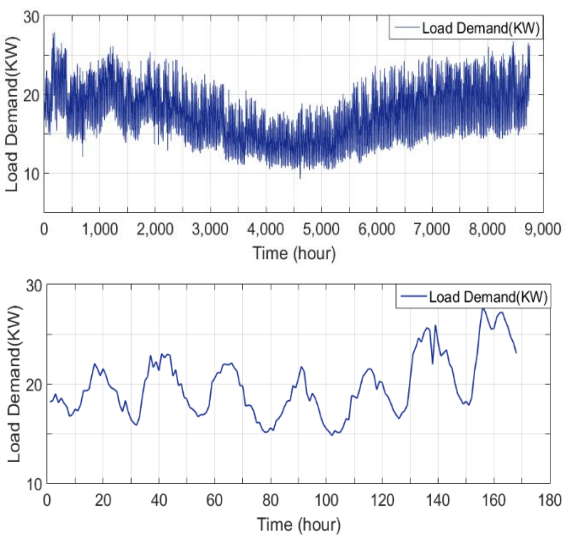


Fig. 7. Hourly electrical load demand: a) during the year, b) the first week of the year

A. Hybrid PV/WT/battery

In this part, the hybrid PV/WT/battery system is considered to electrify an urban area. In this system, two power sources, such as wind turbines and photovoltaic panels generate the electrical power to supply the demanded load, and the battery bank is used to save the balance of energy and deliver the stored energy in deficit situations. The results achieved by different heuristic algorithms for the hybrid PV/WT/battery system are listed in Table IV. This table shows that the minimal value of the local capital cost of the system obtained by heuristic algorithms. TAC (Min. index) achieved for the hybrid PV/WT/battery system is $ 32240.84 which is found with the ALO algorithm. After the ALO method, the best minimum fitness value obtained with, in rank order, PSO, DE, FA, and HS algorithms. In terms of the mean index in the performance of the ALO algorithm is better than other developed algorithms, as well as in terms of max index, the ranking of the investigated algorithms is ALO, PSO, DE, FA, and HS algorithms. Also, it can be found from Table IV that for the optimal PV/WT/battery system, the minimum fitness value is $32240.84. Optimal numbers of decision variables related to the min index for the investigated algorithms are shown in Table V. Optimal values of A_{pv}, A_{wt}, and No_{batt} are seen to be 186.18 m^2, 5.35m^2, and 2011, respectively. It can be found that the optimum rating of wind turbines and solar panels is 5kw and 20.88kw respectively. Concerning the optimal values of the variables, optimal numbers for the hybrid PV/WT/ battery system are reported in Table VI. Since the reliable supply of the electrical load demand at any time depends on the amount of energy stored in the battery bank, the state of charge of the battery in the optimized system during a year and for a period of time (first week of the year) are shown in Fig. 8. The generated power by the solar panels and wind turbines of the optimized PV/WT/ battery system during a year and the first seven days of the year are shown in Figs. 9 and 10 respectively.

TABLE IV

Results obtained with the developed algorithms for the hybrid systems

Hybrid system	Index	Algorithms				
		PSO	HS	FA	DE	ALO
PV/WT/ battery	Min ($)	34856.26	38176.14	37370.69	36687.77	32240.84
	Mean ($)	49419.27	68423.54	69523.12	57265.44	46215.59
	Max ($)	76462.52	106945.74	97274.59	85391.49	71529.68
	Rank	2	5	4	3	1
PV/battery	Min ($)	34828.91	40879.93	37775.65	37819.73	34812.22
	Mean ($)	46443.78	63293.37	58565.25	56294.23	41673.96
	Max ($)	72619.69	97285.85	83767.80	85279.91	74246.48
	Rank	2	5	3	4	1
WT/ battery	Min ($)	103441.11	105876.18	102137.97	105428.51	101023.30
	Mean ($)	121472.45	136404.32	117439.12	127831.37	109428.49
	Max ($)	178645.25	212967.98	196258.48	186594.73	176209.25
	rank	3	5	2	4	1
Average rank		2.33	5	3	3.66	1
Final rank		2	5	3	4	1

TABLE V

Optimal values and optimum rating of the system components in the hybrid renewable energy systems

Hybrid system	Algorithms	A_{pv}	Optimum rating of PV	A_{wt}	Optimum rating of wind turbine	$N_{battery}$
PV/WT/ battery	HS	191.53	21.48	7.49	7	2495
	FA	188.32	21.12	8.56	8	2196
	DE	186.18	20.88	6.42	6	2198
	PSO	188.32	21.12	6.42	6	2214
	ALO	186.18	20.88	5.35	5	2011
PV/battery	HS	245.03	27.48	--	--	2871
	FA	239.68	26.88	--	--	2591
	DE	238.61	26.76	--	--	2729
	PSO	235.4	26.40	--	--	2514
	ALO	235.4	26.40	--	--	2512
WT/ battery	HS	--	--	213.52	68	5890
	FA	--	--	197.82	63	5719
	DE	--	--	204.10	65	5794
	PSO	--	--	194.68	62	5680
	ALO	--	--	191.54	61	5612

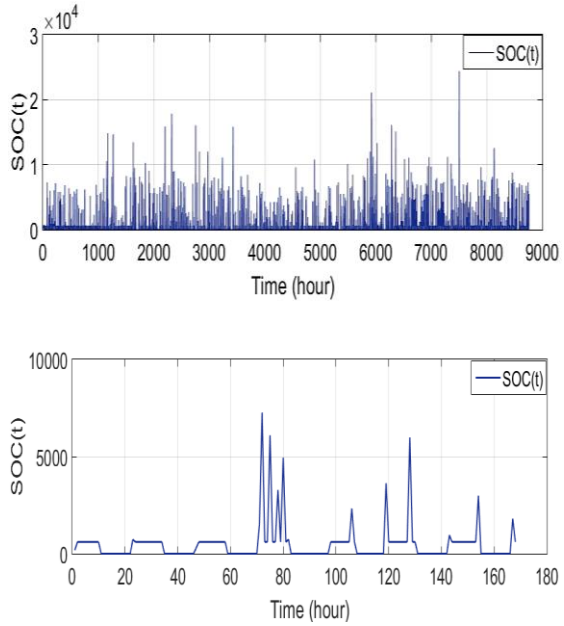


Fig. 8. State of charge of battery bank during the year and for the first week of the year for hybrid PV/WT/battery system

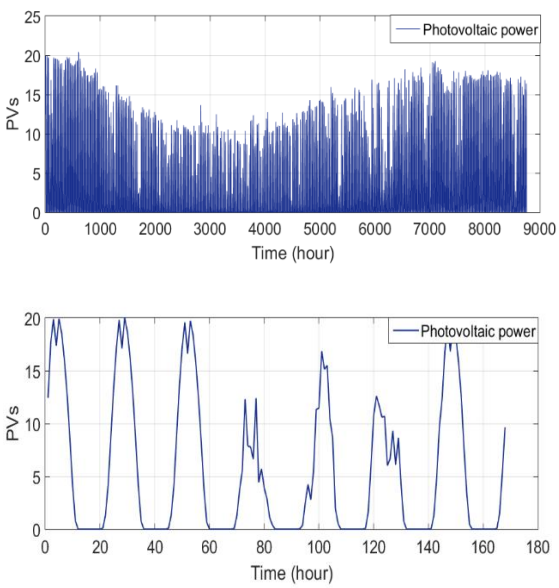


Fig. 9. Generated power produced by the set of PV panels in hybrid PV/WT/battery system both (a) during a year and (b) for the first week of the year

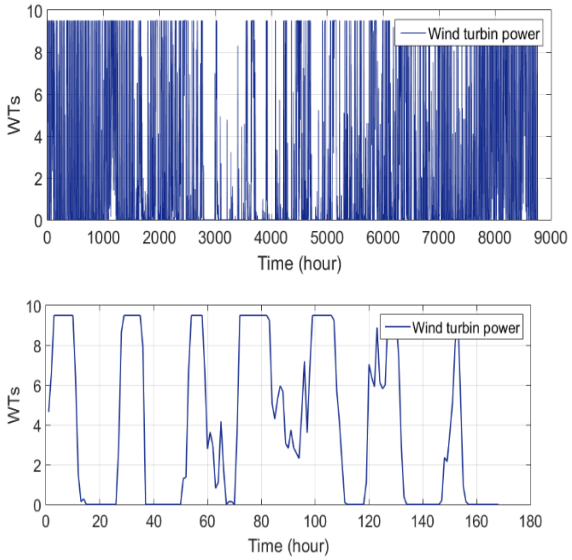


Fig. 10. generated power produced by wind turbines in hybrid PV/WT/battery system both (a) during a year and (b) for the first week of the year

B. Hybrid WT/battery system

The results achieved by the developed algorithms for the hybrid WT/ battery renewable energy system are shown in Table IV. In this system, the hybrid WT/ battery system is considered to electrify a remote area include 5 typically homes. This table shows that the minimal value of the total annual cost of the system obtained by investigated algorithms. TAC (Min. index) achieved for the hybrid WT/ battery system is $ 101023.30, which is found with the ALO algorithm. After the ALO algorithm, the best min index with, in rank order, FA ($102137.97), PSO ($103441.11), DE ($105428.51), and HS ($105876.18). The performance of the ALO algorithm in terms of maximum and mean indexes is more economical than other methodologies. The optimal values of the variables are reported in Table V. Also, the optimal numbers related to the optimal decision variables for the evolutionary algorithms are listed in Table VII. Moreover, it can be seen from Table V that A_{wt} and No_{batt} are 191.54 m^2 and 5612, respectively. Fig. 11 shows the state of charge of the battery in a hybrid WT/battery system during a year and the first week of the year (168 hours).

TABLE VII

Optimum numbers related to the optimal values achieved by heuristic algorithms in WT/battery system

System	Algorithms	NO_{pv}	NO_{wt}
WT/ battery	HS	N/A	68
	FA	N/A	63
	DE	N/A	65
	PSO	N/A	62
	ALO	N/A	61

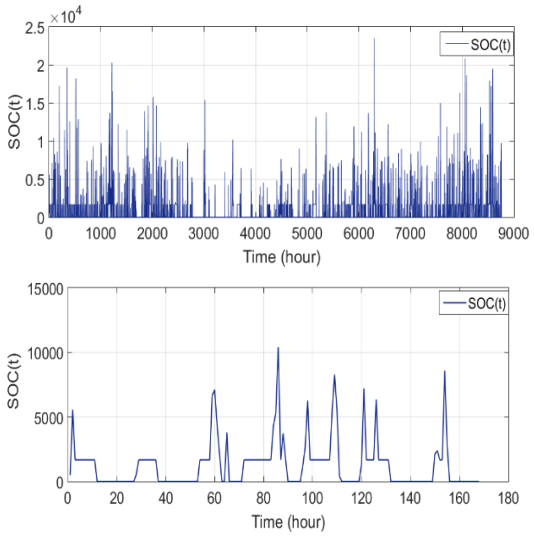


Fig. 11. The expected hourly amount of energy stored in the battery bank, (a) during the year and (b) during the first week of the year in hybrid WT/battery system

C. Hybrid PV/battery system

In the hybrid PV/battery system, the power is generated by solar panels only. The results achieved by the studied evolutionary algorithms are shown in Table IV. It can be understood from the presented table that the minimum TAC value of the hybrid system is for the ALO algorithm ($74264.48) and after the ALO algorithm, the best minimum value within rank order, PSO, FA, DE, and HS. In the PV/FC system, the power is provided by photovoltaic panels only. Also, in terms of mean and maximum indexes the ant lion optimizer algorithm is the most cost-effective algorithm among other investigated algorithms. The optimal values of variables for the hybrid PV/battery system with respect to the Min. index of each methodology are shown in Table V, where it can be found that the optimal values of this system are 235.4m2 and 2512 for A_{pv} and No_{batt}, respectively. Also, it can be seen from this table that the optimum rating related to the optimal value in terms min index is 26.4 kw. Table VIII shows the optimal number of PV panels for the investigated algorithms where the ALO algorithm has the minimum quantity which is 220 panels. The state of charge of the battery bank in the hybrid examined PV/battery system during a year (8760 hours) and for the first seven days of the year (a week) are given in Fig. 12. Also, Fig. 13 shows the generated power by the photovoltaic panels during a year and for the first week of the year in the PV/battery system. The local capital cost of the PV/WT/battery, WT/battery, and PV/battery for the optimized hybrid systems are $32240.84, $101023.30 and $74264.48, respectively. It is seen that the PV/WT/ battery system is the most cost-effective system among other examined systems

TABLE VIII

Optimum numbers related to the optimal values achieved by heuristic algorithms in PV/battery system

System	Algorithms	NO_{pv}	NO_{wt}
PV/battery	HS	229	N/A
	FA	224	N/A
	DE	223	N/A
	PSO	220	N/A
	ALO	220	N/A

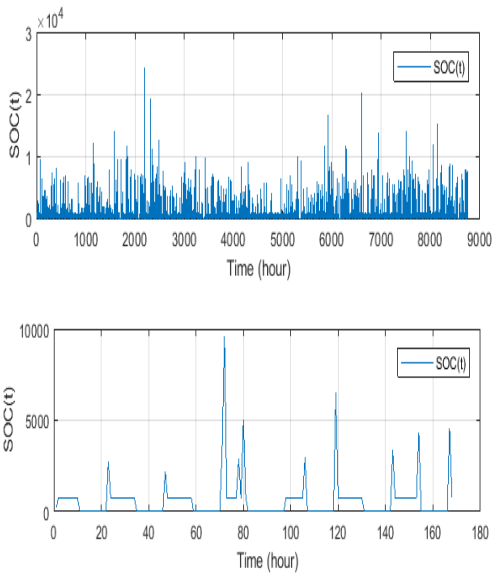


Fig. 12. State of charge of batteries in Hybrid PV/battery system during the year and for the first week of the year

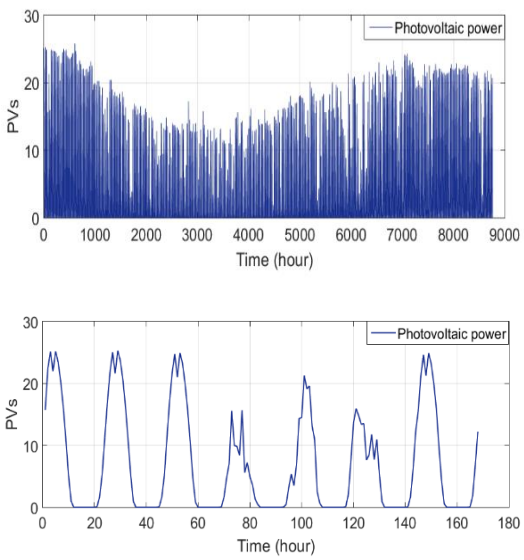


Fig. 13. Hourly produced power by the group of PV panels in the Hybrid PV/battery system

VII. CONCLUSION

This paper aims to grow a global method for the optimum design of a grid-independent PV/wind turbine system with battery storage that can be used in applications such as electrification of a remote area. For obtaining this objective, we have developed a techno-economic approach described by meta-heuristic algorithms. Three sizing parameters have been used in the simulation, i.e., the total area equipped by a group of PV panels, the entire area swept by rotating turbine blades and the number of batteries in the battery bank. Applying the investigated algorithms, all configurations given the rate of 0% of LPSP are retained. Afterward, the optimal hybrid system is estimated based on the minimization of the total annual cost. Besides, the developed model is used to calculate the optimal number related to the optimal values of decision variables. In order to highlight the ant lion optimizer methodology, a case study is used to scrutinize a grid-independent PV/wind hybrid system with battery storage, which is developed to supply a group of ten houses located in Rafsanjan, Kerman, Iran. The algorithms input data set consists of hourly solar radiation, wind speed at the height of 10 meters, the ambient temperature recorded at Rafsanjan for the year 2017, the energy requirements expressed by the load throughout the year and specifications of the system devices. The optimal values of the hybrid system are estimated in terms of loss of power supply (LPSP=0%) and system total annual costs. It is evident from the achieved results that the optimal values of Total Annual Cost (TAC), total area equipped by rotating turbine blades, entire surface equipped by group of PV panels and number of batteries for the hybrid PV/wind/ battery system are obtained for system with the lowest number of wind turbines and the photovoltaic modules. Also, the simulation results have shown that the PV/wind/ battery choice is more economically viable compared to the PV/ battery system or WT/battery system.

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