Optimal Allocation, Sizing and Energy Management of PHEV Parking Lots in Distribution System

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***Abstract*—The emerging of plug-in-hybrid electric vehicles (PHEV) results in the increase in the utilization of vehicles batteries for grid support. This paper presents a multi-objective algorithm to optimally determine the number of parking lots to be allocated in a distribution system. In addition, the algorithm optimally selects the locations and sizes of these parking lots. The proposed algorithm determines also the corresponding energy scheduling of the system resources. The objective of the proposed algorithm is to minimize the overall energy cost of the system. The problem is formulated as an optimization problem which is solved using artificial bee colony (ABC) algorithm taking into consideration the power system and PHEV operational constraints. The proposed algorithm is applied to a 33-bus radial distribution network. The test results indicate an improvement in the operational conditions of the system.**

Keywords—PHEV; Energy management; distribution system; ABC optimization

I. INTRODUCTION

The rapid industrial and modernization growth resulted in a rapid growth of hydrocarbon-based energy consumption. This has been one of the most significant challenges for the environment and human life [1]. In addition, the decrease of fuel quantity, volatility price and the need to decrease the dependency on fossil fuels caused the electric vehicles (EVs) to be considered as an effective resource in transportation and power system [2]. EVs include plug-in-hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). However, electrification of the transportation sector brings more challenges and offers new opportunities to power system planning and operation. The possibility of using the energy stored in the gridable EVs batteries to supply power to the electric grid is commonly referred to as vehicle-to-grid (V2G) [3]. Integration of V2G as distributed energy sources when the vehicles are parked requires an appropriate site selection of optimized on-grid parking lots and an optimal energy resource scheduling.

In recent years, many researchers have addressed the integration of V2G in power system. In [4], authors proposed an algorithm for optimally managing a large number of PHEVs charging at a municipal parking station. They tried to optimally allocate energy to PHEVs while maximizing the average state-of-charge (SOC) of the batteries.

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As the power flow in the presence of PHEVs can be bidirectional, the PHEVs can aid to improve grid efficiency and reliability. The increase of power quality of the grid by using coordinated charging and discharging of PHEVs was presented in [5]. Authors in [6], proposed a practical model for the assessment of the contribution of V2G systems as a support to energy management within a small electric energy systems. In the same context, authors in [3] presented a day-ahead energy resource scheduling for smart grids considering the use of gridable vehicles. The main objective was to minimize the operation cost of the system.

In addition to energy management of PHEVs in pre-located parking lots, the optimal locations and sizes of these lots attracted the attention of many researches too. Optimal allocation of parking lots can reduce the network loss such as other distributed generation (DGs), enhance reliability, improve voltage profile and consequently bring economical benefits for distribution system companies. In [2], authors proposed an algorithm for optimal allocation and sizing of parking lots. Few buses of the system were considered as candidate buses for allocating parking lots. However, the researchers ended up with only determining the optimal size of the allocated parking lots as they placed parking lots at all of the candidate buses. Furthermore, the vehicles were set to charge during off-peak hours and discharge during peak hours. Hence, no energy management approach was applied. Authors in [1] proposed a solution of the optimal DGs siting and sizing problem. Thereafter, they selected the predetermined optimum site of DG to be a location of a parking lot. To satisfy the size of the parking lot an on-grid hybrid renewable energy system was chosen. The energy management algorithm considered an optimum charging rate of PHEVs. However, the contribution of the PHEVs to support the grid with their stored energy was not addressed.

In this paper, an optimization algorithm is proposed to optimally determine the number of parking lots to be placed in a distribution system. The algorithm also determines the optimal locations and sizes of these parking lots taking into consideration two types of these lots, i.e. commercial and residential ones. The optimal charging and discharging scheme is also suggested so that the energy stored in the PHEVs support the network during heavy loading hours. The objective of the proposed algorithm is to minimize the overall cost of energy loss, energy transported from the main grid, energy supplied by the DGs and the net energy of charging/discharging the batteries of PHEVs. The problem is formulated as an optimization problem which is solved using ABC algorithm taking into consideration the power system and PHEVs operational constraints.

The proposed algorithm is applied to a 33-bus radial distribution system. The test results show the effectiveness of the proposed algorithm to solve such complex problem. The results show also the improvement in the system operating conditions.

II. Artificial Bee Colony Optimization Algorithm

The ABC optimization technique belongs to the group of swarm intelligence techniques. It was introduced in 2005 by Karaboga [7]. 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 [8]. 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 [8-10].

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 [9,10]:

1- Spray the employed bees into the solution space and calculate their fitness values.
2- 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) [10].

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

$i = 1, 2, \ldots\ldots, S$

$k = 1, 2, \ldots\ldots, S \quad k \neq i$

$j = 1, 2, \ldots\ldots, D$

$b = 1, 2, \ldots\ldots, MCN$

where j is the dimension of the solution.

3- 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) [10].

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

III. Problem Formulation

The objective of the proposed ABC based algorithm is to find the optimum locations of PHEVs parking lots out of a certain number of candidate locations in the distribution network. Therefore, neither the number nor the locations of the parking lots are pre-specified. They are left for the optimization algorithm to determine. Two different types of parking lots are considered, i.e. commercial and residential garages. The type of the parking lot is determined according to its selected location and hence, the availability pattern of the PHEVs will differ for each suggested allocation scheme. A charging/discharging schedule of PHEVs batteries is to be determined according to the available resources of the network and the current SOC of the batteries. The main target is to minimize an overall cost function of the system. This function includes the cost of energy loss of the network, the cost of energy imported from the main grid, the cost of the energy supplied by the DGs of the network and the cost of energy supplied by the parking lots during batteries discharge to support the network. In addition, it is required to maximize the power supplied to the parking lots to charge the PHEVs batteries.

A. Objective Function

The objective of the proposed algorithm is to minimize the following function,

$$\min f = \sum_{t=1}^{N} [C_{loss}P_{loss}(t) + C_{grid}P_{grid}(t) + C_{DG}P_{DG}(t) + C_{gr}P_{gr}(t)] \quad (3)$$

Where

$$P_{gr}(t) = P_{disch}(t) - P_{ch}(t) \quad (4)$$

B. Operational Constraints

- *Power balance constraint*

At any time interval t, the total power generation should be equal to the total power demand in addition to the system power loss.

$$P_{DG}(t)+P_{grid}(t)+P_{gr}(t)-P_{loss}(t)-P_{D}(t)=0 \quad (5)$$

- *Grid energy cost constraint*

The cost of energy imported from the grid to the distribution network is assumed to increase by 10% as the power imported at any time interval exceeds its maximum allowable limit. In this paper, the maximum limit of the grid power is assumed to be limited to 30% of the total maximum demand of the distribution network. The cost constraint is given in (6) and (7).

$$C_{grid} = C_{s1} \quad \forall \; P_{grid}(t) \leq P_{grid\text{-}max} \quad (6)$$

$$C_{grid} = C_{s2} \quad \forall \; P_{grid}(t) > P_{grid\text{-}max} \quad (7)$$

where $C_{s2} = 1.1\ C_{s1}$

- *PHEV batteries constraint*

  i. Storage capacity constraint

$$SOC_{min} \leq SOC_i(t) \leq SOC_{max} \tag{8}$$

  ii. Rate of charge constraint

$$P_{ch}(t) \leq R_{ch} \tag{9}$$

  iii. Rate of discharge constraint

$$P_{dsich}(t) \leq R_{disch} \tag{10}$$

  iv. Power balance state

$$SOC_i(t) = SOC_i(t\text{-}1)+P_{ch}(t)X(t)\text{-}P_{disch}(t)Y(t) \tag{11}$$

where

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

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

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

$$X(t)+Y(t) \leq 1 \tag{12}$$

- *Bus voltage limits*

$$V_i^{min} \leq V_i(t) \leq V_i^{max} \qquad i=1,2,\ldots..,nbus \tag{13}$$

- *Line thermal limits*

$$|S_i(t)| \leq |S_i^{max}| \qquad i=1,2,\ldots..,nline \tag{14}$$

- *Generation limits*

$$P^{min}_{DG\text{-}i} \leq P_{DG\text{-}i}(t) \leq P^{max}_{DG\text{-}I}i \quad i=1,2,\ldots..,ng \tag{15}$$

IV. ABC APPLICATION TO THE OPTIMIZATION PROBLEM

In this paper, the ABC algorithm is applied to the optimization problem. The parameters to be optimally selected are the buses at which the parking lots are to be placed and the size of these lots. According to the location of the parking lot, its type is determined and hence the vehicles availability hours. According to the size of the lots and the charging capacity of the vehicles, the suitable energy management scheme is applied in which the optimal generation of the DG units and the state of the vehicles, i.e. charging or discharging, are determined. This way the overall energy cost of the system during the simulation period can be calculated for each proposed solution determining its fitness.

V. TEST RESULTS

The proposed ABC algorithm is applied to a 33-bus radial distribution system shown in Fig.1 [11]. To compare the convergence efficiency of the proposed algorithm, the problem is solved using particle swarm optimization (PSO) algorithm too [12]. 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 are shown in Fig.2.

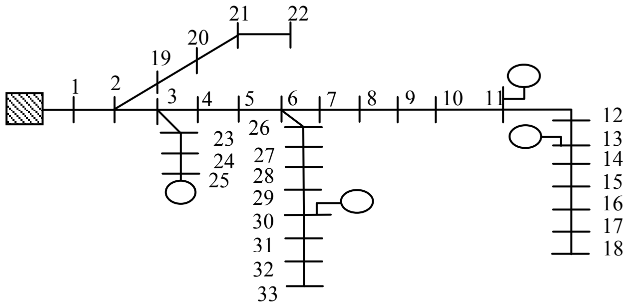

Fig. 1. The radial 33-bus system

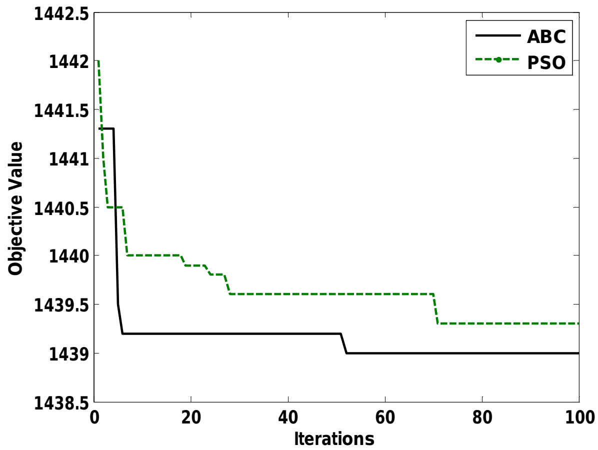

Fig. 2. Objective function convergence for the 33 bus system

As shown in Fig.2, the ABC resulted in better values of the objective function. It is also shown that the ABC algorithm converges sooner than the PSO algorithm.

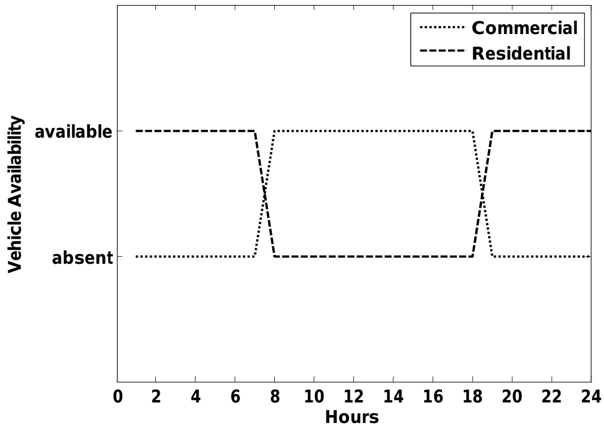

Fig. 3. The vehicles availability during 24 hours

In this paper, the simulating period is 24 hours. The vehicles availability for both commercial and residential garages are shown in Fig.3. It is assumed that the initial SOC of the batteries in each parking lot is as given in Table 1, while the maximum and minimum SOC of the batteries are assumed to be 90% and 25%, respectively. The batteries have a nominal capacity of 16 kWh and their rate of charge/discharge is considered to be 2.3 kW.

TABLE I. INITIAL SOC OF VEHICLES

Initial SOC (%)	30	45	70
Number of vehicles (%)	25	25	25

Applying the ABC algorithm to the system resulted in placing parking lots at seven locations out of nine candidate locations of the system. The location, type and capacity of each parking lot are given in Table 2.

TABLE II. SIMULATION RESULTS

Garages locations	7	8	14	24	29	31	32
Garages type*	R	R	C	C	R	C	C
Garages capacity (vehicles)	100	100	200	170	200	191	110

* R= residential , C=commercial

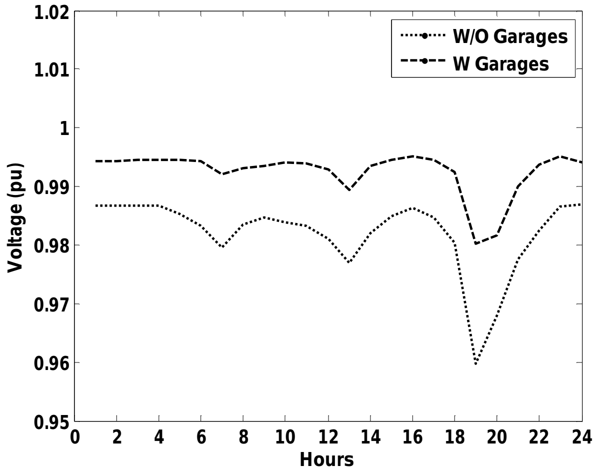

Fig. 4. The profile of the minimum bus voltage

The minimum bus voltage during 24 hours is shown in Fig.4. As shown in figure, the voltage profile improved with the installation of the parking lots. Regarding the energy loss during 24 hours, without installing PHEVs parking lots the energy loss was 7.7343 MWh and with the parking lots the energy loss decreased to 4.0861 MWh.

To study the effect of using the stored energy in the PHEVs batteries to support the power system, the imported power form the main grid is shown in Fig.5. As shown in Fig.5, the amount of grid power with PHEVs is less than that without PHEVs and the periods in which the grid power exceeded its maximum value also decreased. As a result of that the overall energy cost of the system is reduced. In addition, Fig.6 shows the charge/discharge power of the PHEVs batteries, the load power and the DGs power during 24 hours. As shown in Fig.6, whenever the generated power is greater than the demand power the PHEVs batteries can charge and vice versa. Whenever the demand power is greater than the generated power and the SOC of PHEVs batteries are higher than their minimum value, the PHEVs batteries discharge to supply part of the load.

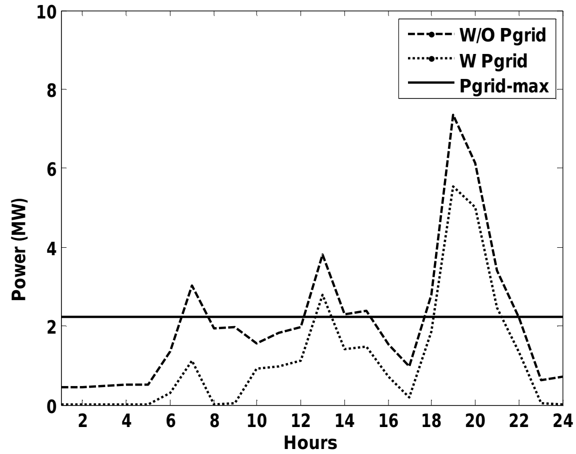

Fig. 5. The power imported from the main grid

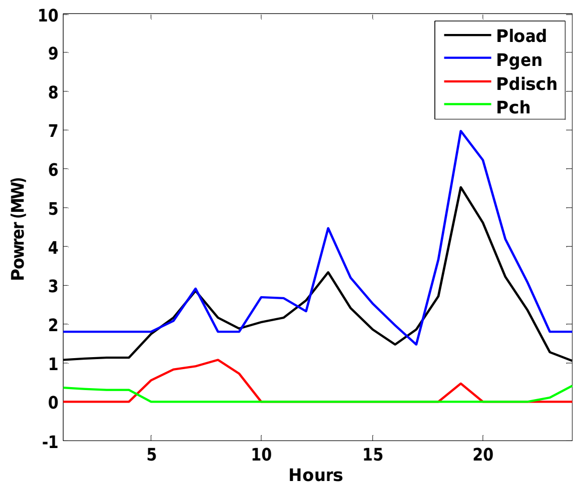

Fig. 6. Power profile during simulation period

VI. CONCLUSION

This paper introduced a multi-objective algorithm to optimally allocate and size PHEVs parking lots in a distribution system. The proposed algorithm optimally determined the number of parking lots to be allocated, their optimum locations and their optimum sizes. According to the determined allocation scheme, a suitable energy scheduling of the system resources was suggested. The objective of the proposed algorithm was to minimize the overall energy cost of the system. The problem was formulated as an optimization problem which was solved using artificial bee colony (ABC) algorithm taking into consideration the power system and PHEV operational constraints. The proposed algorithm was effectively applied to a 33-bus radial distribution network. The test results indicated an improvement in the operational conditions of the system.

LIST OF SYMBOLS

x_i the position of the i[th] onlooker bee
b the iteration number
θ_i the position of the i[th] 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 i[th] parameter
t index of time periods running from 1 to N.
C_{loss} the cost of energy loss
C_{grid} the cost of energy imported from the main grid
C_{DG} the cost of energy obtained from DG units
C_{gr} the cost of garages charge/discharge energy
C_{s1} the cost of energy imported from the main grid when the grid power is less than its maximum limit
C_{s2} the cost of energy imported from the main grid when the grid power is greater than its maximum limit
$P_{loss}(t)$ the power loss at time t
$P_{grid}(t)$ the power obtained from the main grid at time t
$P_{grid-max}$ the maximum limit of the power obtained from the main grid
$P_{DG}(t)$ the power obtained from DG units at time t
$P_{DG-i}(t)$ the power obtained from the i[th] DG unit at time t
$P_{gr}(t)$ the garages charge/discharge power at time t
$P_{ch}(t)$ the garages charge power at time t
$P_{disch}(t)$ the garages discharge power at time t
$P_D(t)$ the demand power at time t
$SOC_i(t)$ the state of charge of the i[th] garage at time t
SOC_{max} the maximum state of charge of a garage
SOC_{min} the minimum state of charge of a garage
R_{ch} the rate of charge of a battery
R_{disch} the rate of discharge of a battery
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
S_{ij} the power capacity in the i[th] distribution line
S_{ij}^{max} the maximum power capacity of the i[th] distribution line
P^{min}_{DG-i} the minimum output power of the i[th] DG unit
P^{max}_{DG-i} the maximum output power of the i[th] DG unit
nbus the number of system's buses
nline the number of system's lines
ng the number of DG units in the system

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