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Optimal and Economic Design of Stand-alone Hybrid Renewable Energy System Integrated with Battery Storage Using Artificial Electric Field Algorithm

***Abstract**. In this paper, the optimal and economic design of a stand-alone hybrid photovoltaic-wind-battery storage (PV/WT/BA) system is performed using an artificial electric field algorithm (AEFA) to minimize the cost of energy generation (CEG) to supply an annual load during the 20 years of the useful life project. The AEFA algorithm is inspired by coulomb electrostatic force and has a high exploration power for optimal global achievement. In this study, the design problem is satisfied considering the probability of the energy not supplied (ENS) as a reliability constraint. The purpose of the design is to determine the number of photovoltaic panels, wind turbines, and batteries, taking into account the CEG and satisfaction of the ENS to provide annual load using the AEFA method. To verify the proposed AEFA, the results are compared with particle swarm optimization (PSO) and sine cosine algorithm (SCA) in view of CEG and ENS. The results show that the AEFA is superior to the PSO and SCA methods in finding the optimal solution with lower CEG and ENS (higher reliability).*

***Streszczenie.** W artykule przedstawiono optymalny i ekonomiczny projekt autonomicznego hybrydowego systemu magazynowania energii fotowoltaicznej z wiatrem (PV/WT/BA) z wykorzystaniem algorytmu sztucznego pola elektrycznego (AEFA) w celu zminimalizowania kosztów wytwarzania energii (CEG). dostarczać roczny ładunek w ciągu 20 lat projektu okresu użytkowania. Algorytm AEFA jest inspirowany siłą elektrostatyczną kulomba i ma wysoką moc eksploracyjną dla optymalnych globalnych osiągnięć. W niniejszym opracowaniu problem projektowy został rozwiązany, biorąc pod uwagę prawdopodobieństwo niedostarczenia energii (ENS) jako ograniczenie niezawodności. Celem projektu jest określenie ilości paneli fotowoltaicznych, turbin wiatrowych oraz baterii z uwzględnieniem CEG i satysfakcji ENS z zapewnienia rocznego obciążenia metodą AEFA. Aby zweryfikować proponowaną AEFA, wyniki porównuje się z optymalizacją roju cząstek (PSO) i algorytmem sinus cosinus (SCA) pod kątem CEG i ENS. Wyniki pokazują, że metoda AEFA przewyższa metody PSO i SCA w znalezieniu optymalnego rozwiązania o niższym CEG i ENS (wyższa niezawodność).(**Optymalny i ekonomiczny projekt samodzielnego hybrydowego systemu energii odnawialnej zintegrowanego z magazynowaniem baterii przy użyciu algorytmu sztucznego pola elektrycznego**)*

Keywords: Hybrid PV/WT/BA system, Cost of energy generation, reliability, artificial electric field algorithm.
Słowa kluczowe: Hybrydowy system PV/WT/BA, Koszt wytwarzania energii, niezawodność, algorytm sztucznego pola elektrycznego.

Introduction

Increased energy demand due to population growth and industrialization, high cost of construction and operation of large power plants, high cost of network development to transfer and distribute energy to customers and the end of the process of fossil fuels as the main sources of production Electricity as well as environmental pollution from fossil fuels for electricity generation has led to an increase in the use of small, low-capacity power plants as distributed generation sources, especially based on new energy sources such as solar panels and wind turbines [1-2]. Fluctuations in the production capacity of solar panels and wind turbines due to fluctuations in irradiance and wind speed, respectively, are one of the challenges of using these resources. By combining different energy sources in the form of hybrid systems, the weakness of each is resolved alone. In addition to using this type of source as a hybrid, in order to generate energy and supply a continuous load, a storage system such as batteries should be used to create the conditions for electrical programming for a continuous supply of load [2]. In optimizing hybrid systems, technical and economic indices are assessed. The technical index measures the ability of the system to supply load and the economic index indicates the costs of the system for energy production. Therefore, the purpose of optimizing the hybrid system is to determine the optimal capacity of the equipment with the aim of minimizing the cost of energy production of the system and takes into account the reliability of the load supply. In the optimization of hybrid systems, the problem of optimization is often presented as a single purpose and taking into account the technical constraints. Therefore, the aim of optimizing the hybrid system is to specify the optimal capacity of the equipment with the purpose of minimizing the energy production costs of the system and considering the load supply [2]. In recent years, the hope of unreliable energy load has been presented as one of the important indices of reliability in the optimization of hybrid energy systems and has been used in studies. This indicator represents the part of the load demand that the system is not able to supply, in other words, it is interpreted as the ability of the hybrid system to supply the load [3].

In recent years, many studies have been conducted on the design of hybrid systems, taking into account various objective functions and constraints, as well as various optimization methods. In [4], the optimal design of PV/WT/BA system has been done with the aim of minimizing the annual costs of energy production and taking into account the reliability constraint of the possibility of unmet load using a genetic algorithm (GA). In [5], the design of PV/WT/BA system has been studied with the aim of minimizing the annual costs of the system and considering the power balance constraint using a discrete harmony search algorithm (DHSA). In [6], achieving the equipment capacity of PV/WT/BA system is presented with the aim of achieving the desired load reliability and the lowest annual cost of the system using the GA method. In [7], a multi-criteria design is developed with minimization of the total cost, environmental emissions of fuel and load shortage using an evolutionary differential (DE) algorithm to determine the optimal capacity of diesel-equipped PV/WT/BA system. In [8], the grey wolf optimizer (GWO) algorithm is used to optimally design the PV/WT/BA system with the aim of minimizing costs and considering reliability constraints. In [9], the reliability/cost evaluation of the PV/WT/Fuel cell system is presented to minimize the annual costs of the system plus the cost of unmet energy load using particle swarm optimization (PSO). [10] The optimal design of a PV/WT/Fuel cell system is presented to minimize system energy production costs and unmet energy costs of the system load using the imperial competition algorithm (ICA). In [11], the optimization of component capacity of PV/WT/Hydro system using biogeography optimization algorithm (BBO) is presented with the aim of determining the optimal equipment capacity. In [12], the design of the PV/WT/Fuel cell system is presented with the aim of minimizing the cost and considering the reliability constraint using the grey wolf-sine cosine optimization algorithm (GWO-SCA). The cost/reliability evaluation for an off-grid PV/WT system is introduced with the aim of minimizing energy production costs and unsupplied load energy using the PSO [13]. In [14], the optimal design of a PV/WT/Fuel cell energy system is presented. The purpose of the problem is to determine the optimal capacity of the equipment with the aim of minimizing production costs during the study period and achieving the best probability of load supply. In [15], the design of a hybrid PV/Fuel cell system is performed with minimization of the cost of the total present value and consideration of the loss of power supply probability (LPSP) constraint using the flower pollination algorithm (FPA). In [16], a grid-connected photovoltaic system has been designed with the aim of minimizing the annual cost by considering linear and nonlinear models through GA. In [17], a grid-connected PV/WT system is designed to minimize the cost of power generation via PSO by considering the power balance constraint.

In general, the optimal design of hybrid energy systems with different approaches in terms of cost objective function and reliability constraints as well as system components and optimization methods have been studied. The use of powerful optimization methods in solving the design problem in achieving the lowest cost is crucial. In this study, a new optimization method called artificial electric field algorithm (AEFA) based on physical phenomena is used to provide a favorable structure for the design of the hybrid systems. Proposed design structure for PV/WT/BA hybrid systems is developed with the aim of minimizing the cost of energy production (CEG) and satisfying the energy not supplied (ENS) using the AEFA inspired by coulomb electrostatic force [18] for annual load supply in the 20-year study horizon. The performance of the AEFA optimization method is compared with the well-known PSO and sine cosine algorithm (SCA). Also, the effect of changes in load demand and inverter efficiency on design parameters, cost and reliability has been evaluated.

In Section 2, the PV/WT/BA system is modeled. In Section 3, the problem formulation is explained along with the objective function and constraints. In Section 4, the AEFA optimization method describes its implementation procedure in problem solving. System data and simulation results are given in Section 5 and conclusions are presented in Section 6.

Hybrid system modeling

Based on Figure 1, the hybrid PV/WT/BA system consists of photovoltaic (PV) panels and wind turbines (WT) as the main power sources, the stored battery (BA) bank system, and the converter and regulator. The operation of the system is as follows: if the total energy produced by renewable sources is more than the load demand, extra power is injected into the battery bank to charge the energy. Whenever the total energy produced by renewable sources is lower than the load consumption, in this situation the deficit power is compensated by the battery bank discharge if the batter is not capable to supply the load fully, part of the load can be cut off, which causes energy not supplied (ENS).

a. Photovoltaic panel modeling

The output power of each photovoltaic panel according to the amount of radiation can be calculated using equation (1) [8, 19].

(1) $$P_{PV}(t)=N_{PV}\times P_{PV-_{rated}}\times\frac{S(t)}{1000}\times\left[1+N_T(T_C(t)-T_{ref})\right]$$

(2) $$T_C(t)=T_A(t)+\frac{NOCT-20}{800}\times S(t)$$

Where, $P_{PV}(t)$ is output power of the solar array, N_{PV} is the number of solar panels, $T_C(t)$ is temperature of the solar cell in terms of degrees celsius in time *t*, N_T is temperature coefficient of the photovoltaic panel. Solar cell temperature in standard conditions (equal to 25 degrees Celsius), $S(t)$ is intensity of sunlight at time, $NCOT$ is the nominal temperature of cell operation, and $T_A(t)$ is ambient temperature in terms of degrees Celsius at time *t* [19].

b. Modeling of wind turbine generator

Wind turbine power based on low cut-off speed (V_{co}), high cut-off speed (V_{ci}) and also nominal speed (V_r) is obtained from the following equation [8, 19].

(3) $$P_{WT}=\begin{cases}0 & ;v\le v_{ci},v\ \ge v_{co}\\ P_{WT-rated}\times\left(\dfrac{v\ -v_{ci}}{v_r-v_{ci}}\right) & ;v_{ci}\le v\ \le v_r\\ P_{WT-rated} & ;v_r\le v\ \le v_{co}\end{cases}$$

Where, *v* is wind speed, P_{WT}-rated is rated power and P_{WT} is wind turbine power.

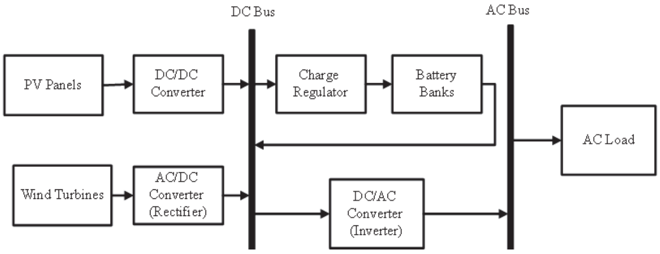

Fig. 1. Schematic of the hybrid PV/WT/BA system.

c. Batery modeling

Due to fluctuations in the production capacity of solar panels and wind turbines, the battery storage system is used to manage the continuous supply of load energy. The capacity of the battery bank is constantly changing in the hybrid system due to fluctuations in the production capacity of PV and WT. Therefore, when the total output power of solar panels and wind turbines is more than the load demand, the battery bank is in charge mode. The amount of battery bank charge at time *t* can be obtained by the following equation [19].

(4) $$E_{Bat}(t)=E_{Bat}(t-1)+\begin{bmatrix}(N_{PV}\times P_{PV}(t)\times\eta_{con_{DC/DC}}\\ +N_{WT}\times P_{WT}(t)\times\eta_{rec_{AC/DC}})\\ -\dfrac{P_{Load}(t)}{\eta_{inv_{DC/AC}}}\end{bmatrix}\times\eta_{Bat_{ch}}$$

That is, $E_{Bat}(t)$ and $E_{Bat}(t-1)$ are the battery charge values at time *t* and *t*-1. $\eta_{con_{DC/DC}}$, $\eta_{rec_{AC-DC}}$ and $\eta_{inv_{DC/AC}}$ are gain of converter, rectifier and inverter. $P_{Load}(t)$ is load and the $\eta_{Bat_{ch}}$ is charge efficiency of the battery bank.

The battery is in discharge mode when the total output power of PV panels and wind turbines is less than the load. Therefore, the amount of battery bank charge at time *t* can be defined as follows [19-22].

$$E_{Bat}(t)=E_{Bat}(t-1)-\begin{bmatrix}\dfrac{P_{Load}(t)}{\eta_{inv_{DC/AC}}}\\ -(N_{PV}\times P_{PV}(t)\times\eta_{con_{DC/DC}}\\ +N_{WT}\times P_{WT}(t)\times\eta_{rec_{AC/DC}})\\ \end{bmatrix}/\,\eta_{Bat_{disch}} \tag{5}$$

Where, $\eta_{Bat_{disch}}$ is discharge interest is the battery bank.

Optimization problem

In this study, the optimal design of the hybrid system is presented with the aim of minimizing the CEG and considering the ENS constraint. In this section, the objective function is described along with the constraints of the problem.

a. Object function

The optimal design of solar-wind-battery system is considered based on energy production cost minimization (CEG). CEG includes investment cost (TCC), maintenance cost (TMC) and replacement cost (TRC). The equipment used in the CEG function includes solar panels, wind turbines, batteries, DC/DC converter, AC/DC rectifier and DC/AC converter (inverter) [19-22].

$$Minimize\ \ TCS=TCC+TMC+TRC \tag{6}$$

The investment cost of a hybrid system based on its equipment is defined as follows [10].

$$TCC=C_{Cap}\times CRF(i,y) \tag{7}$$

$$CRF(i,y)=\frac{i(1+i)^{y}}{(1+i)^{y}-1} \tag{8}$$

$$i=\frac{(i^{'}-f)}{(1+f)} \tag{9}$$

Where, C_{Cap} is investment cost of each equipment is in dollars during the useful life of the project. CRF is relative capital return coefficient for calculating the present value of a set of equal annual cash flows. i is real interest rate is the annual interest rate, $i^{'}$ is nominal interest rate and f is annual inflation rate.

The cost of maintenance of hybrid system equipment is a function of TCC, equipment reliability and useful life are defined as follows [5].

$$TMC=C_{Cap}\times(1-\lambda)/\,y \tag{10}$$

System equipment replacement cost (TRC) is the cost of replacing equipment during the useful life of the project. In this study, the equipment that needs to be replaced includes batteries, DC/DC converter, DC/DC converter and inverter. The lifespan of solar panels and wind turbines is considered to be equal to the useful life of the system and therefore no replacement cost is considered for them. TRC is calculated as follows [19-22].

$$TRC=C_{\mathrm{Re}\,p}\times SFI(i,y_{rep}) \tag{11}$$

$$SFI=\frac{1}{(1+i)^{y-1}} \tag{12}$$

Where, $C_{\mathrm{Re}\,p}$ is cost of replacing equipment in dollars, SFI is sinking fund index that is a ratio to calculate the future value of a set of equal annual cash flows, and y_{rep} is useful life of equipment in years.

b. Problem Constraints

The limitations considered in this study are as follows:

• Minimum and maximum number of hybrid system component

$$N_{i_{\min}}\le N_{i}\le N_{i_{\max}} \tag{13}$$

Where, N_i is the number of equipment *i*, $N_{i_{\min}}$ and, $N_{i_{\max}}$ is the minimum and maximum number of component *i*.

• Minimum and maximum amount of battery bank charge

$$E_{Bat_{\min}}\le E_{Bat}\le E_{Bat_{\max}} \tag{14}$$

$E_{Bat_{\max}}$ is maximum amount of battery charge is equal to the nominal capacity of the battery bank (SBA). $E_{Bat_{\min}}$ is minimum charge of the battery bank is obtained with the maximum discharge depth (DOD) [8, 19].

$$E_{Bat_{\min}}=(1-DOD)\times S_{Bat} \tag{15}$$

• Not-supplied energy (ENS) during the year

In a hybrid power system, in order to have a reliable system, the unsupplied energy index must be considered.

$$\%ENS\le\%ENS_{Max} \tag{16}$$

$$\%ENS=\frac{\sum_{t=1}^{8760}\left[\dfrac{P_{Load}(t)}{\eta_{inv_{DC/AC}}}-(N_{PV}\times P_{PV}(t)\times\eta_{con_{DC/DC}}+N_{WT}\times P_{WT}(t)\times\eta_{rec_{AC/DC}})\right]}{\sum_{t=1}^{8760}P_{Load(t)}} \tag{17}$$

$\%ENS_{Max}$ is the percentage permissible for *ENS* (5% in this study) during the year and $\%ENS$ is the percentage of *ENS* during the year acquired by the following equation [8, 19].

Proposed optimization method

a. Artificial electric field algorithm

Based on Coulomb's law of electrostatic force, the artificial electric field algorithm (AEFA) is inspired that this law represents the electrostatic reactions between the electrical charges [18]. The magnitude of the electrostatic force is directly related to the charges magnitude, and is inversely related to the square of the distance between them. In the proposed algorithm, the charged particles are selected as agents and the resistance of each agent is evaluated based on their charges. The AEFA algorithm is modeled based on electrostatic attraction force. In this way, the charged particle with the highest amount of electric charge, with higher power of attraction force pulls the particles towards it and also moves in search spaces [18].

The first law of coulomb states that the charged particles repel each other and otherwise those attract each other. Also, the second law of coulomb notes that there is an attractive force between opposing charges and a repulsive force between same name charges, which is directly related to the multiplication of the charges and inversely related to the distance between them. Moreover, the motion law remarks that the velocity of each charge is equal to the sum of the previous velocities to the velocity changes, or the acceleration of each charge is equal to the inserted force divided by its mass. Suppose the i^{th} particle position in *d*-dimensional search space as $x_i = \left(x_i^1, x_i^2, \ldots, x_i^d\right)$, $(i = 1, 2, \ldots, N)$ where x_i^d refers to the position of the i^{th} particle in the *d*-dimension. In the AEFA, the best position corresponding to the best fitness obtained from charged particles is determined. The position of the best value of the fitness achieved by any particle *i* at time *t* is defined as follows [18]:

$$p_i^d(t+1) = \begin{cases} p_i^d(t) & if \quad f(p_i(t)) < f(x_i(t+1)) \\ x_i^d(t+1) & if \quad f(p_i(t)) \geq f(x_i(t+1)) \end{cases} \tag{18}$$

The best fitness is defined as $P_{best} = X_{best}$.

At time *t*, the force inserted on the charge *i* by the charge *j* is calculated by [18],

$$F_{ij}^d(t) = K(t) \frac{Q_i(t) * Q_j(t)\left(p_j^d(t) - x_i^d(t)\right)}{R_{ij}(t) + \varepsilon} \tag{19}$$

Where, $Q_i(t)$ and $Q_j(t)$ refer to the charged particles of *i* and *j* at time *t*, $K(t)$ indicate the Coulomb constant at time *t*, ε is a small positive constant, and $R_{ij}(t)$ defined as Euclidean distance among two charged particles of *i* and *j* is calculated by [18].

$$R_{ij}(t) = \left\| X_i(t), X_j(t) \right\|_2 \tag{20}$$

The Coulomb constant $K(t)$ is calculated as a function of iteration number and maximum iteration (*max.iter*), which is defined by [18].

$$K(t) = K_0 * \exp(-\alpha \frac{iter}{\max \ iter}) \tag{21}$$

Where, α refer to parameter and K_0 is initial value. To explore the AEFA, first the Coulomb constant value is considered a large value. Then this value has a decreasing trend to control the accuracy of the AEFA by increasing the iteration according to Fig. 2.

The inserted electric force on particle *i* by all other particles is defined in *d* search space at time *t* as follows [18]:

$$F_i^d(t) = \sum_{j=1, j \neq i}^{N} rand(\cdot) F_{ij}^d(t) \tag{22}$$

Where, $rand(\cdot)$ refers to a uniform number randomly in [0, 1] and this value is applied to provide a random nature to the AEFA. *N* indicates the particles number in search space, and F_i refers to the force inserted on the charged particle *i* according to Fig. 3.

The electrical force of particle *i* in *d*th-dimension search space at time *t* is illustrate by [18];

$$E_i^d(t) = \frac{F_i^d(t)}{Q_i(t)} \tag{23}$$

So, using the second law of Newton's named motion law, the acceleration of the particle *i* is defined by;

$$a_i^d(t) = \frac{Q_i(t) E_i^d(t)}{M_i(t)} \tag{24}$$

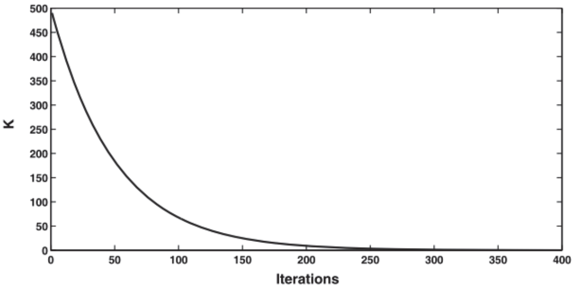

Fig. 2. Decreasing trend of Columbus constant value [18]

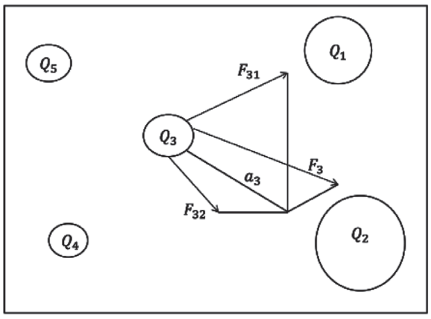

Fig. 3. The electrical force inserted on a charge particle [18]

$M_i(t)$ refers to the *i* particle mass at time *t*. The velocity of charge particle and its position are updated by [18]:

$$V_i^d(t+1) = rand(\cdot) * V_i^d(t) + a_i^d(t) \tag{25}$$

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1) \tag{26}$$

For the minimization or maximization problem, the fitness should have a downward or upward trend, respectively.

$$Q_i(t) = Q_j(t) \qquad i, j = 1, 2, \ldots, N \tag{27}$$

$$q_i(t) = \exp(\frac{fit_i(t) - worst(t)}{best(t) - worst(t)}) \tag{28}$$

$$Q_i(t) = \frac{q_i(t)}{\sum_{i=1}^{N} q_i(t)} \tag{29}$$

Where, fit_i refers to the fitness value related to particle *i* at time *t*. The $best(t)$ and $worst(t)$ values of fitness for the maximization problem are formulated by [18]:

$$best(t) = \max(fit_j(t)), \qquad j \in (1, 2, \ldots, N) \tag{30}$$

$$worst(t) = \min(fit_j(t)), \qquad j \in (1, 2, \ldots, N) \tag{31}$$

For the minimization problem, the $best(t)$ and $worst(t)$ values of fitness are defined by [18]:

$$best(t) = \min(fit_j(t)), \qquad j \in (1, 2, \ldots, N) \tag{30}$$

$$worst(t) = \max(fit_j(t)), \qquad j \in (1, 2, \ldots, N) \tag{31}$$

b. Implementation of AEFA algorithm in problem solving

In this study, the optimum capacity of the hybrid PV/WT/BA system has been determined by considering the ENS constraint using the AEFA optimization algorithm. AEFA implementation steps are presented below:

Step 1: Define the input data of the problem including the technical and economic information of the equipment as well as the population application with random locations in each search space.

Step 2: Generate the initial population with random locations in each search space based on optimization variables including the number of solar panels, number of wind turbines and number of batteries.

Step 3: Evaluate the objective function (Eq. (6)) and examine the problem constraints and determine the best member of the population in terms of the value of the objective function as the best member.

Step 4: Update the population position of the algorithm based on (25) - (26), if the best objective function is achieved, it will be replaced with the best member of step 3.

Step 5: If the convergence conditions are met (achieve the best objective function and implement the maximum iteration of the algorithm) go to step 6, otherwise go to step 2.

Step 6: Stop the algorithm.

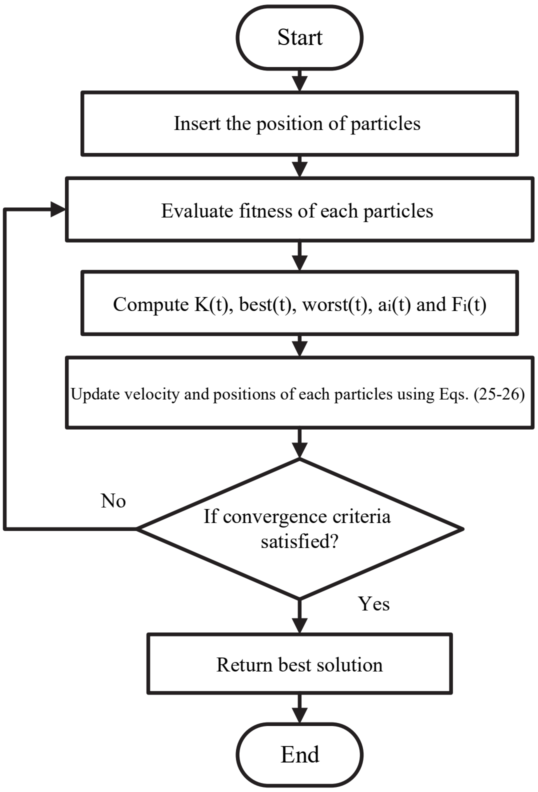

Fig. 4. Flowchart of the AEFA [18]

In the end, the proposed algorithm achieves the optimal number of equipment including solar panels, wind turbines and batteries and of course, as a result, CEG. Also, the flowchart of the AEFA is illustrated in Fig. 4.

5. Simulation and discussion

a. System data

Figs. 5 and 6 show the hourly curve of solar radiation intensity and the curve of wind speed changes over a year, respectively. The load change curve [9-10] over a year is also shown in Fig. 7. According to Fig. 7, the maximum peak load is equal to 50 kW and the total amount of load demand during a year is equal to 269.15 MW. Cost information for solar panels, wind turbines, batteries and other equipment is provided in Table 1. Also, the technical and economic parameters of the equipment including solar panel, wind turbine, battery bank and other equipment are presented in Table 1.

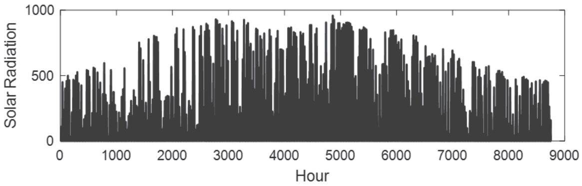

Fig. 5. Irradiance during a year

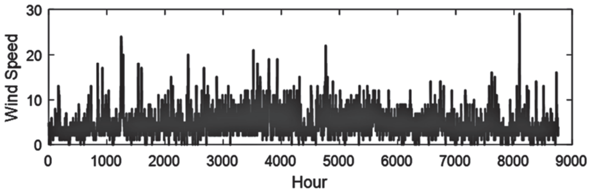

Fig. 6. Wind speed over a year

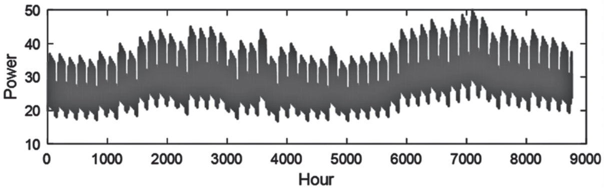

Fig. 7. Load demand over a year [9-10]

Table 1: Technical and economic information of hybrid system design [19]

Component	Parameters	Values
PV		
	PPV-rated	1 kW
	NT	-0.0037 (1/C°)
	T_{ref}	25 $
	PV lifetime	20 yrs
	PV capital cost	2000
	PV replacement cost	Null
WT		
	PWT-rated	1 kW
	V_{ci}	2.5 m/s
	V_r	11 m/s
	V_{co}	13 m/s
	WT lifetime	20 yrs
	WT capital cost	3200
	WT replacement cost	Null
Battery		
	$E_{Bat-max}$	1 kA h
	$E_{Bat-min}$	0.2 kA h
	$\eta_{Bat_{ch}}$	1
	$\eta_{Bat_{disch}}$	1
	DOD	0.2
	Bat lifetime	5 yrs
	Bat capital cost	100
	Bat replacement cost	100
Converters		
	$\eta_{inv_{DC/AC}}$	0.95
	$\eta_{con_{DC/DC}}$	1
	$\eta_{rec_{AC-DC}}$	1
	lifetime	10 yrs
	capital cost	700
	replacement cost	700
Others		
	i'(%)	9
	f (%)	3
	System lifetime (*y*)	20

b. Simulation results

In this section, the simulation results of hybrid PV/WT/BA system design using AEFA are presented. The maximum values of the control variables, including the number of panels, turbines and batteries, are considered to be 500, 500 and 1000, respectively, and the minimum values of all variables are set to zero. The capability of AEFA method has been compared with PSO and SCA methods, which are very powerful algorithms in solving power optimization problems. The population number of optimization algorithms has been determined using trial and error to achieve the best convergence accuracy. The number of populations and the maximum iterations of the algorithm are considered to be 50 and 100, respectively.

b.1 Design of hybrid system in different combinations

The results of hybrid system design in different combinations including hybrid PV/WT/BA, PV/BA and WT/BA systems using AEFA are presented and also the results of the proposed algorithm are compared with PSO and SCA methods, in this section. The convergence curves obtained from AEFA, PSO and SCA methods in system design in different combinations are presented in Fig. 8. As shown, the AEFA method in optimizing the hybrid system obtained a lower CEG value, which indicates the superiority of the proposed method in designing the system with lower energy costs. The results of system design for various combinations using different optimization algorithms for a 20-year study period are illustrated in Table 2. According to Table 2, it can be seen that in all hybrid system combinations, the AEFA method obtained lower CEG and ENS values in all system combinations than the PSO and SCA methods. The results show that when wind and solar sources are used in hybrid systems, with the created overlap, they have a better ability to supply load at a lower cost compared to solar-battery and wind-battery systems. In the design of PV/WT/BA systems, the CEG values using AEFA, PSO and SCA methods are obtained at 1.016, 1.022 and 1.031 M$, respectively, and the ENS values for these methods are 4.82, 4.89 and 4.94%, respectively. The results showed better performance of the AEFA method with lower cost and better reliability. Also, the results obtained in the design of PV/BA and WT/BA compounds indicate the better and more effective performance of the AEFA method with CEG and ENS compared to other methods. The results also clear that the PV/WT/BA combination is more reliable and more economical than other hybrid system combinations with lower cost and higher reliability.

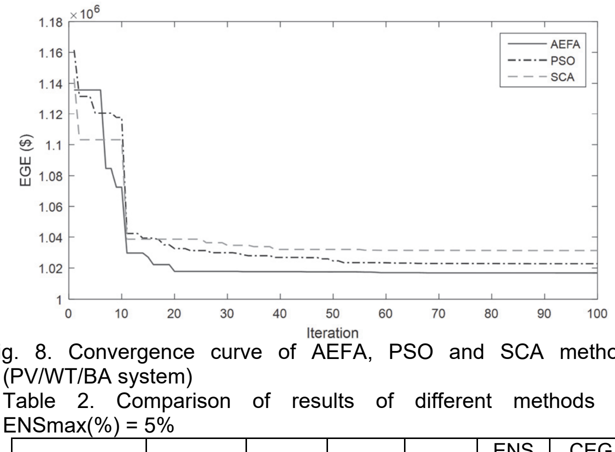

Fig. 8. Convergence curve of AEFA, PSO and SCA methods (PV/WT/BA system)

Table 2. Comparison of results of different methods for ENSmax(%) = 5%

System	Method	NPV	NWT	NBA	ENS (%)	CEG (M$)
PV/Bat	AEFA	385	--	697	4.95	1.442
	PSO	387	--	675	4.98	1.457
	SCA	389	--	637	4.99	1.470
WT/Bat	AEFA	--	147	700	4.97	1.045
	PSO	--	151	531	4.99	1.087
	SCA	--	151	545	4.99	1.083
PV/WT/Bat	AEFA	163	83	561	4.82	1.016
	PSO	140	93	555	4.89	1.022
	SCA	162	86	468	4.94	1.031

The amount of power generated by solar panels and wind turbines as well as the difference between production and consumption based on charge and discharge management of the battery bank for continuous load management managed according to AEFA method during one year to design PV/WT/BA system in Figs. 9-11 is shown. Fig. 12 shows the ENS curve for one year for the PV/WT/ BA system. It should be noted that the ENS curve represents the part of the system load that has been interrupted due to the inability of the hybrid system to supply it.

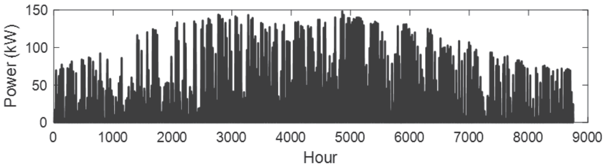

Fig. 9. Production capacity of solar panels based on AEFA during one year (PV/WT/BA system)

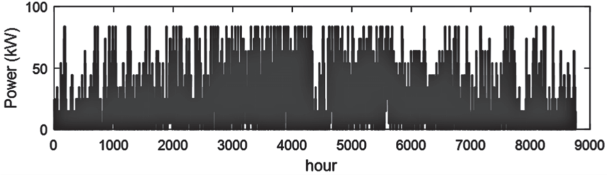

Fig. 10. Production capacity of wind turbines based on AEFA during one year (PV/WT/BA system)

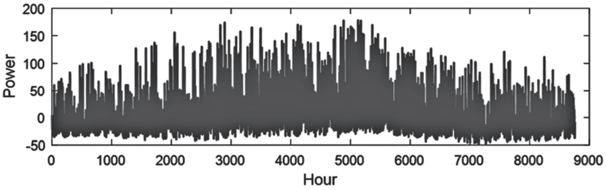

Fig. 11. AEFA based load capacity and demand over a year (PV/WT/BA system)

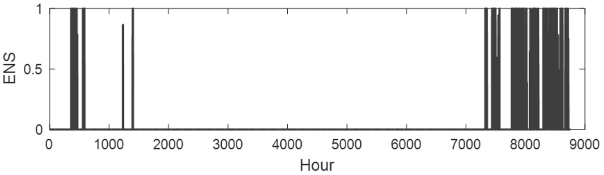

Fig. 12. ENS curve based on AEFA over a year (PV/WT/BA system)

b.2 Evaluate the effect of ENSmax(%) changes on hybrid system design

In this section, the system design results for different combinations for different ENS_{max}(%) of 1 and 5% for the PV/WT/BA system are evaluated and the results are presented in Table 3. As can be seen, with the reduction of the reliability constraint, the system costs increase. It is due to more power generation by the energy generating units to satisfy the load demand by reducing the ENS_{max}(%) constraint.

Table 3. Results of PV/WT/BA system design for ENS_{max}(%) =5 based on AEFA

System	ENS_{max} (%)	NPV	NWT	NBA	ENS (%)	CEG (M$)
PV/Bat	1	413	--	998	0.999	1.751
	5	385	--	697	4.950	1.442
WT/Bat	1	--	165	996	0.989	1.404
	5	--	147	700	4.950	1.045
PV/WT/Bat	1	109	134	405	0.982	1.370
	5	163	83	561	4.820	1.016

It can be seen that in all combinations of hybrid systems, with decreasing ENS_{max}(%), system costs have increased based on increasing the production participation of renewable units.

b.3 Evaluate the effect of load changes on the hybrid system design

The effect of load changes is investigated in this section, which involves load demand changes on the design and optimal capacity of the PV/WT/BA system using the AEFA method. Evaluation of load changes on system design for ENS_{max}(%) equal to 5% has been done. The results in different combinations of hybrid systems are presented in Table 4. According to Table 5, it can be seen that with increasing load, the amount of system costs has increased and the reliability index has been maintained at the desired level.

Table 4. PV/WT/BA system design results for load changes

Load Change	NPV	NWT	NBA	ENS (%)	TPC (M$)
$0.8\times P_{load}$	120	71	458	4.80	0.810
P_{load}	163	83	561	4.82	1.016
$1.2\times P_{load}$	162	107	923	4.84	1.179

b.4 Evaluate the effect of inverter efficiency changes on the hybrid system design

The effect of inverter efficiency changes on the design of the PV/WT/BA system is investigated. The results of different combinations of hybrid systems are presented in Table 5. According to Table 5, it can be seen that with increasing inverter efficiency, system cost decreases and the ENS index decreases, in other words, the reliability level is improved by providing more load.

Table 5. PV/WT/BA system design results for inverter efficiency changes

Inverter Efficiency (%)	NPV	NWT	NBA	ENS (%)	TPC (M$)
90	88	119	339	4.91	1.090
95	196	77	297	4.87	1.056
100	163	83	561	4.82	1.016

Conclusion

In this paper, the optimal design of a stand-alone hybrid PV/WT/BA system is presented with the aim of minimizing the CEG during the 20 years life span of the project using the AEFA considering ENS constraints. In order to verify the performance of the proposed method, the results were compared and analyzed with the PSO and SCA methods. In the design of the hybrid PV/WT/BA system, the CEG values in AEFA, PSO, and SCA methods are obtained at 1.016, 1.022, and 1.031 M$, respectively, and the ENS values for these methods are achieved at 4.82, 4.89 and 4.94%, respectively. The results showed better performance of the AEFA compared to other methods with lower cost and better reliability. The results also cleared that the hybrid PV/WT/BA combination is technically and economically more cost-effective than the other compounds. In addition, the results demonstrated that by reducing the reliability constraint, the system CEG increase, by increasing the inverter efficiency, the system CEG decrease and the reliability level improves, and in addition, by increasing the peak load, the system CEG and ENS increases.

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REFERENCES

[1] Jäger-Waldau, A., "Photovoltaics and renewable energies in Europe", *Renewable and Sustainable Energy Reviews*, 11(7), (2007), 1414-1437.

[2] Nema, P., Nema, R. K., & Rangnekar, S., "A current and future state of art development of hybrid energy system using wind and PV-solar: A review". *Renewable and Sustainable Energy Reviews,* 13(8), (2009), 2096-2103.

[3] Billinton, R., & Allan, R. N., "Reliability assessment of large electric power systems". *Springer Science & Business Media,* (2012).

[4] Abdelhamid Kaabeche, Rachid Ibtiouen," Techno-economic optimization of hybrid photovoltaic/wind/diesel/battery generation in a stand-alone power system", *Solar Energy* 103 (2014), 171–182.

[5] Hongxing Yang, Wei Zhou, Lin Lu, Zhaohong Fang," Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm", *Solar Energy,* 82 (2008), 354–367.

[6] Katsigiannis, Y.A., Georgilakis, P.S., Karapidakis, E.S., "Multiobjective genetic algorithm solution to the optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables". *Renew. Power Gen., IET* 4 (5), (2010), 404–419.

[7] Dufo, L.R., Bernal, A.J.L., "Multi-objective design of PV–wind– diesel–hydrogen–battery systems." *Renew. Energy* 33 (12), (2008), 2559–2572.

[8] Hadidian-Moghaddam, M. J., Arabi-Nowdeh, S., & Bigdeli, M. "Optimal sizing of a stand-alone hybrid photovoltaic/wind system using new grey wolf optimizer considering reliability." *Journal of Renewable and Sustainable Energy,* 8(3), (2016), 035903.

[9] Baghaee, H. R., Mirsalim, M., Gharehpetian, G. B., & Talebi, H. A. "Reliability/cost-based multi-objective Pareto optimal design of stand-alone wind/PV/FC generation microgrid system". *Energy,* 115, (2016), 1022-1041.

[10] Gharavi, H., Ardehali, M. M., & Ghanbari-Tichi, S. "Imperial competitive algorithm optimization of fuzzy multi-objective design of a hybrid green power system with considerations for economics, reliability, and environmental emissions". *Renewable Energy,* 78, (2015), 427-437.

[11] Bansal, A. K., Kumar, R., & Gupta, R. A. "Economic analysis and power management of a small autonomous hybrid power system (SAHPS) using biogeography based optimization (BBO) algorithm". *IEEE Transactions on smart grid,* 4(1), (2013), 638-648.

[12] Jahannoosh, M., Nowdeh, S. A., Naderipour, A., Kamyab, H., Davoudkhani, I. F., & Klemeš, J. J. "New hybrid meta-heuristic algorithm for reliable and cost-effective designing of photovoltaic/wind/fuel cell energy system considering load interruption probability." *Journal of Cleaner Production,* 278, (2021), 123406.

[13] Baghaee, H. R., Mirsalim, M., Gharehpetian, G. B., & Talebi, H. A. "Reliability/cost-based multi-objective Pareto optimal design of stand-alone wind/PV/FC generation microgrid system." *Energy,* 115, (2016), 1022-1041.

[14] Maleki, A., Pourfayaz, F., & Rosen, M. A. "A novel framework for optimal design of hybrid renewable energy-based autonomous energy systems: a case study for Namin, Iran." *Energy,* 98, (2016), 168-180.

[15] Samy, M. M., Barakat, S., & Ramadan, H. S. "A flower pollination optimization algorithm for an off-grid PV-Fuel cell hybrid renewable system." *International journal of hydrogen energy,* 44(4), (2019), 2141-2152.

[16] Mohamed, M. A., Eltamaly, A. M., & Alolah, A. I. "Swarm intelligence-based optimization of grid-dependent hybrid renewable energy systems." *Renewable and Sustainable Energy Reviews,* 77, (2017), 515-524.

[17] Zhang, G., Shi, Y., Maleki, A., & Rosen, M. A. "Optimal location and size of a grid-independent solar/hydrogen system for rural areas using an efficient heuristic approach." *Renewable Energy,* (2020).

[18] Yadav, A. "AEFA: Artificial electric field algorithm for global optimization." *Swarm and Evolutionary Computation,* 48, (2019), 93-108.

[19] Ahmadi, S., & Abdi, S. "Application of the Hybrid Big Bang–Big Crunch algorithm for optimal sizing of a stand-alone hybrid PV/wind/battery system." *Solar Energy,* 134, (2016), 366-374.

[20] Mirjalili, S., Mirjalili, S. M., & Lewis, A. "Grey wolf optimizer." *Advances in engineering software,* 69, (2014), 46-61.

[21] Kaabeche, A., Diaf, S., & Ibtiouen, R. "Firefly-inspired algorithm for optimal sizing of renewable hybrid system considering reliability criteria." *Solar Energy,* 155, (2017), 727-738.

[22] Hosseinalizadeh, R., Shakouri, H., Amalnick, M. S., & Taghipour, P. "Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: case study of Iran." *Renewable and Sustainable Energy Reviews,* 54, (2016), 139-150