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OPTIMAL ALLOCATION AND DESIGN OF GRID CONNECTED HYBRID DISTRIBUTED GENERATION SYSTEMS

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ABSTRACT

This paper presents an artificial bee colony (ABC) based algorithm to optimally allocate, design and schedule hybrid photovoltaic-diesel distributed generation in distribution systems. The objective of the proposed algorithm is to minimize the overall investment, replacement and operation and maintenance costs of each component of the hybrid photovoltaic-diesel systems (HPVDS). The algorithm considers also the minimization of the distribution system power loss, the amount of un-served load and the imported power from the transmission grid. Meanwhile, the algorithm aims to maximize the excess generated power by the HPVDS that may be injected into the distribution network. These objectives are to be achieved while satisfying the operational constraints of the system. The proposed algorithm is applied to two test systems to validate its effectiveness.

وتستعرض هذه الورقة خوارزم يعتمد على مستعمرة النحل الاصطناعي (ABC) لتحديد المكان و التصميم الامثل وجدولة وحدات التوليد الهجين من الديزل و وحدات الطاقة الشمسية الموزعة في نظم التوزيع. والهدف من هذا الخوارزم المقترح هو الحد من الاستثمار الكلي فى هذه الوحدات ، وتكاليف استبدال و تشغيل وصيانة كل عنصر من عناصرها. الخوارزم يهدف أيضا الى تقليل فقدان القدرة الكهربية فى نظام التوزيع، وتقليل مقدار الاحمال المفصولة ومقدار القدرة المستوردة من شبكة النقل. وفي الوقت نفسه، يهدف الخوارزم إلى تعظيم فائض الطاقة التي تولدها HPVDS التي يمكن حقنها في شبكة التوزيع. و يراعى فى تحقيق هذه الأهداف أن تلبي القيود التشغيلية للنظام. يتم تطبيق الخوارزم المقترح على نظامى اختبار للتحقق من صحة فعاليته.

Keywords: Hybrid photovoltaic-diesel systems (HPVDS), Artificial bee colony (ABC), Distributed generation (DG), Load shedding

LIST OF SYMBOLS

x_i the position of the ith onlooker bee
t the iteration number
θ_i the position of the ith employed bee which is selected by roulette wheel
θ_k the position of a randomly selected employed bee
u a random variable in the range of [-1 , 1] or [0 , 1] as used in this paper
S the number of employed bees
D the number of parameters to be optimized
MCN the maximum number of iterations of the search process
r random number in the range of [0 , 1]
θ_{ij}^{min}, θ_{ij}^{max} the minimum and maximum limits of the ith parameter
A, B the fuel curve coefficients
P_{Ngen} the diesel generator rated capacity
Pr_{fuel} the fuel price
$C_{O\&Mgen}$ the diesel generator's hourly operation and maintenance cost
$C_{rep\ gen\ h}$ the diesel hourly replacement cost
$C_{cycling\_bat}$ the cost of cycling energy through the batteries
C_{PV} the PV panels cost
$C_{PV\text{-}inv}$ the investment cost of PV panels
$C_{PV\text{-}rep}$ the replacement cost of PV panels
$C_{PV\text{-}O\&M}$ the operation and maintenance cost of PV panels
C_{ds} the diesel generators cost
$C_{ds\text{-}inv}$ the investment cost of diesel generators
$C_{ds\text{-}rep}$ the replacement cost of diesel generators
$C_{ds\text{-}O\&M}$ the operation and maintenance cost of diesel generators
C_b the batteries banks cost
$C_{b\text{-}inv}$ the investment cost of batteries banks
$C_{b\text{-}rep}$ the replacement cost of batteries banks
$C_{b\text{-}ch}$ the energy cost for charging the batteries banks
$C_{b\text{-}dis}$ the energy cost for the discharge of the batteries banks
C_{sh} the cost of energy not served
C_{loss} the cost of energy loss of the distribution network

C_{slack} the cost of energy imported from the transmission grid
C_{ex} the cost of excess energy of HPVDS injected to the distribution network
P_{PV} the power generated by photovoltaic panels
P_{ds} the power generated by diesel generators
$P_{b\text{-}dis}$ the batteries banks power discharge
$P_{b\text{-}ch}$ the batteries banks power charge
P_{sh} the un-served (shed) power
P_{slack} the imported power from the transmission grid
P_{loss} the active power loss of the distribution network
P_D the load (demand) power
P_{PV}^{max} the PV maximum generation capacity
P_{ds}^{max}, P_{ds}^{min} the diesel maximum and minimum generation capacity, respectively
P_S the batteries banks power state
P_S^{max}, P_S^{min} the maximum and minimum batteries banks capacity limits, respectively
P_{HDG} the hybrid distributed generation capacity
P_D^{max} the maximum load power
P_{slack}^{max} the maximum limit of the slack bus power
V_i the voltage magnitude at the i^{th} bus
V_i^{max}, V_i^{min} the maximum and minimum limits of bus voltage magnitude
nbus the number of system's buses
S_{ij} the power capacity in the distribution line between bus i and bus j
S_{ij}^{max} the maximum power capacity of the distribution line between bus i and bus j

1. INTRODUCTION

Distributed generation (DG) has been considered as an important alternative to centralized energy resources. As the penetration of DG systems into distribution and transmission networks increase, they are more likely to be grid connected. These DG systems are located in close proximity to energy users. To grid, the loads supplied by DGs can be considered as magnitude controlled loads. Such controllable loads may be constant, increase during night and off-peak hours, when the electricity is cheaper, and be held to zero consumption during times of system stress. The DGs and their loads can operate as grid connected or in a stand-alone (islanded) mode [1,2]. Therefore, these systems are to be rated and designed as if they are to operate in stand-alone mode.

The interest in DGs increases because it can provide reliable, secure, efficient and sustainable electricity from renewable energy resources [3]. The deregulated energy environment has encouraged the usage of DG sources near the energy consumers. These sources comprise many technologies such as diesel engines, wind turbines, photovoltaic, microturbines, hydroturbines, etc. [1]. Hybrid energy systems are recognized as a viable alternative to grid supply or conventional fuel-based power supplies [4]. Optimal design of various combinations of these technologies have been studied in stand-alone and/or grid connected modes [1-11]. Optimal placement of DG units was also presented by many researchers. The optimization problem was solved using either analytical or evolutionary computational methods [12-17]. However, up till now, these two problems of siting the hybrid DG systems and designing (sizing) them have been separately solved.

This paper deals with both siting and sizing of HPVDS in distribution networks which will operate in a grid connected mode. The two problems are formulated as one optimization problem which is solved using artificial bee colony (ABC) algorithm. The main idea of this paper is that, while sizing the hybrid DG systems, these systems are designed as if the will operate in stand-alone mode although they are grid connected. The systems are designed such that they totally support their local loads with no need to take any power from the distribution network. That is why each system located in the network is designed to include storage batteries.

Recently, many blackout incidences in many cities around the world such as the ones occurred in Newdelhi , India and Cairo, Egypt were because of the overloading and tripping of one or more of the lines connecting the distribution network of the cities to the transmission grids. Therefore, the power taken by the distribution network from the transmission network must be limited. In this paper, the HPVDS are assumed to be grid connected just to support the distribution network by supplying it with their extra PV power. This support will reduce the purchased power from the main transmission grid (reduce the carrying capacity of up stream feeders) and reduce the amount of un-served (shed) loads during heavy loading hours. The distribution network is assumed to be connected to the transmission network through the slack bus. Therefore, in addition to including the slack bus power in the objective function to be minimized, the slack bus power is limited to certain percentage of the total demand of the distribution network.

The proposed algorithm is applied to two test systems to validate its ability to solve the problem. The two systems are the radial 33-bus test system and the Egyptian meshed 45-bus system of Alexandria.

2. ARTIFICIAL BEE COLONY OPTIMIZATION ALGORITHM

The ABC optimization technique belongs to the group of swarm intelligence techniques. It was introduced in 2005 by Karaboga [18]. The performance of the ABC algorithm was compared with those of some well-known population based optimization algorithms such as GA and PSO. The results and the quality of the solutions matched or improved over those obtained by other methods [19]. The ABC algorithm is developed by simulating the behaviors of the real bees on finding food source, which is called the nectar, and sharing the information of food sources to the bees in the hive. The colony of artificial bees consists of three groups of bees which are the employed bees, the onlooker bees and the scout bees. Each of them plays different role in the process by flying around in a multi-dimensional search space representing the solution space. The employed bees randomly search for food source positions (solutions) and provide the neighborhood of the source in their memory. The onlooker bees get the information of food sources form the employed bees in the hive. Each onlooker bee selects one of the food sources exploited by the employed bees according to the quality of that food source. That means that good food source positions attract more bees. This phase of solution mimics the behavior of PSO in which each particle in the swarm uses the experiences and positions exploited by other particles. The last phase of ABC algorithm is the scout phase. The scouts control the exploration process where the scout bee is responsible for finding new food sources according to the foraging behavior of the honey bee. This phase of the algorithm mimics the mutation process of GA [19-21].

The ABC algorithm proceeds by setting one half of the colony size to be employed bees and the other half to be onlooker bees. Each cycle of the ABC algorithm consists of three steps [20,21]:

Spray the employed bees into the solution space (food sources) and calculate their fitness values (nectar amounts).

Move the onlooker bees by selecting a food source to move to using a selection method such as roulette wheel selection. The move of onlooker bees follows (1) [21].

$$x_{ij}(t+1) = \theta_{ij}(t) + u * (\theta_{ij}(t) - \theta_{kj}(t)) \tag{1}$$

i = 1 , 2 , …….. , S

k = 1 , 2 , …….. , S $\quad k \neq i$

j = 1 , 2 , …….. , D

t = 1 , 2 , …….. , MCN

where j is the dimension of the solution.

Move the scout when the fitness of the employed bee does not improve for a number of iterations called Limit. When the food source position has been abandoned, the employed bee associated with it becomes a scout. The scout then produces a completely random new food source position according to (2) [21].

$$\theta_{ij} = \theta_{ij}^{\min} + r * (\theta_{ij}^{\max} - \theta_{ij}^{\min}) \tag{2}$$

The three steps are repeated for a number of cycles (iterations) equal to MCN. The best fitness value and position are memorized each cycle to determine the global best solution at the end of iterations.

3. PROBLEM FORMULATION

The optimal siting and sizing of HPVDS in distribution networks is formulated as an optimization problem. The objective is to find the optimal locations of HPVDS out of a certain number of candidate locations in the distribution network. At each location, the optimal sizing and scheduling of each component of the HPVDS are determined. The main objective is to find the minimal overall cost function of the system. This function consists of several terms to be minimized along with other terms to be maximized for which they are introduced with a negative sign. The costs to be minimized are the investment, replacement and operation and maintenance (O&M) costs of each component of the HPVDS. It is also required to minimize the active power loss in the distribution network, the power purchased from the main transmission network and the un-served (shed) power in the distribution network. In addition, it required to increase the amount of HPVDS power injected to the distribution network.

The simulation span in this paper is one day (24 hours) which can be extended to a month, year or several years.

3.1 Operation Strategy

Each HPVDS is composed of PV energy source, diesel generator and batteries. As mentioned before, the HPVDS are designed as stand-alone systems which take no power from the distribution network to supply their local loads. Meanwhile, these systems are grid-connected to supply the distribution network with their extra (surplus) PV power. The relation between the HPVDS and the distribution network will formulate the operation strategy and hence the generation schedule of the HPVDS components. The operation strategy will be as follows:

a) In the presence of PV power:

- If the PV power is greater than the local load and the batteries are not fully charged, the remaining PV power will first be used to charge the batteries. When the batteries are fully charged and there is still extra PV power remaining, this power is supplied to the distribution network.
- If the PV power is lower than the local load and the batteries can meet the remaining load, the PV power will be used to partially supply the load and the remaining load will be supplied either by the batteries or the diesel generator according to "Frugal" option [4].

b) In the absence of the PV power:

- If the batteries cannot meet the local load, the load will be supplied by the diesel generator.
- If the batteries can meet the local load, then the "Frugal" option is applied again to determine if the load will be supplied by the batteries or by the diesel generator.
- According to "Frugal" option [4], the diesel generator meets the net load whenever the net load is above the critical discharge load (Ld), regardless of whether or not the battery bank is capable of meeting the net load. The critical discharge load is the net load above which the marginal cost of generating energy with the diesel generator is less than the cost of drawing energy out of the batteries [4].

$$L_d = \frac{(B * P_{Ngen} * Pr_{fuel} + C_{O\&Mgen} + C_{repgen_h})}{C_{cycling\_bat} - A * Pr_{fuel}} \quad (3)$$

This strategy is very similar to the load following strategy [4] except for the grid connection part. According to the proposed strategy, the batteries will only be charged whenever the PV power exceeds the power required by the local load and never be charged by the diesel generator. Also, the diesel generator will operate at a rate that produces only enough power to meet the net load that is not supplied by PV and it will not exchange power with the distribution network.

3.2 Objective Function

The objective is to minimize the following function,

$$\min f = C_{PV} + C_{ds} + C_b + C_{sh} + C_{loss} + C_{slack} - C_{ex} \quad (4)$$

Where

$$C_{PV} = C_{PV\_inv} + C_{PV\_rep} + C_{PV\_O\&M} \quad (5)$$

$$C_{ds} = C_{ds\_inv} + C_{ds\_rep} + C_{ds\_O\&M} \quad (6)$$

$$C_b = C_{b\_inv} + C_{b\_rep} + C_{b\_dis} - C_{b\_ch} \quad (7)$$

3.3 Operational Constraints

- ***Power balance constraint:***
  At any time interval ***t***, the total power generation should be equal to the total system power demand in addition to the distribution network power losses as follows.

$$P_{PV}(t) + P_{ds}(t) + P_{b\_dis}(t) + P_{sh}(t) + P_{slack}(t) - P_{b\_ch}(t) - P_{loss}(t) - P_D(t) = 0 \quad (8)$$

- ***PV power generation limits:***
  The PV is assumed to produce electricity in proportional to the capacity limit of the installed system and the amount of the solar irradiation.

$$0 \le P_{PV}(t) \le P_{PV}^{max} \quad (9)$$

- ***Diesel generator output power limits:***
  The diesel generator may be operating at a time ***t*** or it may be shut down. When it is operating, its output power is limited by a minimum and a maximum value.

$$P_{ds}^{min} \le P_{ds}(t) \le P_{ds}^{max} \quad (10)$$

- ***Storage batteries constraints:***
  The storage batteries have the same characteristics. Therefore, the batteries bank is considered as one battery having the following technical constraints:

i. Storage capacity limits:

$$P_S^{min} \le P_S(t) \le P_S^{max} \quad (11)$$

ii. Maximum power discharge limits:

$$P_{b\_dis}(t) \le P_S(t-1) - P_S^{min} \quad (12)$$

iii. Maximum power charge limits:

$$P_{b\_ch}(t) \le P_S^{max} - P_S(t-1) \quad (13)$$

iv. Power balance state:

$$P_S(t) = P_S(t-1) - P_{b\_dis}(t) * X(t) + P_{b\_ch}(t) * Y(t) \quad (14)$$

Where

$$X(t) = \begin{cases} 1 & \text{if the batteries are discharging} \\ 0 & \text{if the batteries are not discharging} \end{cases}$$

$$Y(t) = \begin{cases} 1 & \text{if the batteries are charging} \\ 0 & \text{if the batteries are not charging} \end{cases}$$

v. The batteries cannot charge and discharge power at the same time interval. That can be formulated as the following constraint.

$$X(t) + Y(t) \le 1 \quad (15)$$

- ***The penetration level of HPVDS:***

$$P_{HDG} \le 30\% * P_D^{max} \quad (16)$$

- ***Slack power limits:***
  In this paper, the maximum value of the power imported from the transmission grid to the distribution network through the slack bus is

limited to 30% of the total maximum demand of the distribution network.

$$P_{slack}(t) \leq P_{slack}^{max} \quad (17)$$

- ***The bus voltage limits:***

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i = 1\ldots.\ nbus \quad (18)$$

- ***The power capacity limits of distribution lines:***

$$S_{ij}(t) \leq S_{ij}^{max} \qquad i = 1..nbus,\ j = 1..nbus,\ i \neq j \quad (19)$$

3.4 Load Shedding

To limit the slack bus power to its required limit during peak hour loads when there is not enough generated power in the distribution network, load shedding is considered. In another words, load shedding is performed to satisfy the constraints given in (8) and (17).

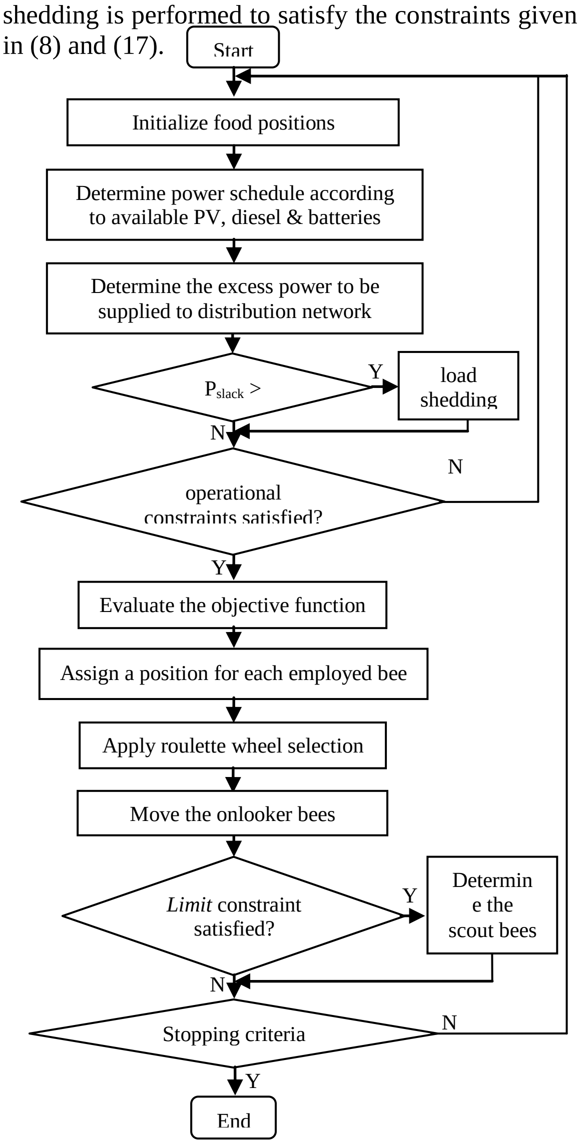


Fig.1, A flow chart of the proposed algorithm

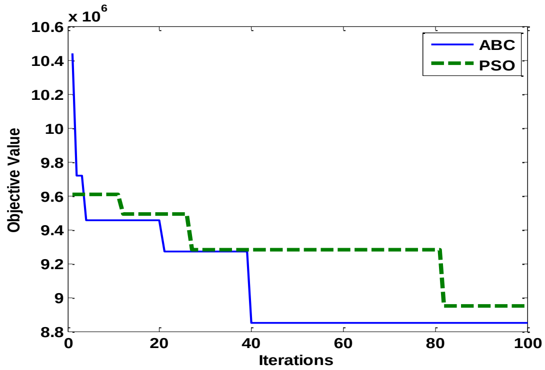
In the load shedding procedure, the loads are shed according to their priority and starting with lower priority loads. In this paper, the priorities of loads are determined according to the amount of load where higher loads are assigned with higher priority.

4. ABC APPLICATION TO HPVDS SITING AND SIZING PROBLEM

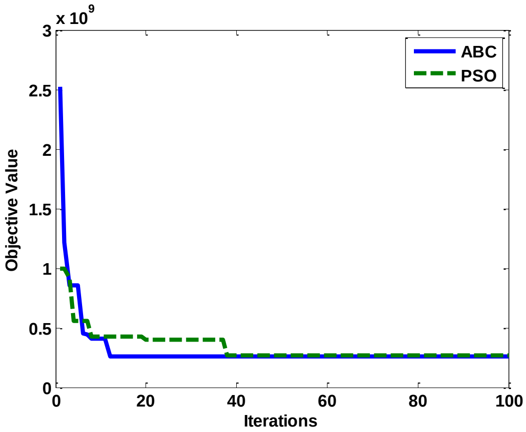
In this paper, the ABC algorithm is applied to the optimization problem. The parameters to be optimized are the buses at which HPVDS are placed, the rating of the PV systems and the ratings of the batteries banks. As for the diesel generators, they are assumed to have ratings equal to the maximum local load at the buses they are connected at because, as will be seen in section 5, the peak load hours are not the maximum solar irradiation hours. The flow chart of the proposed algorithm is shown in Fig.1.

5. TEST RESULTS

The proposed ABC algorithm is applied to two test system. The first one is the 33-bus, radial system [22]. The second system is the Egyptian 45-bus, meshed system of Alexandria [23].To compare the convergence efficiency of the proposed algorithm, the problem is solved using particle swarm optimization (PSO) algorithm too. A population size of 50 solutions and maximum cycle of 100 is considered for both ABC and PSO. The convergence characteristics of the objective value for the two systems are shown in Fig.2.



(a) Objective function convergence for the 33 bus system

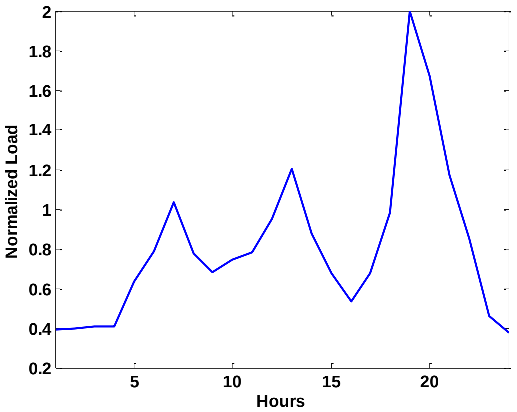


(b) Objective function convergence for the 45 bus system

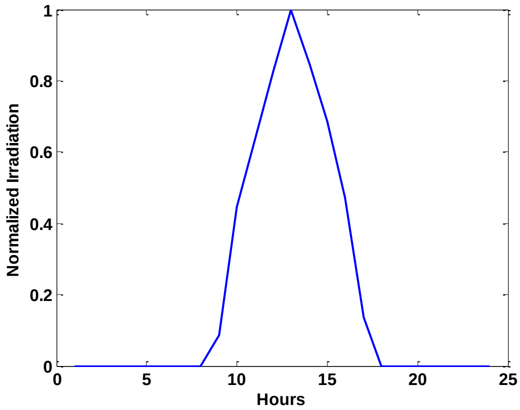
Fig.2, Convergence characteristics of the objective function of the two test systems

As shown in Fig.2, the ABC resulted in better values of the objective function in case of the 33 bus system while reached almost the same objective function value in case of the 45 bus system. It is also shown that the ABC algorithm converges sooner than the PSO algorithm.

The normalized load curve and the normalized daily irradiation curve used for simulating both test systems are shown in Fig.3. For both systems the minimum diesel generator output is assumed to be 18% of its rated capacity and at the beginning of the simulation the batteries are assumed to be fully charged.



(a) The normalized load curve



(b) The normalized daily irradiation

Fig.3, The normalized daily loading and solar irradiation of test systems

5.1. Radial 33-bus System

The 33-bus system is a radial system with 32 lines and is connected to transmission grid through bus 1. The system generators are placed at buses 11, 13, 25 and 30 with maximum capacity of 1 MW. The system is shown in Fig.4 and the system data are given in [22].

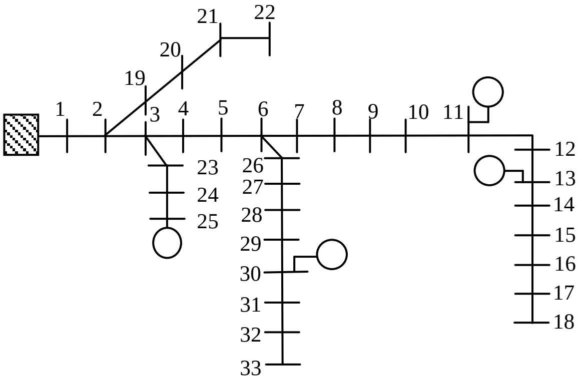
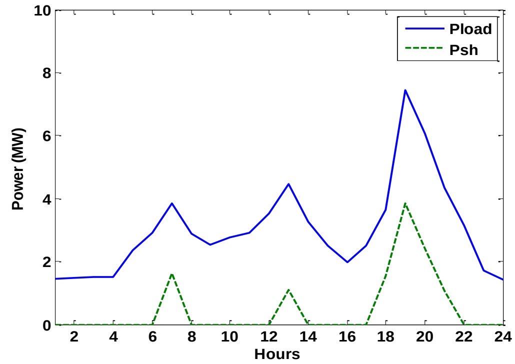
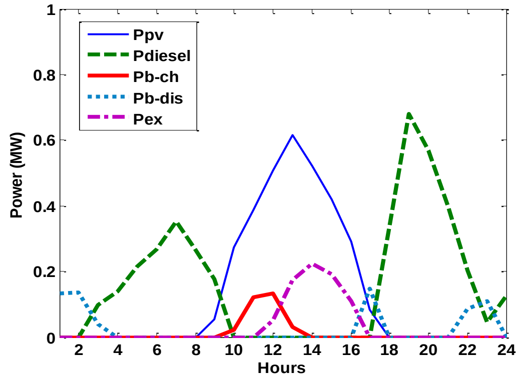


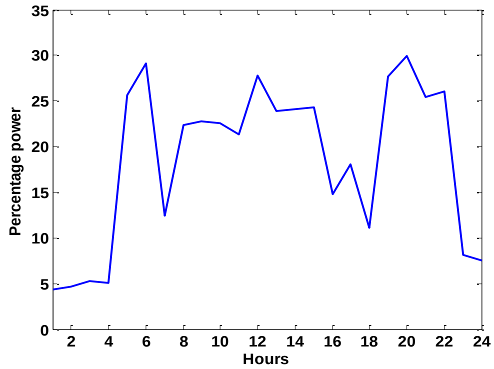
Fig.4, The radial 33-bus system



(a) The load served and the load shed



(b) Power schedule of the HPVDS



(c) The slack power as percentage of the total load power

Fig.5, The load and generation schedule of the radial 33-bus system

Applying the ABC algorithm to the system resulted in placing three HPVDS at buses 2, 14 and 29. The ratings of each HPVDS components are given in Table 1. It is also shown in Table 1 that the diesel generator minimum output does not fall below 18%.

Table 1, the ratings of HPVDS components for the radial 33-bus system

Locations	Ratings (MW)			Min. diesel output (%)
	PV	Diesel	Battery	
2	0.176	0.2	0.1874	18.9
14	0.2112	0.24	0.1596	18.92
29	0.227	0.24	0.1874	18.92

The system's load and generation schedule are shown in Fig.5. As shown in Fig.5 (a), the load is partially shed at few hours with a total load shedding of 11.62 MW which is about 16% of a total load of 72.16 MW. As shown in Fig.5 (b), the diesel generator starts supplying power when the PV power is not enough and the batteries charge only when enough PV power is available. It is also shown that the HPVDS supply power to the distribution network only when excess PV power is available. As shown in Fig.5 (c), the power imported from the transmission network does not exceed 30% of the load. The total power loss during the 24 hours is 4.12 MW which is about 5.7% of the total load.

5.2. Meshed 45-bus System

The Egyptian 66 kV, 45-bus system of Alexandria is a meshed system with 47 lines, and connected to the 220 kV grid through buses 1, 2, 5 and 9. The system generators are placed at buses 2, 5 and 9 with maximum capacity of 853 MW. The system is shown in Fig.6 and the system data are given in [23].

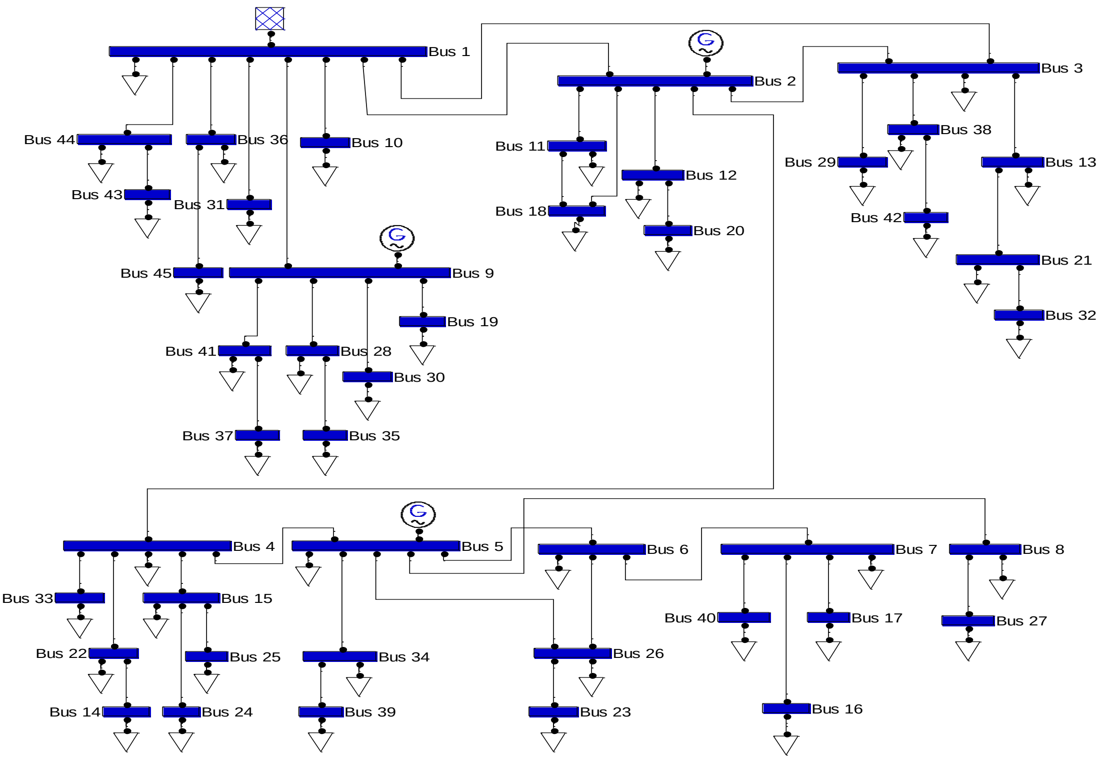


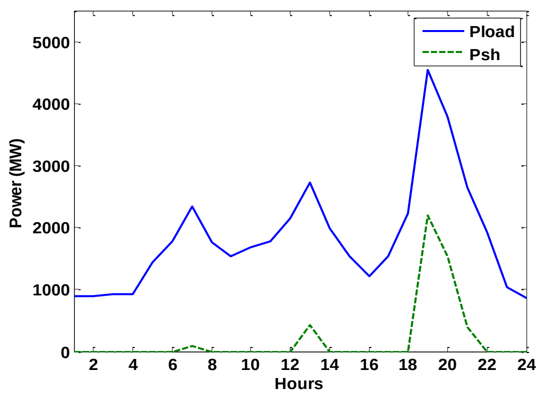
Fig.6 The meshed 45-bus system

Applying the ABC algorithm to the system resulted in placing three HPVDS at buses 11, 24 and 27. The ratings of each HPVDS components are given in Table 2. It is also shown in Table 2 that the diesel generator minimum output does not fall below 18%.

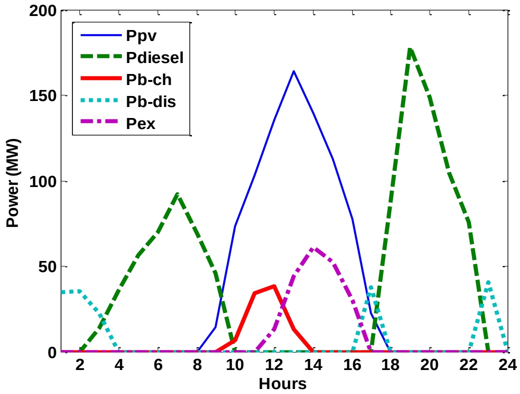
Table 2, The ratings of HPVDS components for the meshed 45-bus system

Locations	Ratings (MW)			Min. diesel output (%)
	PV	Diesel	Battery	
11	5.72	8	6.8012	18.9
24	5.368	8	7.8422	18.9
27	6.072	8	4.8788	20.27

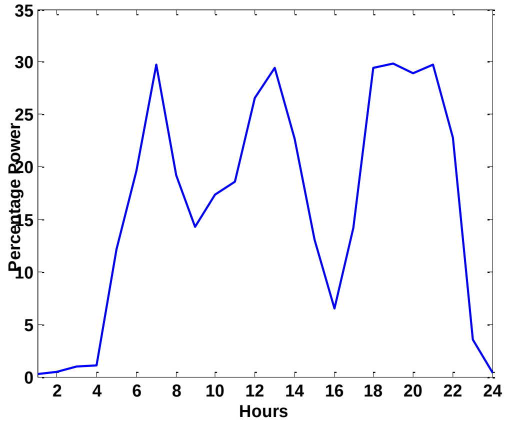
The system's load and generation schedule are shown in Fig.7. As shown in Fig.7 (a), the load is partially shed at few hours with a total load shedding of 4640 MW which is about 10.5% of a total load of 44141.9 MW. As shown in Fig.7 (b), the diesel generator starts supplying power when the PV power is not enough and the batteries charge only when enough PV power is available. It is also shown that the HPVDS supply power to the distribution network only when excess PV power is available. As shown in Fig.7 (c), the power imported from the transmission network does not exceed 30% of the load. The total power loss during the 24 hours is 686.087 MW which is about 1.5% of the total load.



(a) The load served and the load shed



(b) Power schedule of the HPVDS



(c) The slack power as percentage of the total load power

Fig.7 The load and generation schedule of the meshed 45-bus system

6. CONCLUSION

In this paper an artificial bee colony (ABC) based algorithm was presented to optimally allocate, design and schedule hybrid photovoltaic-diesel distributed generation in distribution systems. The objective of the proposed algorithm was to minimize the overall costs of the HPVDS. It was required also to minimize the distribution system power loss, the amount of un-served or shed load and the imported power from the transmission grid. Meanwhile, the algorithm tried to maximize the excess generated power by the HPVDS that may be injected into the distribution network. These objectives were achieved while satisfying the operational constraints of the system. The proposed algorithm was applied to radial and meshed test systems and, as shown by the results, it was capable of dealing successfully with both systems.

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