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Optimal, Reliable and Cost-Effective Framework of Photovoltaic-Wind-Battery Energy System Design Considering Outage Concept Using Grey Wolf Optimizer Algorithm–Case Study for Iran

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ABSTRACT In this paper, an optimal, reliable, and cost-effective framework for designing a renewable hybrid photovoltaic-wind-battery system is presented to minimize the total net present cost (TNPC) and to consider reliability constraint as loss of load probability (LPP) for the city of Ahvaz, Iran, considering the components outage rate (COR). The decision variables include the number of photovoltaic panels, wind turbines, batteries, and the angle of the photovoltaic panel optimized by the grey wolf optimizer (GWO) algorithm. The performance of the proposed method is compared with the particle swarm optimization (PSO) method. The results of a system designed in different combinations with and without considering COR are evaluated. The simulation results confirm that the GWO algorithm is superior to the PSO method by yielding lower TNPC (1.199 M$ for GWO and 1.201 M$ for PSO) and better LPP (0.653% for GWO and 0.655% for PSO) for optimal combination (photovoltaic-battery system). The results also showed that a photovoltaic-wind combination is not the most cost-effective and reliable for the Ahvaz region, and the implementation of hybrid systems based on wind power is not cost-effective in this region. In addition, the results showed that considering COR gives the designers of these systems a more accurate view of the cost and reliability. Moreover, considering COR increases the cost of load supply and undermines the load reliability.

INDEX TERMS Hybrid photovoltaic-wind-battery systems, cost/reliability assessment, outage rate, loss of load probability, grey Wolf optimizer.

I. INTRODUCTION

In recent years, the importance of utilizing renewable energy sources has increased. Iran is one of the richest countries in the world in terms of access to various energy sources. In Iran, both fossil fuels such as oil and natural gas and renewable sources such as photovoltaic, wind, geothermal, hydrogen and biomass are abundant. A country like Iran with abundant oil and gas reserves should not rely on fossil fuels and should plan to develop a variety of energy sources. Due to the dispersed nature of many regions of Iran, stand-alone energy systems that use renewable energy sources are suitable options for supplying electricity to isolated areas. The unpredictability of output and the high investment cost of renewable energy technologies are one of the main challenges of using these types of resources [1], [2]. In this regard,

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to create a reliable and cost-effective system, different renewable energy systems are combined to cover each other's deficiencies [3]. The purpose of designing hybrid power systems is to determine the optimum capacity of system components. The main indices in the design of these systems are economic and technical indices. The economic index refers to the costs incurred by the system for generating energy and the technical index is related to the system's capability to supply [4]. The overall purpose of the design is to optimize components capacity so that in addition to minimizing system costs, load demand can be properly met with high reliability [5]. Therefore, achieving optimum components capacity is important in optimizing the design of hybrid systems. It should be noted that the lack of precise optimization will increase the cost of the system and on the other hand, the system load will not be adequately supplied [6]. In [7], optimal design of the hybrid wind-photovoltaic-diesel system is presented with a battery storage system to minimize system annual costs, energy not supplied probability and fuel pollution costs using the multi-objective co-evolutionary algorithm that the wind-photovoltaic-diesel system is determined as optimal combination. In [8], a wind-photovoltaic-fuel cell system designing is presented to minimize the annual cost of the system considering load energy not supplied probability using artificial bee colony (ABC) algorithm that the system with all sources and fuel cell storage is determined as optimal combination with less cost. In [9], the optimal design of the wind-photovoltaic system based on probability of load deficit power, extra generation power, probability of unused energy, cost of project lifespan, and levelized cost of energy are presented along with the battery bank. In [9], the hybrid wind-photovoltaic-battery is selected as cost-effective and reliable system for load supply. In [10], the optimal design of hybrid wind-photovoltaic-diesel-battery systems is investigated with the aim of minimizing the cost of present value and taking into account the overall energy shortage of the system. In [10], the optimal combination of system is obtained based on wind-photovoltaic-diesel-battery with lowest cost. In [11], the design of a hybrid wind-photovoltaic-diesel hybrid system considering battery storage system to minimize the annual cost of the system and considering reliability and pollution using a particle swarm optimization (PSO) algorithm is presented. The results showed that the PSO is capable to determine the optimal combination of hybrid system based on renewable units, diesel and battery storage. In [12], the optimal design of hybrid photovoltaic-wind-fuel cell system is investigated with an objective of net present cost minimization and based on reliability index using flower pollination algorithm (FPA). The results are clear that the fuel cell plays important role in decreasing the costs and in improving the load reliability. In [13], the design of a hybrid wind-photovoltaic-diesel system with battery storage and a fuel cell is presented with the objective of minimizing project life costs using simulated annealing (SA) algorithm. The results show that using the battery storage system gives a lower cost compared to the fuel cell. In [14], the hybrid wind-photovoltaic system with battery storage is used to supply load. The purpose of the study is to optimize the system components with minimizing the energy cost and considering loss of power probability (LPP). In [14], firefly algorithm (FA) is used to solve the optimization problem. The optimum size of the system components is determined in terms of reliability constraints and the results showed feasibility of the proposed designing for the LPP up to 3%. In [15], an optimal design of a photovoltaic-wind system with fuel cell storage with the aim of minimizing project life costs and considering LPSP reliability constraints is presented. The results showed that using fuel cell improves system load reliability and photovoltaic-wind-fuel cell combination is the best system economically and technically. In [16], the optimal sizing of a photovoltaic-wind-battery system is studied with the aim of minimizing the cost of per kWh load supply and considering LPSP as reliability constraint in Saudi Arabia using Differential Evolutionary (DE) Algorithm. The results showed that photovoltaic panels have the highest contribution and diesel the least contribution to load supply. Optimization of a photovoltaic-wind-battery hybrid system in [17] is presented using hybrid GA-PSO and multi-PSO to reduce the investment, maintenance, operation and replacement costs of components and improving the system reliability. The results showed that the cost of per kWh energy is 0.502 $. In [18], Potential Assessment Optimization of a photovoltaic-battery-diesel system is investigated with the objective of minimizing energy cost and loss of load probability (LLP) using PSO for Algeria [18]. The results showed that the cost of per kWh under full supply is 0.38 $ and the largest contribution to load supply is by photovoltaic panels.

Studies on the design of the hybrid system have shown that optimization of the photovoltaic-wind hybrid system in a particular region requires the use of solar radiation, temperature and wind speed data. It can be said that climatic conditions including the intensity of solar radiation and the wind speed in each geographical region have a direct impact on the contribution of renewable solar and wind units. Moreover, the literature review showed that most studies have not addressed the impact of reliability concept in view of hybrid system components outage rate (COR). Since in real condition, the performance probability of the hybrid system components is not 100% [6], the optimal design of the hybrid system should be done based on this concept. As observed in most previous studies, this concept has been overlooked and the hybrid system design is done with 100% availability of renewable units and not considering the outage of these generation units and inverters. In the literature review, the researches are concentrated on the optimization algorithm, cost function and reliability constraint. Considering COR for photovoltaic panels and wind turbines is more realistic and precise approach in optimal designing of the photovoltaic-wind hybrid system than not considering the COR [19].

Optimal, reliable and cost-effective framework for designing of a renewable hybrid photovoltaic-wind-battery system for Ahvaz region is presented by reliability/cost evaluation. The objective function of the design problem is based on economic evaluation to minimize the total net present cost (TNPC) value of energy generation, including initial investment, maintenance, operation and replacement costs. Also in reliability assessment, the reliability constraint is presented as the loss of load probability (LPP), which indicates the ability of the hybrid system to supply the load. The problem variables include the number of photovoltaic panels, wind turbines, batteries and angle of photovoltaic panel that are optimally optimized. The optimization variables are determined in different combinations of the hybrid system. Meta-heuristic grey wolf optimizer (GWO) [6] method is used that inspired the hunting behavior of grey wolves. The GWO is a powerful method to solve the optimization problems and has high convergence speed. The optimal design and energy management of the different combinations of the hybrid system including photovoltaic-wind-battery, photovoltaic-battery and wind-battery hybrid systems are investigated and compared based on GWO method for Ahvaz region. The best combination of the hybrid system for load supply in this region is determined in view of cost and reliability. The difference between the studies explained in the literature review and our own presented study is that our study includes consideration of COR of photovoltaic and wind renewable energies and also inverter. The effect of COR in previous studies has not been investigated or evaluated in a very limited way. In this study, the effect of the COR is investigated in the design and energy management of the hybrid systems, cost and reliability as well as on the energy of the storage system. The COR is an actual concept that must be taken into account for real and accurate design of hybrid systems so that energy system engineers can know the exact cost and reliability of such system. Moreover, to investigate the GWO method, its performance in hybrid system design is compared and analyzed with PSO. The PSO algorithm is a very powerful algorithm for solving electrical optimization problems that in most electrical engineering researches the capability of new methods is evaluated with this algorithm [10], [12]. For this reason, the feasibility of the proposed GWO method is compared with the PSO method.

In section 2, the system under study and its operation is described. Each of the different parts of the hybrid system is also modeled. Section 3 presents the problem formulation. Section 4 describes the proposed optimization method and its implementation steps. The simulation results are presented in Section 5 and conclusion is placed in Section 6.

II. HYBRID SYSTEM UNDER STUDY

In this paper, a stand-alone hybrid system including photovoltaic panels, wind turbines and battery bank is used to supply. The most important issue in designing a photovoltaic-wind hybrid system is the changing weather conditions such as sunlight and wind speed reduction. The battery system is used to continuously supply the load demand and increase reliability. The hybrid system under study is illustrated in Figure 1. The main components include photovoltaic panels, wind turbines, batteries and inverters.

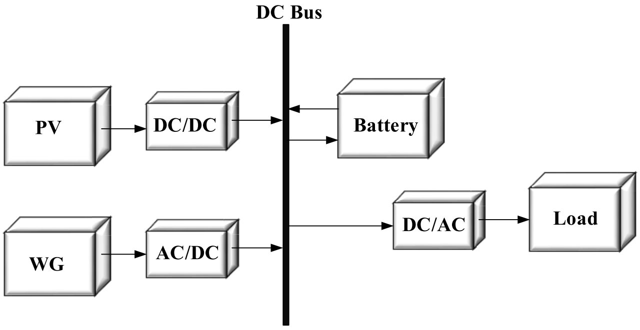

FIGURE 1. Photovoltaic-wind-battery hybrid system.

A. OPERATION OF HYBRID SYSTEM

Operation of the photovoltaic-wind-battery hybrid system is as follow:

- Sum of energy produced by renewable sources equals to load demand. In this case, all power generated by renewable sources is injected into the load.
- Total energy produced by renewable sources is greater than the load demand. In this situation, the surplus power generated by the wind and solar units are directed to the battery to be stored. If the battery capacity is full, extra power will be dumped in a load.
- Total energy produced by renewable sources is less than the load demand. Under these conditions, deficit power is compensated by the battery. If this deficiency exceeds the rated capacity of the battery, part of the load must be disconnected.

B. MODELING THE SYSTEM UNDER STUDY

In this section mathematical modeling of each component of the photovoltaic-wind-battery hybrid system is presented.

1) PHOTOVOLTAIC PANEL

In the photovoltaic panel, the total solar radiation on the oblique surface is equal to the sum of the radiated, scattered and reflected components on the oblique surface [20]. The scattered and reflected sections are ignored because they make up only a small portion of the total radiation. Instantaneous radiation on a diagonal plane can be expressed by the following equations. The schematic of solar radiation is shown in Figure 2. Eq. (1) is used to calculate the solar deviation (δ) through the Earth's deviation from its period ($\theta = 23.44^\circ$) [7].

$$\delta = \theta \times sin(360^\circ \times \frac{284 + n}{365}) \tag{1}$$

where n is the number of days in a year.

The angle of solar altitude (h), which is the angle between the path of the sun and the horizon, can be estimated using

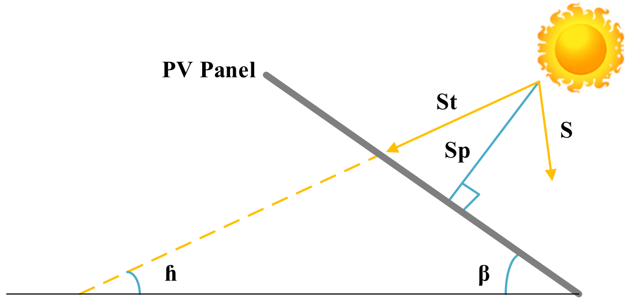

FIGURE 2. **Schematic of solar radiation [7].**

the following equations [7].

$$sinh = sin\Phi sin\delta + cos\Phi cos\lambda \tag{2}$$

$$\lambda = \frac{360(12 - lt)}{24} \tag{3}$$

where, Φ latitude, λ hour angle and lt local time ($0 \leq lt \leq 23$). According to Figure 2, the instantaneous radiation on the diagonal surface (S_t) can be calculated as follows from the horizontal component of solar radiation (S) [7].

$$S_t = \frac{S}{sinh} \tag{4}$$

$$S_P = S_t \times sin(h + \beta) \tag{5}$$

where S_P is the affective component of solar radiation perpendicular to the diagonal plane. S_P is defined based on instantaneous radiation on the diagonal surface (S_t), solar elevation angle (h) and PV panel tilt angle (β).

Using the calculated S_p, the maximum output power of the PV panels is determined as follows.

$$P_{PV} = P_{PV,Rated} \cdot \eta_{PV,MPPT} \cdot \frac{S_P}{1000} \tag{6}$$

where $P_{PV,Rated}$ is the nominal power of each photovoltaic panel and $\eta_{PV,MPPT}$ is photovoltaic tracking efficiency. The number of 1000 also represents standard radiation at the panel level. In this PV generation model, the effect of temperature is also ignored. A PV panel can be generate its peak power in standard test condition (STC) it means in 1000 w/m ^{2} radiation and 25$^{\circ c}$. According to manufacturer's specifications, each PV panel can be generating 1 kW power in STC.

2) WIND TURBINE

The wind turbine generated power in terms of wind speed is obtained from the following equation [10].

$$P_{WG} = \left\{ \begin{array}{cc} P_{WG,max} \times \left(\frac{V^2 - V_{cut-in}{}^2}{V_{rated}^2 - V_{cut-in}{}^2} \right); & V_{cut-in} \leq V \leq V_{rated} \\ P_{WG,max}; & V_{rated} \leq V \leq V_{cut-out} \\ 0 & Otherwise \end{array} \right\} \tag{7}$$

where P_{WG} is wind turbine output power, V is wind speed, V_{cut-in} cut-in speed, $V_{cut-out}$ cut-out speed, $P_{WG,max}$ maximum turbine output power in kW and V_{rated} is rated wind speed. The cut-in speed is 3, nominal speed is 10 and cut-out speed is considered 15 m/s.

3) RENEWABLE RESOURCES GENERATED POWER

The total power generated by photovoltaic panels and wind turbines represents the amount of power generated by renewable units. Assuming that the number of photovoltaic panels and wind turbines is respectively equal to N_{PV} and N_{WG} then the power generated by all renewable units injected into the DC bus is calculated as follows:

$$P_{ren} = N_{WG}.P_{WG} + N_{PV}.P_{PV} \tag{8}$$

To calculate the reliability of the hybrid system, the component outage rate (COR) must be applied. If the number of photovoltaic n_{PV}^{fail} and the number of wind turbines n_{WG}^{fail} are out of the system due to outage, then the total power generated by the renewable units are calculated as follows:

$$P_{ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right) = (N_{WG} - n_{WG}^{fail}).P_{WG} + (N_{PV} - n_{PV}^{fail}).P_{PV} \tag{9}$$

4) BATTERY STORAGE

In photovoltaic-wind-battery hybrid systems, the storage system operates as follows:

If the energy produced by the hybrid systems (the total energy output of photovoltaic panels and wind turbines) at time t exceeds the load demand, the surplus energy is injected into the battery and stored. The amount of energy stored in the battery at time t is obtained by

$$E_{Stor}(t) = E_{Stor}(t-1) + \Big[(P_{PV}(t) + P_{WG}(t)) - \frac{P_{Load}(t)}{\eta_{Inv}}\Big].\Delta t \tag{10}$$

where $E_{Stor}(t)$ and $E_{Stor}(t-1)$ is the energy stored at time t and t-1, respectively. η_{Inv} is inverter efficiency. Δt is time step (1 hour).

When the load demand exceeds the energy produced by the hybrid system, the battery is used to offset the load shortage. In this case, the amount of battery storage energy at hour t is defined as follows:

$$E_{Stor}(t) = E_{Stor}(t-1) - \left[\frac{P_{Load}(t)}{\eta_{Inv}} - (P_{PV}(t) + P_{WG}(t)\right].\Delta t \tag{11}$$

C. RELIABILITY INDICES

The loss of power probability (LPP) index is considered as a reliability index for hybrid load reliability assessment, which is described below [6].

$$LOEE = EENS = \sum\nolimits_{t=1}^{N} E[LOE(t)] \tag{12}$$

where *E[LOE(t)]* is loss of energy expectation in the t that is defined by

$$E[LOE] = \sum\nolimits_{s \in S} Q_s \times f_s \tag{13}$$

where Q_s is loss of load value (kWh) when system encounters state s and $\boldsymbol{f}_s$ is the probability of encountering state s. The LPP is calculated as follows:

$$LPP = \frac{LOEE}{\sum_{i=1}^{N} D(t)} = \frac{\left(\frac{P_{Load}}{\eta_{Inv}}\right).\Delta t - (P_{ren}.\Delta t + E_{Stor})}{\sum_{i=1}^{N} D(t)} \tag{14}$$

where $D(t)$ is the load demand in kWh at time step t and Δt is the time step (1 hour).

The outages of PV, WG, and inverter are taken into consideration [8]. The outage rate of PV and WT is considered 4% or availability of these components is considered 96%. According to given n_{WG}^{fail} out of total $\mathrm{N_{WG}}$ installed WGs, and n_{PV}^{fail} out of total $\mathrm{N_{PV}}$ installed PVs are failed, the probability of encountering this state is determined as follows:

$$\begin{aligned} & f_{Ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right) \\ & = \left[\binom{N_{WG}}{n_{WG}^{fail}} \times A_{WG}^{N_{WG}-n_{WG}^{fail}} \times (1-A_{WG})^{n_{WT}^{fail}}\right] \\ & \quad \times \left[\binom{N_{PV}}{n_{PV}^{fail}} \times A_{PV}^{N_{PV}-n_{PV}^{fail}} \times (1-A_{PV})^{n_{PV}^{fail}}\right] \end{aligned} \tag{15}$$

where A_{PV} and A_{WG} are availability of wind turbines and photovoltaic panels, respectively.

III. PROBLEM FORMULATION

In this section problem Formulation of the optimal, reliable and cost-effective framework of hybrid photovoltaic-wind-battery system designing is presented. The purpose is to determine the optimum capacity of system component including the number of wind turbines, the number photovoltaic panels, the number of batteries, and angle of installation of photovoltaic panels with minimizing the system power generation costs as objective function and considering reliability constraint and component outage rate (COR).

A. OBJECTIVE FUNCTION

The total net present cost (TNPC) of hybrid system is defined as follows [10]:

$$TNPC_i = N_i.(CC_i + RC_i.K_i + OM_i.\frac{1}{CRF(ir, R)}) \tag{16}$$

where N is the number of units or components in kW or kg, CC refers to initial investment cost ($), RC is replacement cost ($), OM_i is maintenance and operation cost ($/yr) and R is project life span (20 years). The real interest rate (6%) is given by nominal, nominal interest rate and the annual inflation rate (f) as follows:

$$ir = \frac{ir_{nominal} - f}{1 + f} \tag{17}$$

CRF and K are capital recovery factor and present value factor of the fixed payment, respectively, as defined below.

$$\frac{1}{CRF\ (ir, R)} = \frac{(1 + ir)^R - 1}{ir\ (1 + ir)^R} \tag{18}$$

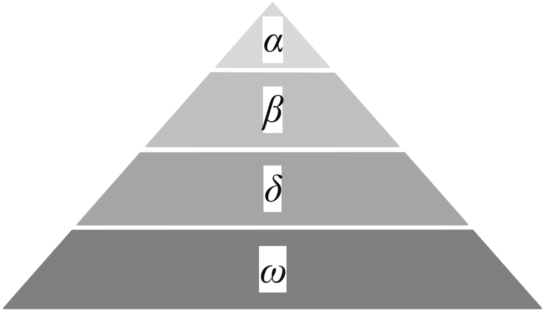

FIGURE 3. Hierarchy of grey wolves [21].

$$k_i = \sum_{n=1}^{yi} \frac{1}{(1 + ir)^{n.Li}} \tag{19}$$

where y and L are the number of replacements and the useful life of the components, respectively.

B. PROBLEM CONSTRAINTS

The objective function should be optimized with the following constraints:

$$LPP_{min} \leq LPP \leq LPP_{max} \tag{20}$$

$$0 \leq N_i \leq N_{i,max} \tag{21}$$

$$0 \leq \beta_{PV} \leq 90 \tag{22}$$

$$E_{Stor,min} \leq E_{Stor} \leq E_{Stor,max} \tag{23}$$

where LPP_{min} and LPP_{max} are minimum and maximum of reliability constraint, $N_{i,max}$ is the maximum number of components, θ_{PV} is the angle of photovoltaic panel installation and $E_{store\ min}$ and $E_{store\ max}$ are minimum and maximum values of the battery storage energy, respectively. The minimum capacity of each battery is 20% of its maximum capacity.

IV. PROPOSED OPTIMIZATION METHOD

A. OVERVIEW OF GWO

Grey wolf optimizer (GWO) is provided by Mirjalili based on the grey wolf's group hunting manner in 2014 [21]. The hierarchy of grey wolves is shown in Figure 3. Wolf Alpha (α) is the group's best member and leader in terms of group management and decision making on hunting and other purposes. Beta wolves (β) follow alpha wolves and collaborate with them in decision making and group activities. Omega wolves (w) surrender to other wolves and the previous wolves are allowed to eat hunting. Delta wolves (δ) must defer to the α and β, but they must dominate omega. Also, wolf's group hunting is another good social manner of the grey wolves. The hunting steps of wolves are as the pursuit and chasing to the prey, siege and harassment of the prey and attacking it.

The mathematical modeling of the prey siege behavior is as follows [21]:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X^P}(t) - \vec{X}(t)\right| \tag{24}$$

$$\vec{X}\ (t+1) = \overrightarrow{X^P}\ (t) - \vec{A}.\vec{D} \tag{25}$$

where t refers to actual iteration, $\vec{A}$ and $\vec{C}$ refer factors vectors, $\overrightarrow{X^P}$ is vector of the prey position and $\vec{X}$ is grey wolf position vector wolf. The vectors of $\vec{A}$ and $\vec{C}$ are obtained by [21].

$$\vec{A} = 2\vec{a}.\overrightarrow{r_1} - \vec{a} \tag{26}$$

$$\vec{C} = 2\overrightarrow{r_2} \tag{27}$$

where $\vec{a}$ is linearly reduced from 0 to 2 during iterations and r_1 and r_2 are random vectors in the range [0, 1]. For simulation the grey wolves hunting manner, it is assumed that wolf α, β and δ that have more knowledge of prey position. Therefore, they are saved as the three present best solutions while the omega wolves should update its position based on the best search factors as follows [21].

$$\overrightarrow{D^\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X^\alpha} - \vec{X}\right|, \quad \overrightarrow{D^\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X^\beta} - \vec{X}\right|, \; \overrightarrow{D^\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X^\delta} - \vec{X}\right| \tag{28}$$

$$\overrightarrow{X_1} = \overrightarrow{X^\alpha} - \overrightarrow{A_1}.\overrightarrow{D^\alpha}, \quad \overrightarrow{X_2} = \overrightarrow{X^\beta} - \overrightarrow{A_2}.\overrightarrow{D^\beta}, \; \overrightarrow{X_3} = \overrightarrow{X^\delta} - \overrightarrow{A_3}.\overrightarrow{D^\delta} \tag{29}$$

$$\vec{X}\,(t+1) = (X_1 + X_2 + X_3)/3 \tag{30}$$

B. IMPLEMENTATION OF GWO IN PROBLEM SOLUTION

Flowchart of GWO implementation in problem solution is illustrated in Figure 4. The GWO implementation steps to solve the problem of designing and optimizing the hybrid system are as follows:

Step 1): Initialize the hybrid system data. In this step, Ahvaz City's solar radiation and wind speed data, load demand data, technical and economic design parameters are applied.

Step 2): Initialize the algorithm parameters. In this step, the maximum iteration of the algorithm and the population of the algorithm are determined based on trial and error and user experience in extracting the results. The decision variables, the capacity of the hybrid system components are also assigned randomly for the algorithm population.

Step 3): Calculate the TNPC for each population member of the GWO. In this step, the value of the objective function is calculated for each population member of the algorithm.

Step 4): Define the best population member. In this step, the TNPC values of each member of the algorithm population are evaluated and the member (grey wolf) with the lowest cost is considered as the best solution.

Step 5): Update the algorithm population. In this step, the population of the algorithm is updated.

Step 6): Calculate the TNPC for the new population. In this step, the TNPC value is calculated for each newly updated population.

Step 7): Determine the best solution. By evaluating and comparing the objective function in steps 4 to 6, it replaces it if the TNPC in step 6 is better than step 4.

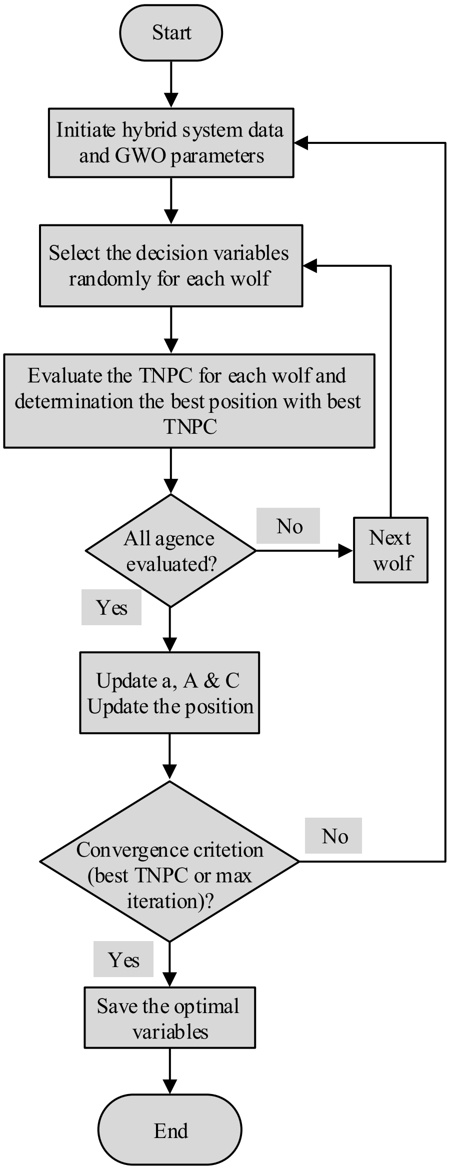

FIGURE 4. Flowchart of GWO implementation in problem solution.

Step 8): Are the convergence conditions (achieving the lowest TNPC and maximum algorithm iterations) met? If yes go to step 9 and otherwise go to step 5.

Step 9): Determine the best optimal variables and print the results.

Step 10): Stop the Algorithm.

V. SIMULATION RESULTS

A. DESIGNING DATA

The optimal design and energy management of hybrid photovoltaic-wind-battery systems for Ahvaz city is presented. Figure 5 shows the location of Ahvaz city in Iran country and Figure 6 shows its location in Khuzestan province. The geographical location of Ahvaz is 31° 20'N and 48°40'E [22]. Different cities of Khuzestan province have a high potential for solar radiation. Although the wind situation

TABLE 1. Values of the hybrid system components parameters [11], [12], [25].

Lifetime (Yr)	COR (%)	Efficiency (%)	Rated Size (kW)	Maintenance and operation cost (US$/unit-yr)	Replacement cost (US$/unit)	Capital cost (US$/unit)	Component
20	4	-	1kW	33	3200	3200	WT
20	4	-	1kW	10	1800	2000	PV
5	--	85	1kAh	5	80	100	Batt
10	0.11	90	1kW	7	600	700	Inverter

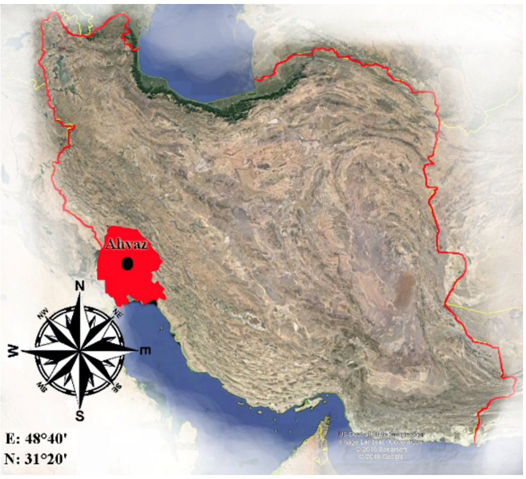

FIGURE 5. Location of Ahvaz city in Iran [22].

FIGURE 6. Location of Ahvaz City in Ahvaz Province [22].

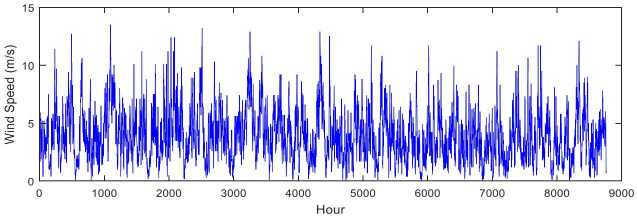

FIGURE 7. Wind speed of Ahvaz city during one year [24].

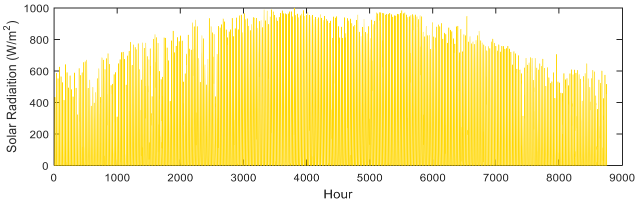

FIGURE 8. Irradiance of Ahvaz city during one year [22].

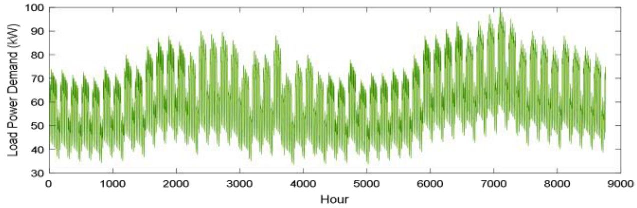

FIGURE 9. IEEE Annual Load Curve with Peak 100 kW [8].

is also favorable in Ahvaz province, it seems that the potential of solar radiation is more suitable than wind speed for the generation of renewable energy that in this paper, the design of hybrid photovoltaic-wind systems is evaluated based on real data of radiation and wind speed of Ahvaz region.

The annual wind speed, the solar radiation for the city of Ahvaz [24] and the load demand are shown in Figs. 7-9, respectively. The project has a useful life of 20 years, a peak load of 100 kW and an interest rate of 6%. The total load is 538.308 MWh over a year. The values of the hybrid system components parameters are presented in Table 1. The COR value for renewable units is 4% and for inverters equal to 0.11%, which is adapted with [23]. The lifetime of the PV and WT is 20 years and the outage rates of these components are considered same as generation units. It should be noted that in [23], the effect of the COR on the system design, cost and reliability values as well as the energy storage of the system has not been evaluated and is intended only as data for the components.

B. SIMULATION SCENARIOS

The optimum design of hybrid systems including photovoltaic-battery (PV/Bat), wind-battery (WG/Bat) and photovoltaic-wind-battery (PV/WG/Bat) for Ahvaz city are carried out. The optimization of the hybrid systems is

TABLE 2. Optimal design results without COR and with LPPmax = 1% (Scenario 1#).

Hybrid System	Algorithm	N_{PV}	N_{WT}	N_{BA}	β_{PV}	*LPP (%)*	*TNPC (M$)*
PV/Bat	GWO	449	0	315	23.09	**0.00653**	**1.199**
	PSO	446	0	335	22.17	0.00655	1.201
WT/Bat	GWO	0	1585	750	--	**0.00850**	**5.987**
	PSO	0	1586	761	--	0.00850	5.993
PV/WT/Bat	GWO	446	0	340	18.38	**0.00640**	**1.200**
	PSO	448	2	316	20.37	0.00641	1.202

performed using GWO algorithm and the performance of the proposed method is compared with the particle swarm optimization (PSO) method. The population number and maximum iterations of the algorithms are considered 50 and 100, respectively. The number of optimization variables is 4 and includes the optimum number of photovoltaic panels, wind turbines, batteries and angle of photovoltaic panels relative to sunlight. The simulation scenarios are as follows:

Scenario 1#: Optimal design of different combinations of hybrid systems without components outage using GWO method and comparing its performance with the PSO method with LPPmax = 1%.

Scenario 2#: Evaluation of optimal design of system different combinations with and without components outage rate using GWO method considering LPPmax = 1%.

Scenario 3#: Comparison of optimal design of different combinations of hybrid systems with components outage rate by GWO under LPPmax variations.

1) RESULTS OF SCENARIO 1#

In the first scenario, the optimal design results of different combinations of hybrid systems without considering the components outage rate using GWO method and comparing its performance with the PSO method with LPPmax = 1% are presented. The components outage rates for photovoltaic panels, wind turbines and inverters are not considered. First, the convergence curves of the GWO method along with the PSO method for solving the design problem for different compounds are plotted in Figures 10-12. According to the Figs 8-10, the proposed GWO method in all hybrid system combinations achieves optimum results with more convergence speed than the PSO method and achieves lower TPCS cost, which confirms the superiority of the proposed method.

The results of the optimal design of hybrid systems without COR and with LPPmax = 1% are presented in Table 2. The design results showed that the wind situation in Ahvaz is not a good potential for energy generation in the form of renewable hybrid systems and also is not economic because of the high cost compared to other system combination. The best hybrid system combination for Ahvaz is the PV/Bat system with the lowest TNPC. The value of TNPC using GWO method for PV/Bat, WG/Bat and PV/WG/Bat systems are 1.119, 5.987 and 1.200 M$, respectively and for the PSO method for PV/Bat, WG/Bat and PV/WG/Bat systems, respectively is obtained 1.201, 5.993 and 1.202 M$ for the 20-year lifespan, which confirmed the superiority of the GWO method in comparison with the PSO method in lower cost. On the other hand, the pattern of radiation data and wind speed affect the cost per kW of load demand supply by hybrid system. In this paper, the cost of PV/Bat system with LPPmax = 1% is 1.199 M$ using GWO, which is cost per kWh with a total load of 538.308 MW in 20 years of system life span for Ahvaz city is equal to 0.11 $. In [23], the cost of per kWh for load supply using hybrid photovoltaic-wind-battery system for Nahavand, Rafsanjan and Khash is equal to 1.87, 0.32 and 0.35$, respectively. Three regions in [23] are related to Iran country.

The results also show that GWO method has lower LPP value or better reliability compared to the PSO method. In Figure 13, the power curve of the photovoltaic panels for the optimal PV/Bat system for LPPmax = 1% without

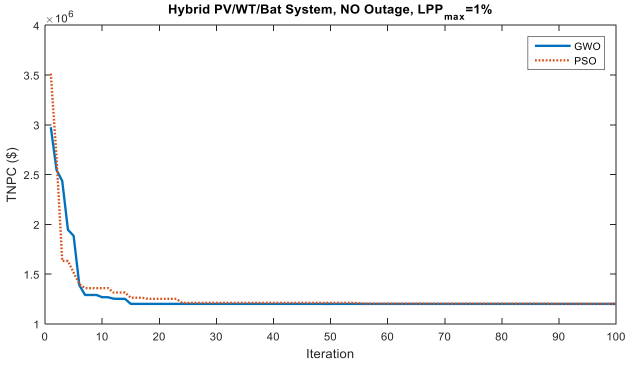

FIGURE 10. Convergence curve of optimization methods in PV/WT/Bat system design without COR and LPPmax = 1%.

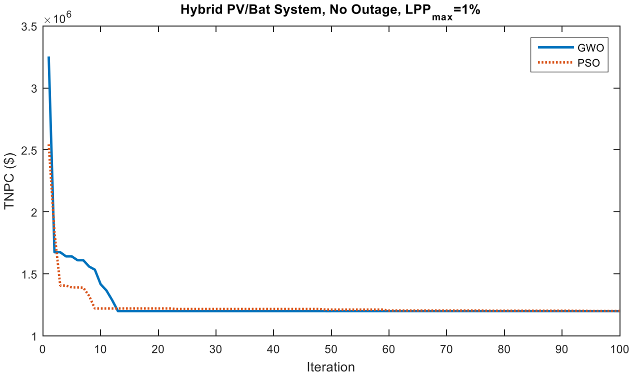

FIGURE 11. Convergence curve of optimization methods in PV/Bat system design without COR and LPPmax = 1%.

TABLE 3. Optimal designing results considering COR using GWO method and $LPP_{max} = 1$ (Scenario 2#).

Hybrid System	Algorithm	N_{PV}	N_{WT}	N_{BA}	β_{PV}	LPP (%)	TNPC (M$)
PV/Bat	Without COR	449	0	315	23.09	0.00653	1.199
	With COR	465	0	326	18.31	0.00702	1.244
WT/Bat	Without COR	0	1585	750	--	0.00850	5.987
	With COR	0	2008	686	--	0.00864	7.409
PV/WT/Bat	Without COR	446	0	340	18.38	0.00640	1.200
	With COR	466	0	324	17.76	0.00730	1.245

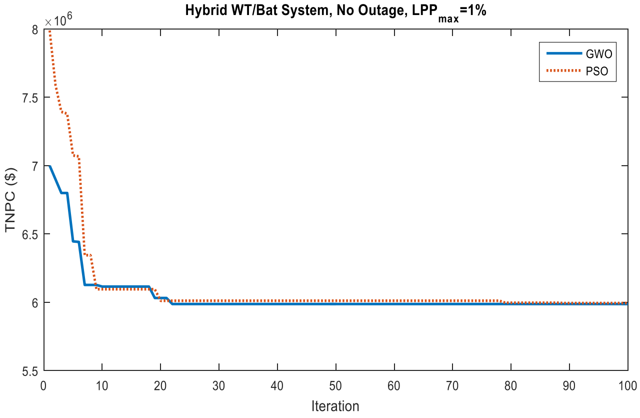

FIGURE 12. Convergence curve of optimization methods in WT/Bat system design without COR and $LPP_{max} = 1\%$.

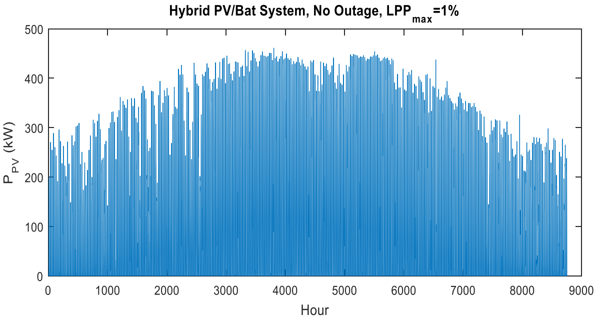

FIGURE 13. Photovoltaic panels power generation variations in PV/Bat system for LPPmax = 1% (Scenario 1#)) without COR.

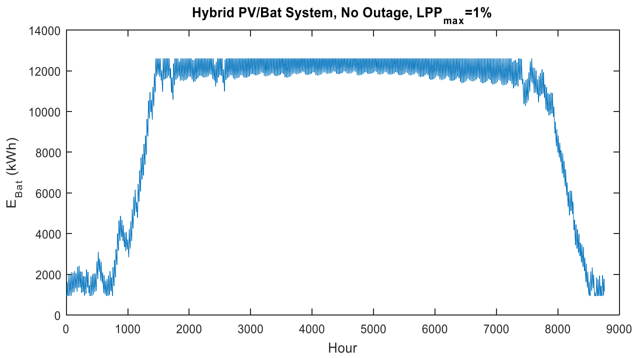

FIGURE 14. Battery bank energy changes in PV/Bat system for $LPP^{max} = 1\%$ (Scenario 1#) without COR.

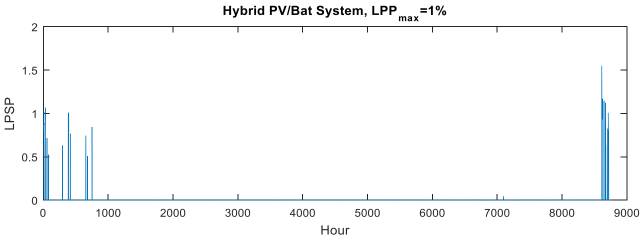

FIGURE 15. LPP changes in PV/Bat composition for $LPP^{max} = 1\%$ (Scenario 1#) without COR.

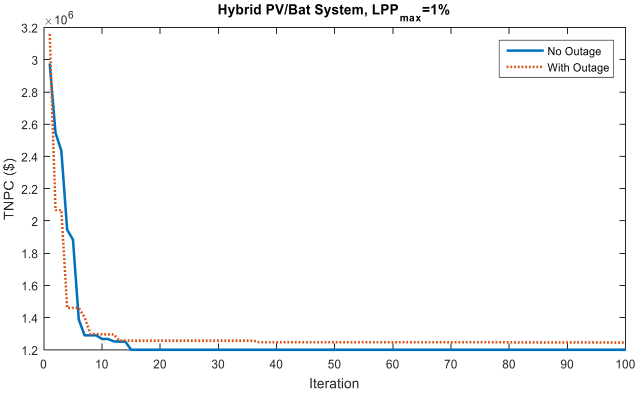

FIGURE 16. Convergence curve of GWO in PV/Bat designing for LPPmax = 1% (Scenario 2#) with and without COR.

COR is shown. Also, the battery bank energy change curve in Figure 14 and the LPP reliability index curve in Figure 15 are illustrated for the optimal PV/Bat combination for LPPmax = 1%.

2) RESULTS OF SCENARIO 2#

In the second scenario, the optimal design results of different hybrid system combinations with COR using GWO method and with LPPmax = 1% are presented. In this section, the COR of photovoltaic and wind units plus the inverter are considered according to Table 1. The convergence curve of the PV/Bat optimal designing is plotted in Figure 16, considering COR. As can be seen, considering the COR, the TNPC has increased. According to Figure 16, considering COR the TNPC is increased from 1.199 M$ to 1.244 M$ for PV/Bat system. This increasing is cleared for PV/WT/Bat and also WT/Bat system, too.

According to Table 3, TPCS value without and with COR in PV/Bat system design are 1.199 and 1.244 M$, respectively and LPP value without and with COR are 0.0065 and

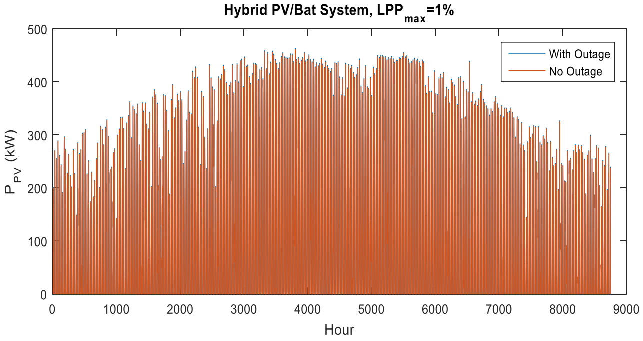

FIGURE 17. Generation Curve of Photovoltaic panels with and without COR for PV/Bat Composition Considering LPPmax = 1% Using GWO Method (Scenario 2#).

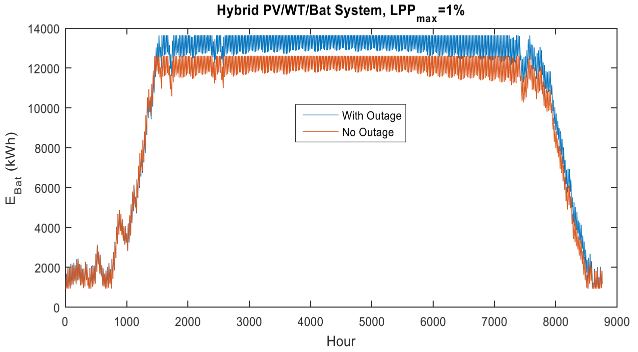

FIGURE 18. Battery energy change curve with and without COR for PV/Bat combination with LPPmax = 1% using GWO method (Scenario 2#).

0.0072 respectively. The results showed that considering COR which represents a more accurate design of the hybrid power systems, has resulted increasing the costs of load supply as well as LPP value increasing which means that the reliability of the hybrid systems is compromised. According to Table 3, the results showed that by considering the COR, the generation rate of the resources for optimal load supply has increased, this problem led to higher system costs. Considering COR causes reduction in renewable unit's capacity and therefore the number of renewable units and also battery number must be increased for desirable load supply. Increasing the number or size of system components causes the increasing the system TNPC.

The power curve of the photovoltaic panels with and without COR for the PV/Bat combination with LPPmax = 1 using the GWO method is shown in Figure 17.

The curve of changes in energy storage of the battery with and without COR for the PV/Bat combination with LPPmax = 1% using the GWO method is shown in Figure 18. As can be seen, the storage level of the system has been reduced considering COR.

The variation curves of LPP with and without COR for the PV/Bat combination with LPPmax = 1% using the GWO method are shown in Figure 19. As shown in Figure 19, it is clear that considering COR has increased the level of LPP and thus weakened the load reliability. Of course, considering the COR is a real issue that is not addressed in most energy system studies. As such, the design obtained from hybrid energy systems is not an accurate design and costs are not properly estimated.

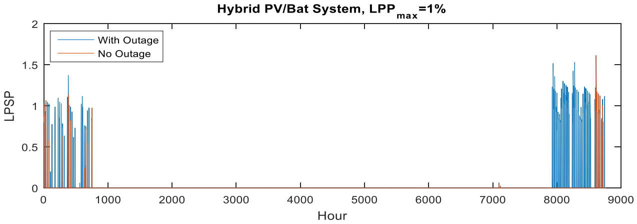

FIGURE 19. LPP change curve with and without COR for PV/Bat system considering $\text{LPP}_{\text{max}} = 1$ using GWO method (Scenario 2#).

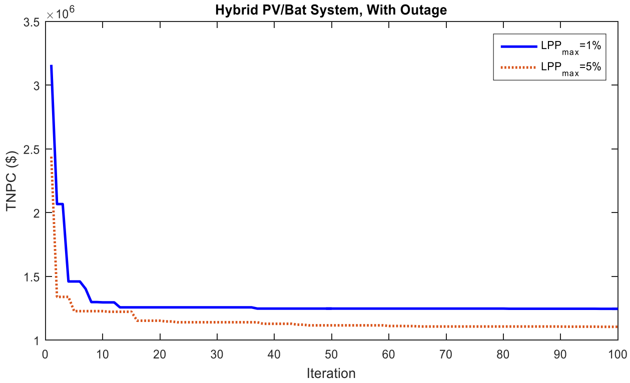

FIGURE 20. Convergence curve of PV/Bat combination considering COR with different LPPmax=5% using GWO method.

3) RESULTS OF SCENARIO 3#

In the third scenario, the optimal design results of different hybrid system combinations in terms of TNPC and reliability constraint namely LPPmax are presented using GWO method. In the first and second scenarios, the design of different combinations for LPPmax = 1% is considered. In this section, hybrid systems are designed for LPPmax=5%. The convergence curve of the optimal combination of hybrid systems considering COR with LPPmax = 1&5% using the GWO method is shown in Figure 20. As can be seen, the value of TNPC decreased with increasing LPPmax constraint. An increase in LPPmax means a reduction in load supply, which naturally reduces the capacity of the system generation, thereby reducing the TNPC of hybrid systems.

The optimal design results of the hybrid systems considering COR with LPPmax=1, 5% using the GWO method are presented in Table 4. The results showed that the increase in LPPmax constraint reduces the level of sources generation and thus reduces system load supply costs. The power curve of the photovoltaic panels for PV/Bat composition considering different LPPmax using the GWO method is shown in Figure 21. As can be seen, with increasing LPP_{max}, the level of photovoltaic panels generation are decreased.

The curve of changes in battery energy storage for PV/Bat composition considering different LPPmax using the GWO

TABLE 4. Optimal design results of PV/Bat system considering COR with different LPPmax using GWO method.

Hybrid System	Algorithm	N_{PV}	N_{WT}	N_{BA}	β_{PV}	*LPP (%)*	*TNPC (M$)*
PV/Bat	LPP_{max}=5%	421	0	197	18.85	0.03490	1.103
	LPP_{max}=1%	465	0	326	18.31	0.00702	1.244
WT/Bat	LPP_{max} =5%	0	614	2425	--	0.04390	3.012
	LPP_{max} =1%	0	2008	686	--	0.00864	7.409
PV/WT/Bat	LPP_{max} =5%	422	0	197	19.85	0.0349	1.104
	LPP_{max} =1%	466	0	324	17.76	0.00730	1.245

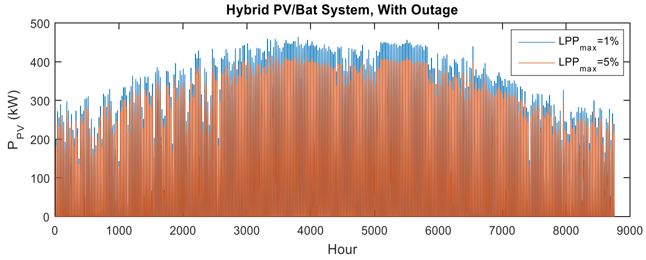

FIGURE 21. Generation Curve of Photovoltaic panels for PV/Bat system with different LPP_{max} Using GWO Method.

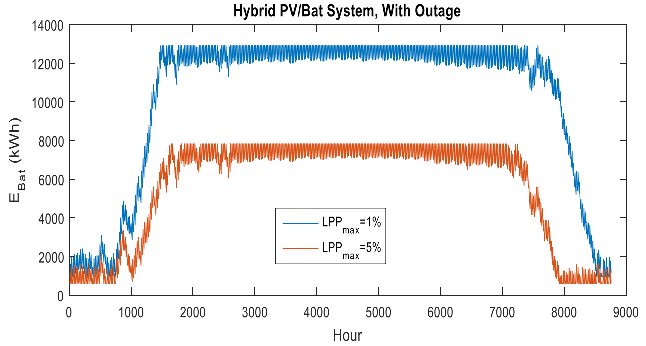

FIGURE 22. Battery energy changing of PV/Bat system considering different LPPmax using GWO method.

method is shown in Figure 22. The storage level of the system decreased with increasing LPPmax.

VI. CONCLUSION

This paper presents the optimal design of a photovoltaic-wind-battery system that minimizes the TNPC of the system and considers the reliability of constraining LPP as a case study for the city of Ahvaz, Iran. The cost of the system is considered as the costs of investment, operation, and replacement of components during the lifespan of the system. A hybrid system optimization is performed using the GWO algorithm with high convergence power and speed. Optimization variables include the number of photovoltaic panels, wind turbines, and batteries and the angle of the photovoltaic panels relative to sunlight. The system design is implemented in various combinations of hybrid systems based on radiation and wind speed in the Ahvaz region and the annual load profile. The simulation results showed that the GWO algorithm could optimally design hybrid systems and determine the optimal combination. The results showed that the photovoltaic-battery combination is the best combination in terms of cost and reliability for the Ahvaz region because of its high solar radiation potential. The performance of the proposed method is also compared with the PSO method and has confirmed the superiority of the GWO method for achieving lower cost and higher reliability. The results also showed that using wind to generate energy in hybrid systems is very costly and not economical for Ahvaz. It is better to use solar energy and battery storage because of its lower cost versus high wind power costs for Ahvaz city. Furthermore, the results showed that considering COR increases the hybrid system cost and undermines reliability. This concept is important for the precise and accurate design of the hybrid power systems and has been overlooked in previous studies. Also given the fact that renewable units are not 100% available and have outages, energy system engineers should consider this for practical implementation to determine accurate cost and reliability when designing hybrid systems. The effect of changes in the reliability constraint on the system design is also evaluated. The results showed that decreasing reliability constraints reduces system costs.

APPENDIX A

Abbreviations of hybrid system modeling presented in bellow Table

NPC_i	Net present value cost for a specific device
N_i	Number of units and/or unit capacity (kW or Kg)
CC_i	Capital investment cost (US$/unit)
RC_i	Replacement cost (US$/unit)
K	Single payment present worth
$O\&MC_i$	Maintenance and repair cost (US$/unit-yr)
CRF	Capital recovery factor
$TNPC_i$	Total net present cost
K	present value factor of the fixed payment
P_{PV}	PV output power
S_P	affective component of radiation perpendicular to the diagonal plane (W/m2)
$P_{PV,Rated}$	rated power of each array, such that $G = 1000\ W/m^2$
$\eta_{PV,MPPT}$	photovoltaic tracking efficiency
S_t	instantaneous radiation on diagonal surface (W/m2)
δ	solar declination ($^\circ$)

β	The angle of the PV panel relative to the surface of the horizon (°)
P_{WG}	WG output power
V	Wind speed
v_{cut-in}	Cut-in speed of turbine (m/s)
$v_{cut-out}$	Cut-out speed of turbine (m/s)
$P_{WG,max}$	Maximum output power of WT (kW)
v_{rated}	Rated speed of turbine (m/s)
PWG, max	Maximum output power of turbine (kW)
N_{PV}	Number of PV
N_{WG}	Number of WG
P_{ren}	Renewable output power (kW)
$P_{ren}\left(n_{WG}^{fail}, n_{PV}^{fail}\right)$	Injected power of renewable units to DC bus
n_{WG}^{fail}	Number of WG being out of the grid
n_{PV}^{fail}	Number of PV being out of the grid
$E_{Stor}(t)$	energy stored in the battery at time t
N_{WG}	Total number of installed wind turbines
N_{PV}	Total number of installed PV arrays
$P_{el-tank}$	EL output power
P_{ren-el}	Delivered electric power to EL
η_{el}	EL efficiency
$E_{tank}(t)$	Stored energy in the hydrogen tank for each step-time
Δt	Duration of each step-time (one hour)
$P_{tank-FC}(t)$	Transferred power from the hydrogen tank to the FC
$\eta_{storage}$	Efficiency of storage system
E_{PV}	PV output energy
E_{WG}	WG output energy
HHV_{H_2}	Higher heating value of hydrogen (39.7 kWh/kg)
η_{Inv}	Inverter efficiency
$E_{load}(t)$	Load demand energy (kWh)
Q_s	Loss of load value (kWh) when system encounters state s
f_s	Probability of encountering state s
$LOE(t)$	loss of energy at step-time t
$LOEE$	Loss of energy expectation
$EENS$	Energy not supplied expectation
$D(t)$	load demand (kWh) in time step t
A_{WG}	Availability of each WG
A_{PV}	Availability of each PV
LPP	Loss of power probability
$LPP_{\min}$	Minimum of LPP
$LPP_{\max}$	Maximum of LPP
$N_{i,\max}$	Maximum number or capacity of component i
$E_{Stor,\min}$	Minimum value of the battery storage energy
$E_{Stor,\max}$	Maximum value of the battery storage energy
$\overrightarrow{A}, \overrightarrow{C}$	Factors vectors
$\overrightarrow{X^{P}}$	Vector of the prey position

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