DESIGN OF HYBRID POWER GENERATION SYSTEMS CONNECTED TO UTILITY GRID AND NATURAL GAS DISTRIBUTION NETWORK: A NEW CONTRIBUTION

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Abstract:

Hybrid power generation system (HPGS) is an active research area, which is in need of a continuous improvement. It represents the best solution for the most complex problems facing the world in the last decades. These problems are known as the shortage of energy, or lack of electricity, which logically are the results of the continuous increasing demand. Therefore, the researchers do their best to overcome all expected roadblocks facing the development, where the most applicable solutions to solve these problems are introduced. In this paper, the HPGS includes; wind turbine (WT), photovoltaic (PV), storage battery (SB), gas turbine (GT), and utility grid (UG). The GT of this system is fueled directly from the natural gas distribution network considering all operational conditions of it, which may be affected by fueling the natural gas for the GT. So, the natural gas distribution network is becoming an important component of the HPGS, and it is included in the HPGS for the first time. Multi meta-heuristic optimization techniques are applied to obtain the components sizing of this system, where cuckoo search algorithm (CSA), firefly algorithm (FA), and flower pollination algorithm (FPA) have been applied. Therefore, this paper introduces a new contribution not only to the new configuration … *applying the new optimization techniques as solving tools. The output results are compared to show the effectiveness and the superiority of the applied techniques as well as extract a recommendation for the best solving technique.*

1 Introduction

All electricity problems should be solved to overcome the obstacles, which e the countries' development strategic plans is facing. Power shortage is the most common problem regarding the

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execution of the countries' development plans. The HPGS is considered the most effective solution to overcome this problem and to meet the power demand. Wind turbine (WT), photovoltaic (PV), storage batteries (SB), gas turbine (GT), and utility are connected together to form the HPGS. Natural gas distribution network is included for the first time to supply the required fuel (natural gas) for the gas turbine, where all its operational conditions are considered. The most important operational conditions should be taken into consideration during the design of this system. They are pressure drop and speed flow. New meta-heuristic optimization techniques have been used to design the mentioned hybrid power system, where CSA, FA, and FPA are used to obtain the HPGS components sizing.

In reference to [1], L. Wang and C. Singhintroduce, the design of a hybrid power system, includes both the wind power and solar power. This design is based on the cost, reliability, and emission criteria. The authors take into consideration failure of the equipment, the stochastic generation, and load variation using the probabilistic methods. The modified particle swarm optimization is applied to obtain the system design for different scenarios.

L. Liqun and L. Chunxia [2], discuss the opportunity of applying a standalone hybrid wind-photovoltaic-battery system for the remote areas of Shanghai. A simulation model is applied for the proposed model and the authors execute financial and risk analysis for it. The authors, also analyze all the environmental and economic considerations. Moreover, the conventional optimization techniques such as genetic algorithm and particle swarm techniques have been applied in order to obtain the cost and emission design for the proposed system.

In reference to [3] S. Trazouei, F. Tarazouei, and M. Ghiamy the design of a standalone hybrid system is introduced, which is combined of wind turbine, photovoltaic system, and diesel generator. The imperialist competitive algorithm (ICA), particle swarm optimization (PSO) and ant colony optimization (ACO) have been applied. The authors consider the annual cost as the objective function should be minimized considering the system reliability constraints. Finally, the hybrid system results are obtained consisting of number of the wind turbines, the number of PV panels, number of diesel generators, the annual cash flow, and the system reliability.

In reference to [4] T. Tahri, A. Bettahar, and M. Douanitry the hybrid system is presented which includes the wind turbine (WT), photovoltaic (PV), and diesel generator for village building in Algeria. The authors consider wind speed and solar radiation measurements in the design of the hybrid system. In addition to the Hybrid Optimization of Multiple Energy Resources (HOMER). a software has been used to obtain the components sizing of the proposed hybrid system. A detailed comparison has been done between the standalone and the utility connected hybrid systems.

In reference to [5] Q. Jawad, K. Gasem, and M.Jawad the ability to build hybrid systems to generate the power for urban areas is studied. Also, the authors show these systems may contain some distributed generation sources such as; WT, PV, and diesel generator. The different combinations have been presented using the above mentioned power sources. Finally, the authors execute a detailed comparison between these combinations to decide what the effective hybrid system is.

H. Farghally, F. Fahmy, and M. Elsayed, [6], study the loads of emergency hospitals, home buildings, and schools. Then, the authors plan a standalone hybrid system consisting of PV-WT for supplying electricity to the above mentioned loads. Therefore, the objective function of the hybrid system is defined, where it is the total annual cost of the system. The target is to minimize this function considering the constraints of the load balance, and the system reliability. The authors apply the HOMER software to find the design of the WT-PV, the number of wind turbine, and the solar panels.

In reference to [7] P. Gajbhiye and P. Suhane the power demand and the weather conditions of a certain area are studied. The authors assume that, the most proper hybrid power system contains both the WT and PV. Also, the authors decide that it is important to add a diesel generator and SB system as a backup system to improve the system reliability and to decrease the system failure potential. So, the authors develop the final hybrid system objective function, which includes the initial cost, operation and maintenance cost, and the fuel cost.

In reference to H. Belmili, M. Haddadi, S. Bacha, and M.Almi [8] the fundamentals of the hybrid power generation, where the techno-economic considerations of a standalone hybrid system are studied. The authors define the components of the hybrid system, the objective function, and the system constraints.

In reference to [9], A. Eltamaly and M. Mohamed the wind speed is collected and the solar irradiance of a certain area to design a hybrid power system. The authors study daily and monthly loads of the researched area. A marketing survey is executed in order to decide which solution is appropriate for this area. Based on the above, the authors claim that, the most proper solution is the hybrid system, where they take this decision based on a study in economics. The study is based on cost function and itshould be minimized to determine the lowest annual cash flow. Finally, the HOMER software is applied to solve the cost function and to get the components of the hybrid system.

A. Maleki and A. Askarzadeh, [10], aim to build a hybrid power system to deliver the power for an urban area, where it is defined that, this system consists of WT, PV, and FC. Then, the authors define the cost function and all esstential constraints should be considered. The bee swarm optimization technique has been applied to solve the objective function considering the reliability index as a system constraint.

In reference to [11], O. H. Mohammed, Y. Amirat, M. Benbouzid, and A. Elbaset a standalone hybrid power system is introduced which consists of PV and FC to supply the power to Brest city, in France. The authors show that, it is not important to include the battery system, where the absence of the battery system decreases the total annual cost. The HOMER software is applied to simulate the PV-FC hybrid system and to obtain the system design.

M. Alam, [12], introduces a combination of different power sources such as wind turbine and fuel cell for a residential load. The author studies the feasibility of this system, where the objective function of the system is built, and the target is to minimize this function in order to obtain the optimal size of WT-FC hybrid system. Therefore, both of the fuzzy logic and the HOMER software have been used in order to solve the WT-FC objective function.

B. Tudu, K. Mandai, and N. Chakraborty, [13] designed a standalone hybrid system, which consists of micro hydro turbine, PV, WT and fuel cell (FC) to supply the power for a certain load. The net present value is considered the objective function for this system, and the authors aim to maximize the utilization of the renewable energy and to minimize the system pollution. Both of bee algorithm and particle swarm algorithm are used to solve the above mentioned objective function. It is claimed that, the applied algorithms are capable of giving the optimal solutions. But it is recorded that, the particle swarm optimization is faster than the bee algorithm in reaching best solution, and the searching time of particle swarm optimization is shorter than the searching time of the bee algorithm.

For the last three decades, the Egyptian government have started in supplying the natural gas to the people to save the importing of the liquefied petroleum gas (LPG). Natural gas (NG) has been supplied for all people as much as possible, even in urban areas. The NG constructions are divided into some phases; discovering, compressing, transmission, and distribution. The distribution phase consists of all equipment which facilitate the NG supplying to the different loads. The used equipment is summarized as; main pressure reduction stations (PRSs), medium pressure distribution networks (MPDNs), distributed reduction units (DRUs), and low pressure distribution networks. The MPDN of an urban has been used to supply the natural gas for the GT of the HPGS.

This paper presents a new configuration of HPGS, where it consists of WT, PV, SB, and the natural gas distribution network, where this network feeds the GT with the natural gas as a fuel. This combination is connected to the utility grid, and the final configuration is WT, PV, SB, natural gas distribution, and utility grid. This configuration is studied at two different scenarios; winter and summer conditions to consider all conditions of the wind speed, solar irradiance, natural gas heating loads, electrical loads. Many meta-heuristic optimization techniques have been applied to solve the multi-objective function of the WT-PV-SB-GT-utility grid HPGS. These techniques are CSA, FA, and FPA. A detailed comparison between the results of the three applied optimization techniques is presented to show and recommend the most appropriate technique for sizing the HPGS components.

2 Operational conditions of the natural gas distribution network

This paper introduces a new configuration of the hybrid power system, which consists of WT, PV, SB, and GT. Moreover, it is connected to the utility grid. The GT of this system is fueled directly from the natural gas distribution network. So, it is necessary to consider all operational factors, which have the influence on the HPGS design. Mainly, there are two important factors which should be included in this design such as; the maximum allowable limit of the flow velocity on the network pipes and the minimum allowable limit of the input pressure of the distributed pressure regulator unit (DPRU). If the flow velocity exceeds 20 m/s, the dust particles or debris will move, which consequently had the bad influence on the cooking devices, pressure regulators, and it may cause erosion to the internal surface of the pipeline [14, 15]. The capacity (Q) of this section might be designed as follows:

$$Q = 7.574 \times T_s \times P_b^{-1} \times f^{-0.5} \times \left\{ \begin{matrix} \left(P_1^2 - P_2^2\right) \times d_{Pline}{}^5 \times \\ \left(S_{NG} \times Z \times T_{NG} \times L_{Pline}\right)^{-1} \end{matrix} \right\}^{0.5} \times 10^{-4} \quad (1)$$

Equation 2 describes the flow velocity (U) in m/sec.

$$U = \frac{353QP_b}{d^2 \left[P_1^2 - \frac{3730 fLQ^2}{d^5} \right] 0.5} \quad (2)$$

Fig. 1 shows a section from the MPDN of the studied area. The green network describes the loads network, and the purple line shows the medium pressure natural gas pipeline, which is considered the main source of the natural gas for the loads through the two pressure regulators. Point 1 shows the inlet point (the source) of the medium pressure line, while point 2 shows the inlet pressure of (DPRUs).

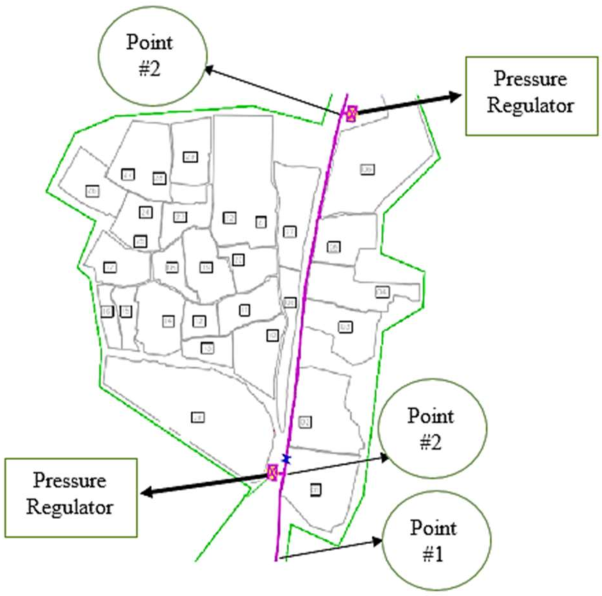

Figure 1. The medium-pressure natural gas network of the urban area

Equation 3 shows the relationship between the regulator input pressure and the regulator capacity (Q_R).

$$Q_R = K_G \times \sqrt{P_{out}\left(P_2 - P_{out}\right)} \quad (3)$$

The minimum input pressure (P_2) for the regulator is 1.34 absolute pressure (bar) according to Equation 3, if the required load from the pressure regulator is 1000 m^3/hr at output pressure of 0.1 (bar) or 1.113 absolute pressure (bar), and the sizing coefficient (K_G) is 2000. As known, the velocity (U_{NG}) of gas flow should not be more than 20 m/sec. So, the maximum capacity of the pipeline could be obtained by solving Equation 4 at input pressure (P_1) is 5.013 absolute pressure (bar) and the minimum input pressure (P_2) is 1.34 bar. It is found that, the maximum capacity (Q_{max}) of the natural gas pipeline may reach to 7132 m^3/hr [16].

3 Problem formulation

Fig. 2 shows the utility-connected to HPGS, which consists of WT, PV, SB, GT, and utility grid. The main objective functions of this system are the total annual cost (TAC) and the system pollution (SP) [1 and 2].
Equation 3 shows that the multi-objective function should be minimized.

$$f = \min(TAC, SP) \quad (4)$$

The weighted sum method has been applied to convert the multi-objective function to a single objective function.

$$f = \min(w_1 \times TAC + w_2 \times SP) \quad (5)$$

Where w_1 and w_2 represent the weight factors.

$$w_1 + w_2 = 1 \quad (6)$$

Equation 7 shows the first objective function, which represents the TAC.

$$TAC = \frac{\sum_i \left(I_i + OM_{P_i} - S_{P_i}\right)}{N_P} + AFC_{NG} + APC_{UG} \quad (7)$$

3.1 TAC Calculations

A. TAC of the wind turbine (WT)

Equation 8 shows the initial cost of the wind turbine, Equation 9 shows the operation and maintenance cost, and Equation 10 show the salvage value of the wind turbine [3].

$$I_w = \alpha_w A_w \tag{8}$$

$$OM_{P_w} = \alpha_{OM_w} A_w \sum_{i=i}^{N_P} \left(\frac{1+v}{1+\gamma} \right)^i \tag{9}$$

$$S_{P_w} = S_w A_w \left(\frac{1+\beta}{1+\gamma} \right)^{N_P} \tag{10}$$

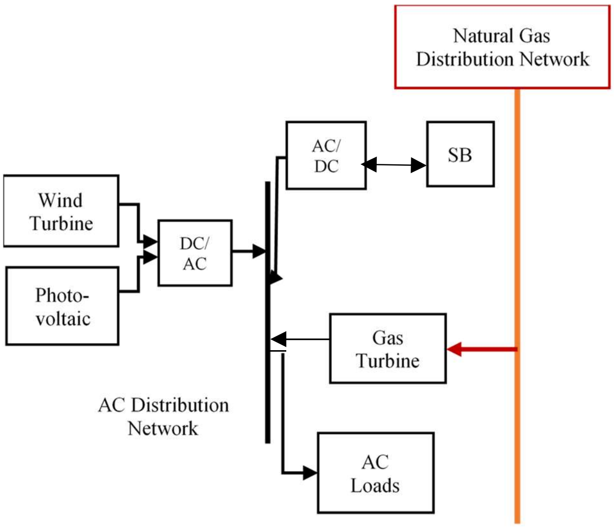

Figure 2. Configuration of a utility connected HPGS

B. TAC of the photovoltaic system (PV)

The total annual cost of the PV system likes the total annual cost of the wind turbine, where Equations 11, 12, and 13 show the initial cost, the operation and maintenance cost, the salvage value respectively [3 and 4].

$$I_{PV} = \alpha_{PV} A_{PV} \tag{11}$$

$$OM_{P_w} = \alpha_{OM_{PV}} A_{PV} \sum_{i=i}^{N_P} \left(\frac{1+v}{1+\gamma} \right)^i \tag{12}$$

$$S_{P_{PV}} = S_{PV} A_{PV} \left(\frac{1+\beta}{1+\gamma} \right)^{N_P} \tag{13}$$

C. TAC of the storage battery system (SB)

This power source has only the initial cost and the operation and maintenance cost, and there is no salvage value, because the aged batteries should be disposed according to the environment regulations. Equation 14 shows the initial cost of the SB, and its lifetime (N_{SB}) actually is lower than the project lifetime (N_P). Equation 15 shows the operation and maintenance cost [5].

$$I_{SB} = \alpha_{SB} P_{SB_{cap}} \sum_{i=i}^{X_{SB}} \left(\frac{1+v}{1+\gamma} \right)^{(i-1)N_{SB}} \tag{14}$$

$$OM_{P_{SB}} = \alpha_{OM_{SB}} P_{SB_{cap}} \sum_{i=i}^{N_{SB}} \left(\frac{1+v}{1+\gamma} \right)^{(i-1)N_{SB}} \tag{15}$$

D. TAC of the gas turbine (GT)

This power element has annual initial cost, annual operation and maintenance cost, annual salvage value [4], and annual fuel cost, as shown in Equations 16, 17, 18, and 19 respectively [17].

$$I_{GT} = \alpha_{GT} P_{cap_{GT}} \tag{16}$$

$$S_{P_{GT}} = S_{GT} P_{cap_{GT}} \left(\frac{1+\beta}{1+\gamma} \right)^{N_P} \tag{17}$$

$$OM_{P_{GT}} = \alpha_{OM_{GT}} P_{cap_{GT}} \sum_{i=i}^{N_P} \left(\frac{1+v}{1+\gamma} \right)^i \tag{18}$$

$$APC_{NG} = \sum_{t=i}^{8760} m \times \varphi_{NG} \tag{19}$$

E. TAC of purchased electricity from the utility

Equation 20 describes the total annual cost of the purchased electricity from the utility grid during one year [4].

$$APC_{UG} = \sum_{t=i}^{8760} P_{UG,t} \times \varphi_P \tag{20}$$

3.2 The Annual System Pollution

Equation 21 shows the total annual system pollution

$$SP = a + b \times \sum_{t=i}^{8760} \left(P_{GT,t}(t) + P_{UG,t} \right) + c \times \left(\sum_{t=i}^{8760} \left(P_{GT,t}(t) + P_{UG,t} \right) \right)^2 \quad (21)$$

There are many constraints that should be satisfied throughout system operations for any feasible solution [5].

3.3 Design Constraints

A. Power balance constraint

Equation 22 shows the most important constraint for design of the hybrid power system, where for any period *t*, the total power delivered from the hybrid system should be equal to the total demand $P_d(t)$and the system loss. It is assumed that, $P_d(t)$ includes the system power loss [1-5].

$$P_{WT}(t) + P_{PV}(t) + P_{SB}(t) + P_{GT}(t) + P_{UG,t}(t) = P_d(t) \quad (22)$$

where,

$$P_{w_i}(t) = \begin{cases} 0 & V_t < V_{ci} \\ \frac{1}{2}\rho V_t^3 C_p & V_{ci} \le V_t < V_r \\ P_{WT_r} & V_r \le V_t < V_{CO} \\ 0 & V_{CO} < V_t \end{cases} \quad (23)$$

$$P_{WT}(t) = P_{w_i}(t) \times A_w \times \eta_{wt} \quad (24)$$

$$P_{PV}(t) = H \times A_{PV} \times \eta_{PV} \quad (25)$$

$$P_{GT}(t) = \eta_{overall} \times m \times HHV \quad (26)$$

Each term on the left hand side terms of Equation 22contains the parameter which should be tuned to obtain the best design of the hybrid power system. Where, A_w is swept area of the wind turbine, and it should be tuned to optimize the total annual cost of the WT. $A_{PV}$is swept area of the PV system, and it should be tuned to optimize the total annual cost of the PV. The third one is $P_{SB}(t)$, which has the instantaneous discharging/ charging power of the storage battery.

m is fuel rate of the gas turbine, also it should be tuned to optimize the total annual cost of the GT. Finally, the delivered power from the utility grid is the last parameter that should be tuned to optimize the total annual cost of the purchased electricity from the grid [17].

B. Bounds of Design Variables

$$A_{w_{\min}} \le A_w \le A_{w_{\max}} \quad (27)$$

$$A_{PV_{\min}} \le A_{PV} \le A_{PV_{\max}} \quad (28)$$

As shown in Equation 29, the state of charge (SOC) of storage batteries $P_{SB_{soc}}$ should not exceed the capacity of storage batteries $P_{SB_{soc}}$ and should be lower than the minimum permissible storage level $P_{SB_{\min}}$.

$$P_{SB_{\min}} \le P_{SB_{soc}} \le P_{SB_{cap}} \quad (29)$$

Equation 30 shows that, the total SB capacity should not exceed the allowed storage capacity $P_{SB_{cap\max}}$.

$$0 \le P_{SB_{cap}} \le P_{SB_{cap\max}} \quad (30)$$

Finally, Equation 31 shows that the hourly charge or discharge power P_{SB} should not exceed the hourly inverter capacity $P_{SB\max}$.

$$P_{SB} \le P_{SB_{\max}} \quad (31)$$

Equation 32 shows the bound limits of the cubic meters of the natural gas of the GT, while Equation 33 shows the bound limits of the power delivered from the utility grid.

$$0 < m < m_{\max} \quad (32)$$

$$P_{UG,t_{\min}} < P_{UG,t} < P_{UG,t_{\max}} \quad (33)$$

4 Application to a case study

Both of the electric and natural gas loads are measure daily and monthly. Also, the wind speed and the solar irradiance have been measured, and it is found that there are two scenarios; one for the winter and the other for the summer [1]. Table 1 shows the average power load in (kW), the natural gas load in (m^3/hr), the wind speed (in m/sec), and the solar irradiance in (W/m^2) for the scenarios of the studied area.

Table 1 - Input data

System parameters	Sc. I	Sc. II
Power demand (kW)	1750	2250
NG demand (m^3/hr)	1700	1300
Wind speed (m/s)	5.3	4.87
Solar irradiance (kW/m^2)	0.1005	0.1728

While, Table 2 shows the required data for the design. It is assumed w_1=w_2=0.5.

As mentioned previously, CSA, FFA, and FPA are applied to optimize the multi-objective function of the proposed hybrid power system [18-20].

Table 2 - The used system parameters

System parameters	Values	Unit
P_b	1.013	bar
d	200	mm
f	0.135	-
P_1	5.013	bar
L	1000	m
T_S	288	K
S	0.6	kg/m^3
Z	0.99	-
T	278	K
φ_{NG}	0.08	\$/m^3
(U)	20	m/sec
P_2	1.34	bar
m	7131	m^3/hr
C_P	0.56	-
P_{WT_r}	2000	kW
η_{WT}	0.5	-
$a\ A_{w_{\min}}$	10000	m^2
$A_{w_{\max}}$	100000	m^2
α_{WT}	150	\$/ m^2
$\alpha_{0M_{WT}}$	25	\$/ m^2
S_{WT}	4.5	\$/ m^2
η_{PV}	0.16	-
α_{PV}	550	\$/ m^2
S_{PV}	10	\$/ m^2
$\alpha_{0M_{PV}}$	3.25	\$/ m^2
$A_{PV_{\max}}$	10000	m^2
$A_{PV_{\min}}$	100000	m^2
α_{SB}	200	\$/kW
$\alpha_{0M_{SB}}$	40	\$/kW
SB system lifetime	10	year
η_{SB}	0.82	-
$P_{SB_{cap.\max}}$	250	kW
$P_{SB_{cap.\min}}$	750	kW
α_{GT}	50	\$/ m^2
$\alpha_{0M_{GT}}$	12.5	\$/ m^2
S_{GT}	8.5	\$/ m^2
η_{GT}	0.41	-
HHV	37.2	MJ/m^3
$P_{GT_{cap.\max}}$	300	kW
$P_{GT_{cap.\min}}$	2000	kW
$k_{1.GT}$	2.25	-
$k_{2.GT}$	-6.5	-
$k_{3.GT}$	4.2	-
$P_{UG_{\max}}$	250	kW
$P_{UG_{\min}}$	1000	kW
a	4.09	-
b	-5.5	-
c	6.5	-
φ_{ele}	0.04	\$/kW
β	0.09	
γ	0.12	
v	0.12	
N_P	20	year

5 Simulation results

As mentioned above, this paper presents a new contribution on design of the HPGS, where the natural gas distribution network (in medium pressure level) has been included for the first time in the field. The GT is directly connected to the natural gas distribution network taking in account all its operational considerations to avoid any unexpected trouble or failure. CSA, FA and FPA have been applied to obtain the components sizing of the HPGS. The obtained results from the three above mentioned optimization techniques are compared in order to decide which technique is the most appropriate for designing these systems.

A. For the scenario I (winter scenario)

As known in the above section, this scenario represents the winter conditions, and the results of applying the same techniques as summarized in

Table 3. This table shows the results of the above mention variables (A_w, A_{PV}, $P_{SB.cap}$, $P_{GT.cap}$, and $P_{UG.t}$). Also, the consequent parameters have been calculated and represented such as; the consumed amount of the natural gas for the gas turbine (m), and the flow velocity (U) of the natural gas distribution network due to the gas turbine consumption. As well as, the effect of the gas turbine consumed amount on the input pressure (P_2) of the gas regulator that has been shown. The FPA shows the lowest values of the TAC function, which is 1.5×10^6 \$/year. With respect to the SP values of the WT-PV-SB-GT-UG hybrid power system in the winter conditions (scenario-I), it is noted that, the superiority is here for the cuckoo search algorithm (CSA), which gives value of 4.42×10^{13} ton of CO_2/year. This value is the lowest value of the emission of this system.
The natural gas consumptions are 109, 31, 42, and 88 m^3/hr due to the GT using FPA, FFA, and CSA respectively. Consequently, the natural gas flow velocity increased from 10.98 m/sec to 11.36 m/sec as in FPA, or it increased to 11.09 m/sec using FFA. This velocity increased to 11.28 m/sec using the CSA. The influence of this consumption on the input pressure of the gas regulator is also shown in the above table, where this pressure reduced from 3.64 bar to 3.53, 3.61, and 3.55 bar using the FPA, FFA, and CSA individually. In order to decide which technique gives the optimal design of the hybrid power system, the multi-objective function should be determined and it is found that, the CSA gives the lowest value for function.

Table 3. The results of Design of the WT-PV-SB-GT-UGhybrid power generation system at Scenario-I

Variable	FPA	FFA	CSA
A_w	25101	25758	22373
A_{PV}	12968	22085	20000
$P_{SB.cap}$	923	500	689
$P_{GT.cap}$	1446	342	2000
$P_{UG.t}$	204	333	205
$P_{GT.t}$	463	130	372
m	109	31	88
m_{tot}	1809	1731	1788
U	11.36	11.09	11.29
P_2	3.53	3.61	3.55
TAC	1500×10^3	1800×10^3	1640×10^3
SP	56900 $\times10^9$	58200 $\times10^9$	44200 $\times10^9$

B. For the scenario II (summer scenario)

This section discusses the design of the WT-PV-SB-GT-UG at the summer conditions (Scenario-II), where Table 4 describes in full the results of the variables and the multi-objective function. The CSA gives the lowest value of the TAC, which is 2.7×10^6 \$/year. Also, it is easy to notice that, CSA gives the lowest value for this function, where it gives value of 1.12×10^{14} ton of CO_2/year. The natural gas consumptions due to the GT is 91, 128, 108, and 155 m^3/hr using FPA, FFA, and CSA respectively. Consequently, the natural gas flow velocity increased from 8.68 m/sec to 9.16 m/sec as in FPA, or it increased to 9.35 m/sec using FFA.

Table 4. The results of design of the WT-PV-SB-GT-UG Hybrid power generation system at scenario-II

Variable	FPA	FFA	CSA
A_w	42606	38223	41253
A_{PV}	30780	34308	30400
$P_{SB.cap}$	840	834	934
$P_{GT.cap}$	848	918	1050
$P_{UG.t}$	491	380	281
$P_{GT.t}$	386	543	657
m	91	128	155
m_{tot}	1291	1328	1355
U	9.16	9.35	9.49
P_2 after GT	4.01	3.98	3.96
TAC	2780 $\times10^3$	2750 $\times10^3$	2700 $\times10^3$
SP	14600 $\times10^{10}$	122 $\times10^{10}$	12200 $\times10^{10}$

This velocity increased to 9.49 m/sec using the CSA. The influence of this consumption on the input pressure of the gas regulator is also shown in the above table, where this pressure reduced from 4.09 bar to 4.01, 3.98, 4, and 3.96 bar using the FP, FFA, and CSA individually. To decide which technique gives the optimal design of the hybrid power system, the multi-objective function should be determined and it is found that, the CSA gives the lowest value for function.

6 Conclusion

This paper presents a new contribution in the field of designing the HPGS, where the natural gas distribution network is included for the first time as a partner in the HPGS. The natural gas distribution network is involved in the HPGS to supply the fuel (natural gas) to the gas turbine. All operational conditions of the natural gas distribution network are studied and the most important parameters of this network are defined. They include pressure drop and flow velocity. The allowable flow rate of the natural gas distribution network is calculated without exceeding the allowable limits of the pressure drop and velocity flow. Only the utility connected mode is discussed in two different scenarios; winter and summer scenarios. Multi-objective functions have been design to sizing the HPGS, and these functions are the TAC and SP. TAC consists of the initial cost, operation and maintenance cost, salvage value, the annual fuel (natural gas) cost, and the annual purchasing electricity from the utility grid, while, SP presents the total annual emission (ton/year). All power system constraints and parameters are considered in the optimization process. The most modern meta-heuristic optimization techniques are used to find the sizing of the HPGS. CSA, FA and FPA have been used to optimize the multi-criteria design of the HPGS, where these techniques are used for the first time in designing the HPGS. Therefore, the contributions of this paper areincluding the natural gas facility as an element of the HPGS and applying new meta-heuristic optimization techniques in the design of the HPGS. All obtained results have been compared, and it is found that, the CSA gives more efficient results than FFA and FPA, where the multi-objective results of the CSA are lower than the results of the other two techniques.

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Appendix A: symbols and abbreviation

List of symbols

Symbol	Meaning
Q	the instantaneous flow of the natural gas
P_b	the absolute pressure at datum conditions (bar) (atmospheric conditions)
d	the internal diameter of the pipe (mm)
f	the friction factor, and it is in the range of (0.009 to 0.015) for corrugated Polyethylene (PE) pipes with smooth inner walls
P_1	the absolute upstream (inlet) pressure (bar)
L	The length of the pipe over which the velocity is being measured (m).
P_b	Absolute pressure
Q_R	the regulator capacity
K_G	the sizing coefficient.
i	indicates the WT, PV, SB, and GT
I_i	the initial cost of each power source (WT, PV, SB, and GT).
OM_{P_i}	the operation and maintenance cost for each power source (WT, PV, SB, and GT).
S_{P_i}	the salvage value of each power source (WT, PV, and GT).
N_P	the project lifetime.
AFC_{NG}	the annual fuel (natural gas) cost.
APC_{UG}	the cost of the annual purchasing electricity.
α_w	the initial cost of wind turbine ($/m^2)
A_w	the swept area of the wind turbine (m^2)
α_{0M_w}	the operation and maintenance cost of wind turbine system ($/m^2)
v	the escalation factor
S_w	the salvage value of wind turbine ($/m^2)
β	the inflation rate
γ	the interest rate
α_{PV}	the initial cost of PV system ($/m^2)
A_{PV}	the swept area of the PV system (m^2)
$\alpha_{0M_{PV}}$	the operation and maintenance cost of PV system ($/m^2)
S_{PV}	the salvage value of PV system ($/m^2)
α_{SB}	is the initial cost of storage battery system ($/kW)
P_{SB}	the storage battery capacity (kW)
N_{SB}	the storage battery lifetime
X_{SB}	the number of times to purchase the batteries during
N_P	the project lifespan
$\alpha_{0M_{SB}}$	the operation and maintenance cost of storage battery system ($/kW)
α_{GT}	the initial cost of gas turbine ($/kW)

$P_{cap_{GT}}$	the gas turbine capacity (kW)
S_{GT}	the salvage value of gas turbine ($/kW)
$\alpha_{0M_{GT}}$	the operation and maintenance cost of gas turbine system ($/kW)
m	fuel rate of the GT from the natural gas in m^3/hr
φ_{NG}	the price of the cubic meter of the natural gas
$P_{UG,t}$	is the power delivered from the utility grid at an instant kW
φ_P	is the power delivered from the utility grid price $/kW
a, b and c	the coefficients approximating the generator emission characteristics.
V_t	the wind speed (m/sec)
V_{ci}	the wind turbine cut-in speed (m/sec)
V_r	the wind turbine rated speed (m/sec)
V_{co}	the wind turbine cut-off speed (m/sec)
$P_{WT,r}$	the rated power of the wind turbine (kW)
C_p	the power coefficient of the WT
$\eta_{overall}$	the gas turbine and the alternator overall efficiency,
m	fuel rate in m^3/hr
HHV	the high heat value in mega-joule per cubic meter MJ/m^3

List of abbreviations

Abbreviation	Meaning
WT	Wind turbine
PV	Photovoltaic
SB	Storage battery
GT	Gas Turbine
UG	Utility grid
HPGSs	Hybrid power generation systems
CSA	Cuckoo search algorithm
FA	Firefly algorithm
FPA	Flower pollination algorithm
ICA	imperialist competitive algorithm
PSO	particle swarm optimization
ACO	ant colony optimization
HOMER	Hybrid optimization of multiple energy resources
FC	fuel cell
NG	Natural gas
PRSs	pressure reduction stations
MPDNs	medium pressure distribution networks
DRUs	distributed reduction units
TAC	total annual cost
SP	system pollution