Energy Conversion and Management 86 (2014) 745–755

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Integrated scheduling of renewable generation and electric vehicles parking lot in a smart microgrid

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ARTICLE INFO

*Article history:*
Received 13 December 2013
Accepted 15 June 2014
Available online 5 July 2014

*Keywords:*
Electric vehicle
Intelligent parking lot
Microgrid
Renewable generation
Vehicle-to-grid

ABSTRACT

Integration of Electric Vehicles (EVs) and Renewable Energy Sources (RESs) into the electric power system may bring up many technical issues. The power system may put at risk the security and reliability of operation due to intermittent nature of renewable generation and uncontrolled charging/discharging procedure of EVs. In this paper, an energy resources management model for a microgrid (MG) is proposed. The proposed method considers practical constraints, renewable power forecasting errors, spinning reserve requirements and EVs owner satisfaction. A case study with a typical MG including 200 EVs is used to illustrate the performance of the proposed method. The results show that the proposed energy resource scheduling method satisfies financial and technical goals of parking lot as well as the security and economic issues of MG. Moreover, EV owners could earn profit by discharging their vehicles' batteries or providing the reserve capacity and finally have desired State Of Charge (SOC) in the departure time.



## 1. Introduction

The concept of microgrid (MG) is proposed to improve the local reliability and flexibility of electric power systems, which is defined as a group of Distributed Energy Resources (DERs), loads, and energy storage units. MG can operate in both gird-connected mode and islanded mode [1]. The idea supporting the formation of the MG is that a paradigm consisting of a cluster of distributed generations and aggregated loads is adequately reliable and economically viable as an operational electric system [2,3]. Due to increasing shortage of the fossil fuel and the environmental concerns, the governments are motivated to utilize renewable energy resources. A MG combined with Renewable Energy Sources (RESs) can be a preferable solution to the raised energy crises as well as environmental concerns [4]. In a centralized controlled microgrid, microgrid central controller (MGCC) makes bids of energy and spinning reserve to electricity market based on forecasting of market prices, renewable power output and load. Day-ahead deterministic unit commitment would be settled according to collected information of market price, power forecasts and status of units. In this way, MGCC settles the bids of energy and spinning reserve, the setpoint of controllable DGs, the charging/discharging states of energy storage system and the interruption of load. Moreover, the dispatch and bidding strategy in MGCC should maximize the total financial income of microgrid including revenue from electricity market and local consumers subtracting operation cost of generating unit and payback cost of load curtailment [5].

On the other hand, Electric Vehicle (EV) is another important component of electric power network in the near future. The widespread deployment of EVs may introduce a solution to the world fossil fuel shortage as well as the air pollution crisis [6,7]. The emission reduction goal is achieved by proper and optimum utilization of the EVs as energy storages and loads in power system integrated with RESs [8–10]. Beyond these advantages, the anticipation of connection of EVs into the power network may bring up many technical challenges that need to be addressed properly. With the widespread adoption of EVs, the power system may face significant challenges due to the huge electricity demand of these loads [11]. Also, a MG is impacted by a growing penetration of EVs, which represents a new dimension for MG management and huge amounts of energy storage will be injected to the grid through millions of EVs [12].

Vehicle-to-Grid (V2G) is a new concept related to an energy storage technology that has the capability to allow bidirectional power flow between a vehicle's battery and the electric power grid [13]. With V2G capability, the state of charge of an EV's battery can go up or down, depending on the revenues and grid's demands. Through V2G, EV owners can make revenue while their cars are

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http://dx.doi.org/10.1016/j.enconman.2014.06.044
0196-8904/

parked; it can provide valuable economic incentives for EV owners. On the other hand, utilities significantly support V2G by having increased system flexibility and reliability as well as energy storage for intermittent RESs such as wind and solar. In order to participate in energy markets, aggregators integrate the large numbers of EVs stored energy and submit their offers to the power market [14,15]. In order to maximize customer satisfaction and minimize grid disturbances, intelligent parking lots can be of great worth [16,17]. In these type of parking lots, customers by providing the desired parameters will charge their EVs and moreover, have the opportunity to sell their stored energy to the local electric loads or the upstream grid and earn money [18]. As the owners of EVs usually use their vehicles in few hours during a day and their vehicles stay in parking lots without using in the rest of the day, the batteries of EVs can be considered as energy storage systems. So, EVs can be considered as a new player to provide the reserve capacity of the system. In [19], the mechanism of participating EVs in spinning reserve market has been developed.

Some studies proposed an energy management system for energy scheduling in a MG in order to realize the V2G concept. Using a suitable control and energy dispatch strategy, the stored energy in EVs' batteries can enhance the stability of power grid, mitigate peak loads and improve behaviors of intermittent renewable generation [20,21]. The randomness of the renewable energy resources causes great difficulty in the planning of MGs, and is a hot topic in MG design research [22–24]. Although generating electricity from renewable energy resources offer clean alternatives to fossil fuels, they are uncertain and variable. Therefore, their large scale integration into an electric power system poses challenges to system operators and planners. Spinning reserve is one of the important ancillary services that is essential to ensure the secure and reliable operation of the power system with high penetration of intermittent renewable generation [25,26].

Some recent literatures discussed about the EVs impacts on power grids [27,28]. In [27], a method for determining the optimal places of plug-in hybrid electric vehicles' (PHEVs) parking lots which provide V2G power as distributed generation has been proposed. Utilizing an optimization algorithm to maximize the advantages of using EVs' batteries as energy storage systems in power grids has been presented in [28].

In [16], the charge/discharge management of a fleet of EVs in a smart parking lot has been carried out where the method aimed at maximizing the state of charge (SOC) of each EV's battery. The charge/discharge strategy has been analyzed with and without considering the constraint of batteries lifetime of EVs. However, the charge/discharge scheduling of EVs in a parking lot without considering the external electricity grid has only been taken into account. Also, the capability of EVs in providing reserve capacity has not been studied in this work.

In [29], an Estimation of Distribution Algorithm (EDA) to schedule large number of EVs charging in a parking lot has been proposed. The method optimizes the energy allocation to the EVs in real-time while considering various constraints associated with EV battery and utility limits. The paper has only proposed charging of EVs and the V2G option is not taken into account. The authors in [30], proposed a Simulated Annealing (SA) approach and heuristic technical validation of the obtained solutions to solve the energy resources scheduling. A case study considering 1000 V2G units connected to a 33 bus network managed by a Virtual Power Plant (VPP) has been presented. In the model, EVs have been distributed through the distribution network and there is no centralized parking lot. In [27], wide use of aggregated EVs in parking lots has been presented to overcome the small storage capacity of an EV. EV parking lots are considered as new players whose roles are collecting the EVs in order to reach high storage capacity from small battery capacity of EVs, affecting the grid. In [31], an optimization problem of scheduling EV charging with energy storage for the day-ahead and real-time markets has been proposed. Also, a communication protocol for interactions among different entities including the aggregator, the power grid, the energy storage, and EVs was considered. The paper focused only on the scheduling EV charging and discussed about utilization of EVs and energy storages together.

In traditional power systems, spinning reserve was generally supplied by free capacity of committed generators. However, after deregulation of the power system, in addition to the generation units, some other resources, such as demand side resources and aggregators can participate in the spinning reserve scheduling. In this study, in addition to MG generation resources, electric vehicles aggregator offers reserve capacity in order to provide the spinning reserve requirement. The model presented here, in contrast to the models from [14,32,33], uses intelligent parking lot as an aggregator to facilitate the managing of EVs, which as shown in [16] is a more practical representation. Moreover, in this paper, the influence of forecast errors corresponding to renewable energy resources is addressed.

In [34], an energy management algorithm for a grid-connected charging park has been developed. The charging park involves PHEVs as well as a photovoltaic system. The energy management algorithm aimed at reducing the overall daily cost of charging the PHEVs, mitigating the impact of the charging park on the main grid, and contributing to shave the peak of the load curve. However, the capability of charging park in providing reserve capacity, and compensating the intermittent nature of RESs has not been taken into account.

To the best of our knowledge, no energy and reserve scheduling model in which the EVs can participate in providing reserve capacity in a MG has been reported in the literature. In addition, the integration of intermittent renewable generation and EVs charge/discharge has not been considered in most of previous studies. In this paper an intelligent parking lot is considered in order to aggregate the stored energy of EVs. Moreover, the role of EVs in providing the reserve for compensating the renewable power forecasting error is studied. The Proposed method considers system constraints and EVs owners' preferences. Moreover, the elapsed time of the EV's battery life is taken into account as a criterion for making decision. A weighting factor is also proposed to prioritize the EVs charging/discharging procedures in the parking lot. The innovative contributions of the proposed method are highlighted as follows:

- Evaluate EVs participations in both energy and reserve scheduling.
- Integrated scheduling and management of intermittent renewable generation and EVs in a MG.
- Using intelligent parking lot as an aggregator to facilitate interaction between EVs owners and microgrid operator.

The rest of the paper is organized as follows: in Section 2, system topology is introduced. Section 3 presents the problem formulation; including the resources and network constraints. A case study and analysis of the results are shown in Section 4. Finally, the most important conclusions of the work are presented in Section 5.

## 2. System topology

This section presents a topology for the proposed MG including an intelligent parking lot, multiple microsources such as photovoltaic (PV) system, wind turbine (WT) system, microturbine (MT) and fuel cell (FC), as shown in Fig. 1. In addition, there is a single

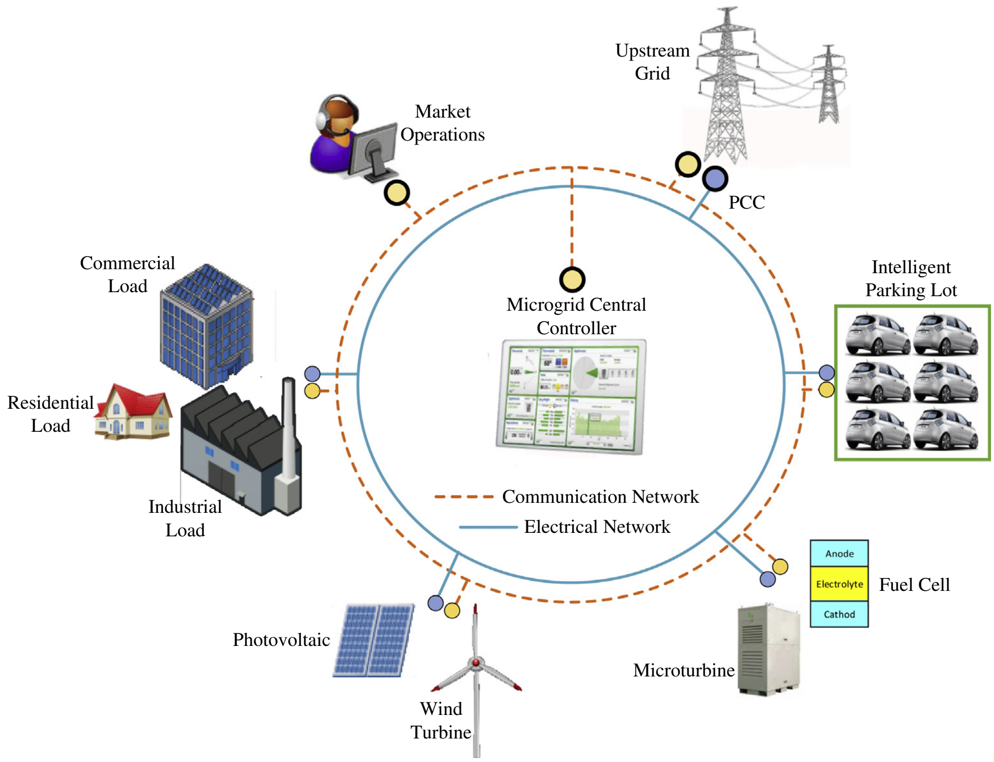


**Fig. 1.** A typical microgrid network.

point of connection to the upstream power network called point of common coupling (PCC).

In order to serve the MG load demand, electrical power can be produced directly by microsources within the MG or transmitted from the upstream power system in grid-connected mode. The MGCC is the main control interface between the upstream grid and the MG. That has the main responsibility to optimize the MG operation. In this paper an intelligent parking lot is also presented that plays the role of an aggregator in order to facilitate the EVs' participation in energy and reserve scheduling. This Section presents details of the MG components as well as the characteristic of renewable energy resources.

### 2.1. EVs parking lot

The proposed EVs parking lot compared to conventional ones provides new opportunities for electric vehicle owners as well as utility. This parking lot receives required parameters from each EV owner, such as desired charging/discharging price limits, approximate duration of presence in the parking lot, and the elapsed time of the EV's battery life. These parameters are considered as the input data. By receiving the elapsed time of the EV's battery life, an extra constraint is considered in the charging/discharging scheduling of EVs. The proposed parking lot not only participates in energy scheduling, but also could provide reserve as an ancillary service. The information flow and architecture of proposed intelligent parking lot in a MG is indicated in Fig. 2.

A weighting factor is also proposed within the model to prioritize the EVs in the parking lot that is defined as follows:

$$W_{Ch}^{i,t} \propto \{RBC^{i,t}, \pi_{Ch,EV}^{i}, 1/RT^{i,t}, 1/AOB^{i}\} \quad (1)$$

$$W_{Dch}^{i,t} \propto \{SOC^{i,t}, \pi_{Dch,EV}^{i}, RT^{i,t}, 1/AOB^{i}\} \quad (2)$$

$$RBC^{i,t} = 1 - SOC^{i,t} \quad (3)$$

where $W_{Ch}^{i,t}$ and $W_{Dch}^{i,t}$ are the charge and discharge weighting factors of the $i$th EV in period $t$, respectively; $\pi_{Ch,EV}^{i}$ and $\pi_{Dch,EV}^{i}$ are the desired charging and discharging price limit of the $i$th EV, respectively; $RBC^{i,t}$ and $SOC^{i,t}$ represent the remaining battery capacity and the state-of-charge of the $i$th EV in period $t$ indicated in Fig. 3, respectively; $RT^{i,t}$ is the remaining time of charging/discharging period of the $i$th EV in period $t$; and $AOB^{i}$ is the age of the $i$th EV's battery which indicates the elapsed time of each EV's battery life. As the parameters in the charge/discharge weighting factor are not in the same scale, they need to be normalized.

The status of available EVs in the parking lot is determined by comparing the desired charging/discharging price limits and the open market electricity price. Each EV parked in the parking lot is situated at one of three charging/discharging/idle modes shown in Fig. 4. The proposed flowchart depicted in Fig. 5 determines the value of charging/discharging/idle mode ($M^{i,t}$) and the status of contribution in the spinning reserve ($SRS^{i}$) of the $i$th EV in period $t$.

### 2.2. Renewable energy sources

The availability of the power supply generated from RESs depends on the availability of the prime sources such as wind speed and solar irradiance. The inherent intermittency and variability of a renewable energy resource located in MG introduces challenges to the conventional operation method [35]. These renewable energy resources tend to fluctuate dramatically depending on the time of day and corresponding to availability of their prime sources. Such variability and uncertainty need to be carefully considered in MG energy management system design. Thus, wind speed and solar radiation forecasting plays a critical role in the secure operation of MG. In this paper, a time series model is used to forecast the wind speed and solar radiation. More details on time series technique and its features are available in [36]. Fig. 6 shows the time series results of the day-ahead forecast for the wind speed and its measurements over a week. Fig. 7 shows

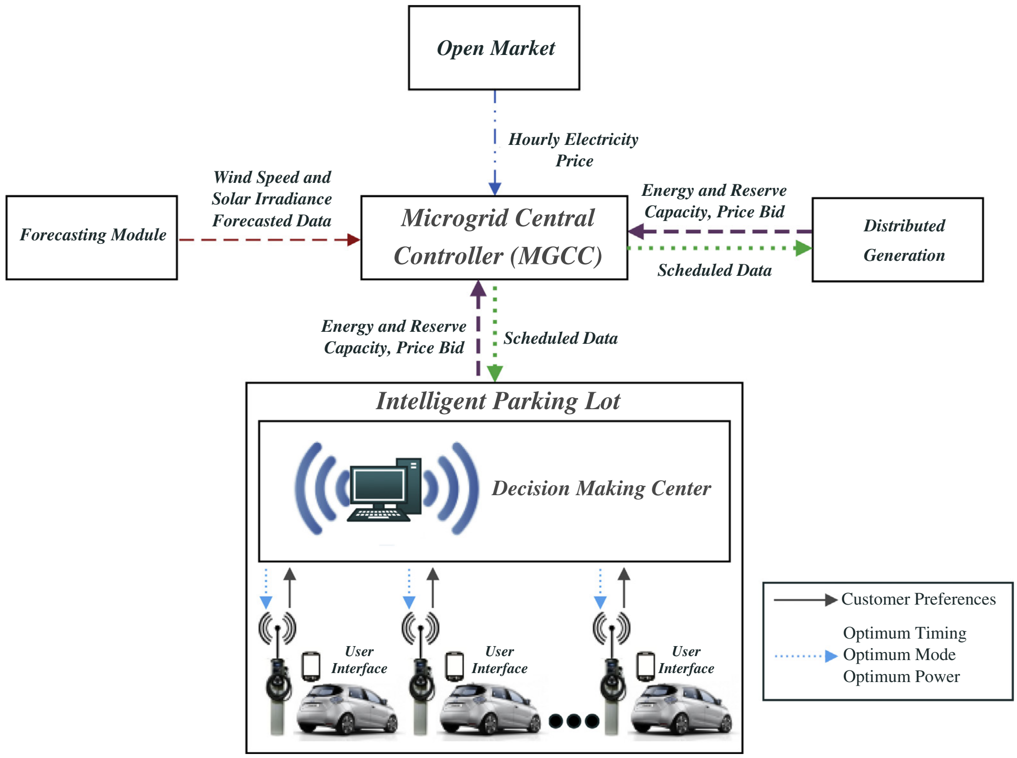


**Fig. 2.** The proposed intelligent parking lot.

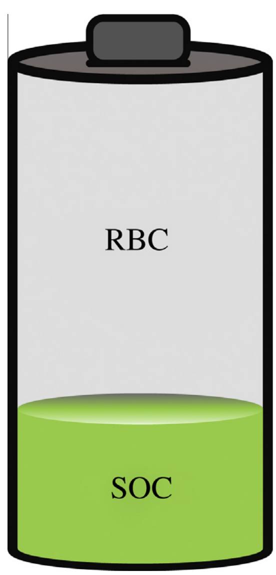


**Fig. 3.** The definition of RBC and SOC.

the time series results of the day-ahead forecast for the solar radiation and its measurements over a daytime. The high forecast accuracy will be obtained using historical data. The collected data over a year period is used in this study [37].

The wind power generation output can be considered as a function of wind speed [38]. A piecewise function can be used to fit the relationship between the output power and wind speed. This function is given as follows:

$$P_W^t = \begin{cases} 0 \text{ if } & : V^t < V_C \text{ or } V^t \geqslant V_F \\ \frac{V^t - V_C}{V_R - V_C} \times P_R \text{ if } & : V_C \leqslant V^t < V_R \\ P_R \text{ if } & : V_R \leqslant V^t < V_F \end{cases} \tag{4}$$

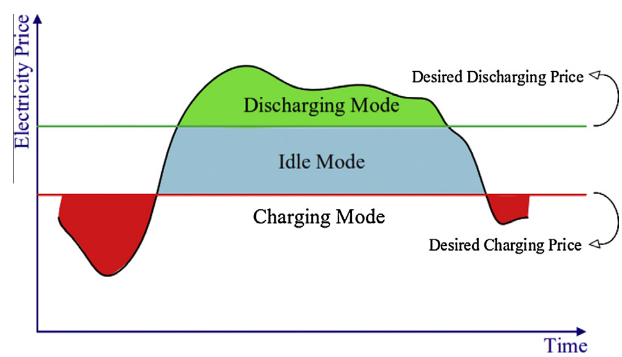


**Fig. 4.** Three modes of a typical EV.

where $P_R$ is the rated electrical power; $V_C$ is the cut-in wind speed; $V_R$ is the rated wind speed; and $V_F$ is the cut-off wind speed.

In the PV system, the maximum power output is presented by Eq. (5) [39].

$$P_{PV}^t = \eta \times S \times I(1 - 0.005 \times (T_a - 25)) \tag{5}$$

where $\eta$ is the conversion efficiency of the solar cell array (%); $S$ is the array area (m$^2$); $I$ is the solar radiation (kW/m); and $T_a$ is the ambient temperature (°C).

### 2.3. Fuel cell and microturbine

Distributed generation units connected near the energy consumers comprise many technologies, such as fuel cells (FCs) and microturbines (MTs) [40]. The MT has great flexibility in that small-scale units can be combined together into larger systems from few kWs to few MWs of power; also it has the environmental advantage of low emissions. Similarly, FCs are quiet and environment friendly, and produce high energy efficiencies under varying load rates [41].

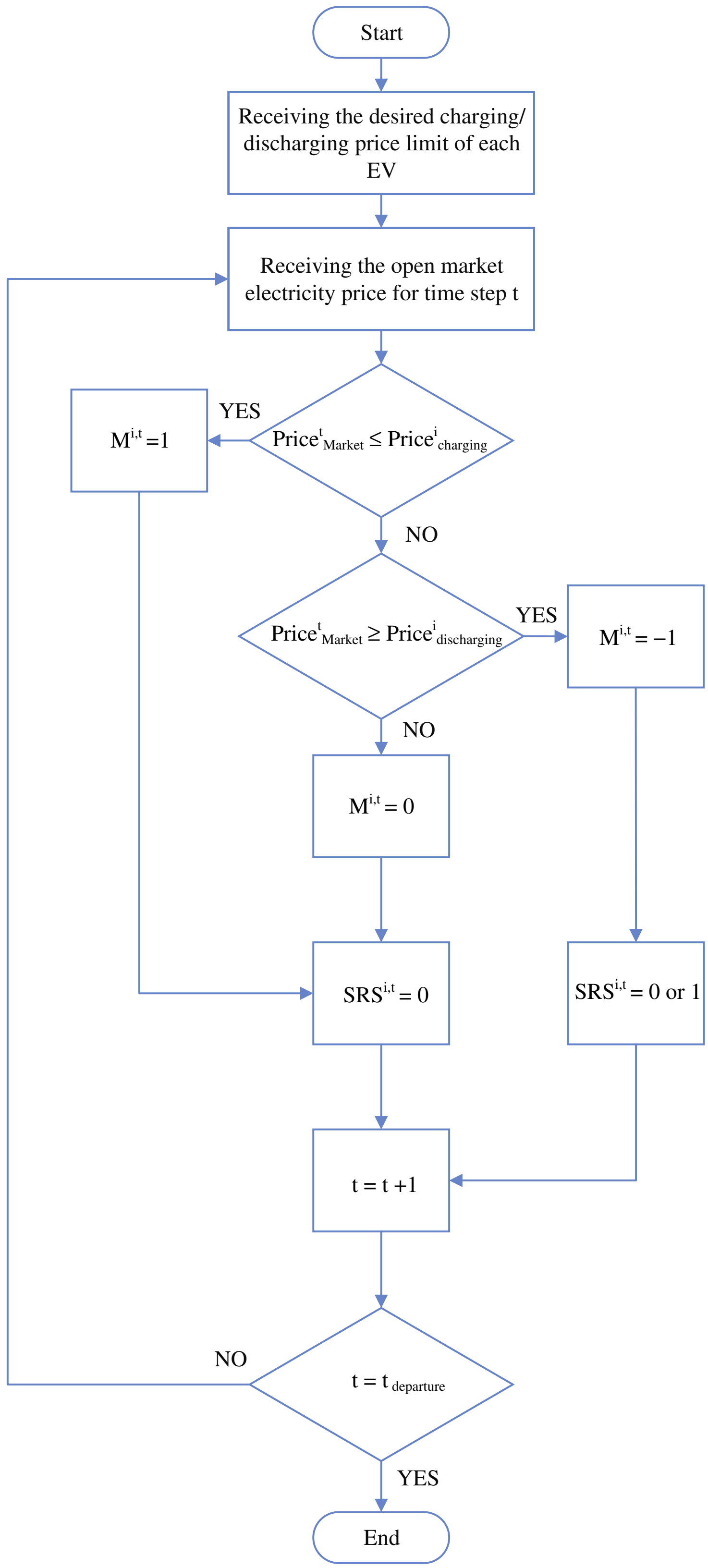


**Fig. 5.** The flowchart of status determination.

## 3. Problem formulation

The main goal of the proposed day-ahead scheduling model is to minimize the MG total operation costs. In order to reduce the risk caused by the intermittent renewable power, reserve capacity should be used to compensate the renewable power forecasting errors [42].

In the proposed model, it is assumed that the DGs and EVs located in the parking lot provide the reserve requirements of MG. The microgrid is generally designed based on delivering local

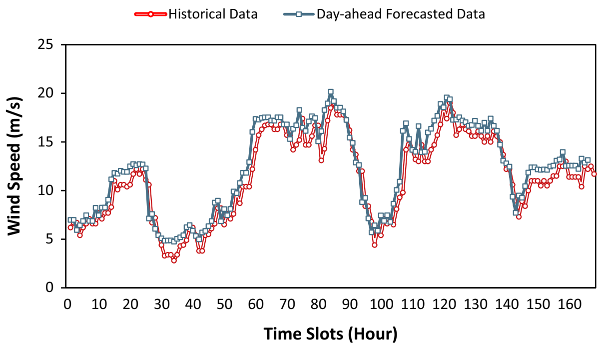


**Fig. 6.** Historical and forecasted wind speed using time series model.

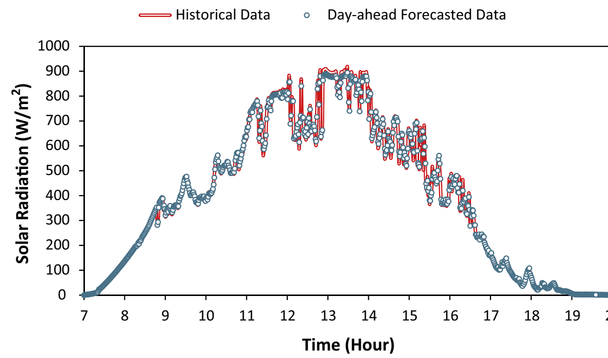


**Fig. 7.** Historical and forecasted solar radiation using time series model.

energy that meets the exact needs of the constituents being served almost independently [43–45]. So, the energy management system tries to operate the microgrid more independently. Providing reserve capacity by MG's local generation increases the independency of MG. On the other hand, purchasing reserve capacity from the main grid in some hours may lead lower cost. However, in this paper, the independency in providing reserve is taken into account and it is supposed that a MG relies on its local resources rather than the upstream grid for providing reserve capacity in order to operate more independently. EVs parking lot receives desired charging/discharging price limits, charging period, initial SOC, and the elapsed time of the EV's battery life from the EV owners as the input data. These data is sent to MGCC in order to optimally determine the charging/discharging mode of each EV at each period. The assumptions used in the proposed method are the following ones:

- The MGCC is allowed to access the day-ahead electricity price for following 24-h scheduling.
- The wind speed and solar radiation forecasts and their forecast errors are received from nearest weather broadcast service.
- EVs' owners send their information to intelligent parking lot for placing their vehicles during the next day [46].

### 3.1. Objective function

The objective function consists of three components:

- The first component which belongs to the exchanged power between the upstream grid and the MG.
- The second component which belongs to the transaction between local dispatchable generators and the MG.
- The third component which belongs to the transaction between the EVs and the MG.

The objective function ($OBJ$) that should be minimized is given as follows:

$$OBJ=\sum_{t=1}^{T}\left[\left(\begin{array}{l}P^{t}_{UG}\times\pi^{t}_{UG}+\\ \sum_{j=1}^{G}(C^{j,t}_{LDG}+SC^{j,t}_{LDG}+(SR^{j,t}_{LDG}\times\psi^{j,t}_{LDG}))+\\ \sum_{i=1}^{N}(-W^{i,t}_{Ch}\times P^{i,t}_{Ch,EV}\times\pi^{i}_{Ch,EV}+W^{i,t}_{Dch}\times P^{i,t}_{Dch,EV}\times\pi^{i}_{Dch,EV}+SRS^{i,t}\times SR^{i,t}_{EV}\times\psi^{i,t}_{EV})\end{array}\right)\times\Delta t\right] \quad (6)$$

where $P^{t}_{UG}$ represents the exchanged power between the upstream grid and MG in period $t$; $\pi^{t}_{UG}$ is the open market electricity price in period $t$; $C^{j,t}_{LDG}$ is the cost of scheduled power of the $j$th local dispatchable generator in period $t$; $SC^{j,t}_{LDG}$ is the start-up cost of the $j$th local dispatchable generator in period $t$; $SR^{j,t}_{LDG}$ and $\psi^{j,t}_{LDG}$ are the scheduled spinning reserve and reserve price provided by the $j$th local dispatchable generator in period $t$, respectively; $G$ is the number of local dispatchable generators located in the MG; $W^{i,t}_{Ch}$ and $W^{i,t}_{Dch}$ are the charge and discharge weighting factor of the $i$th EV in period $t$, respectively; $P^{i,t}_{Ch,EV}$ and $P^{i,t}_{Dch,EV}$ are the charged and discharged power of the $i$th EV in period $t$, respectively; $\pi^{i}_{Ch,EV}$ and $\pi^{i}_{Dch,EV}$ are the desired charging and discharging price of the $i$th EV, respectively; $SR^{i,t}_{EV}$ and $\psi^{i,t}_{EV}$ are the scheduled reserve and reserve price of the $i$th EV in period $t$, respectively; $SRS^{i,t}$ is the reserve status of the $i$th EV in period $t$; $N$ is the number of EVs which are parked in the intelligent parking lot in period $t$; and $T$ is the scheduled time period.

A linear cost function has been assumed for the generated power cost ($C^{j,t}_{LDG}$) of the local dispatchable generators which is presented by Eq. (7). The start-up cost ($SC^{j,t}_{LDG}$) of the local dispatchable generators are presented by Eqs. (8) and (9):

$$C^{j,t}_{LDG}=U^{j,t}\times a^{j}+b^{j}\times P^{j,t}_{LDG};\forall t \quad (7)$$

$$SC^{j,t}_{LDG}\geqslant(U^{j,t}-U^{j,t-1})\times UDC^{j};\forall t \quad (8)$$

$$SC^{j,t}_{LDG}\geqslant 0;\forall t \quad (9)$$

where $P^{j,t}_{LDG}$ is the scheduled power of the $j$th local dispatchable generator in period $t$; $a^{j}$ and $b^{j}$ are the parameters of the $j$th local dispatchable generator in period $t$; $U^{j,t}$ is the binary variable which shows on/off status of the $j$th local dispatchable generator in period $t$; and $UDC^{j}$ is the start cost of the $j$th local dispatchable generator.

### 3.2. Constraints

The minimization of the objective function is subjected to the following constraints.

(1) MG power balance constraint:

$$P^{t}_{UG}+P^{t}_{W}+P^{t}_{PV}+\sum_{j=1}^{G}P^{j,t}_{LDG}+\sum_{i=1}^{N}P^{i,t}_{Dch,EV}=P^{t}_{Load}+\sum_{i=1}^{N}P^{i,t}_{Ch,EV};\forall t \quad (10)$$

This equation guarantees the power balance between power generation and consumption within the MG.

(2) MG spinning reserve constraint:

The energy suppliers in the MG can offer both energy and spinning reserve through bids [47]. During a sudden curtailment in renewable power, the local dispatchable generators and the intelligent parking lot are able to maintain the generation and consumption balance.

$$\sum_{j=1}^{G} SR_{LDG}^{j,t} + \sum_{i=1}^{N} (SRS^{i,t} \times SR_{EV}^{i,t}) \geqslant (\omega_W \times P_W^t + \omega_{PV} \times P_{PV}^t); \forall t \quad (11)$$

where $\omega_W$ and $\omega_{PV}$ are the wind speed and solar radiation forecasting errors, respectively. This equation guarantees the amount of allocated spinning reserve to be equal or greater than the curtailment in renewable power at each period of time.

(3) EV's charger constraint:

$$M^{i,t} \times P_{Ch,EV}^{i,t} \leqslant P_{Ch,\max}^{i}; \forall t \quad (12)$$

$$M^{i,t} \times P_{Dch,EV}^{i,t} + SRS^{i,t} \times SR_{EV}^{i,t} \leqslant P_{Dch,\max}^{i}; \forall t \quad (13)$$

where $P_{Ch,max}^{i}$ and $P_{Dch,max}^{i}$ are the maximum charging and discharging power of the $i$th charger. These constraints determines the maximum charging and discharging rate that the charger can provide.

(4) SOC limits:

$$SOC_{\min}^{i} \leqslant SOC^{i,t} \leqslant SOC_{\max}^{i}; \forall t \quad (14)$$

where $SOC_{\max}^{i}$ and $SOC_{\min}^{i}$ are the maximum and minimum SOC of the $i$th EV, respectively. This constraint allows the SOC to vary between predefined minimum and maximum SOC.

(5) Charging/discharging rate limits:

$$-\Delta SOC_{\max}^{i} \leqslant \Delta SOC^{i,t} \leqslant \Delta SOC_{\max}^{i}; \forall t \quad (15)$$

where $\Delta SOC_{\max}^{i}$ is the maximum allowable rate for charging/discharging of the $i$th EV. The charging and discharging rate of battery are limited by this constraint.

(6) Duration of presence in the parking lot:

$$\sum_{t=t_a^i}^{t_d^i} |M^{i,t}| = T_p^i \quad (16)$$

where $t_a^i$ and $t_d^i$ are the arrival time and the approximate departure time of the $i$th EV, respectively; $T_p^i$ is the approximate duration of presence of the $i$th EV in the parking lot. This constraint allows the MGCC to schedule the charging and discharging of each EV while they are available at the parking lot.

(7) The number of switching between charging and discharging:

The maximum number of switching between charging and discharging is determined by the elapsed time of the EV's battery life.

$$D^{i} \leqslant N_{\max} \quad (17)$$

where $D^i$ represents the number of switching between charging and discharging modes during parked period; $N_{\max}$ is the maximum number of switching between charging and discharging modes.

(8) Battery charging constraint:

$$M^{i,t} \times P_{Ch,EV}^{i,t} \times \eta_{G2V} \times \Delta t \leqslant RBC^{i,t-1} \times Cap^{i,t}; \forall t \quad (18)$$

where $\eta_{G2V}$ is the EV's battery charging efficiency. This constraint limits the charging power of each EV based on the remaining battery capacity in each period of time.

(9) Battery discharging constraint:

$$(M^{i,t} \times P_{Dch,EV}^{i,t} + SRS^{i,t} \times SR_{EV}^{i,t}) \times 1/\eta_{V2G} \times \Delta t \leqslant SOC^{i,t-1} \cdot Cap^{i}; \forall t \quad (19)$$

where $\eta_{V2G}$ is the EV's battery discharging efficiency. This constraint limits the discharging power and the scheduled reserve of each EV based on the stored energy in each period of time.

(10) Departure SOC constraint:

$$SOC_{Departure}^{i} \geqslant SOC_{Arrival}^{i} + \Delta SOC_{F}^{i}) \quad (20)$$

where $SOC_{Departure}^{i}$, $SOC_{Arrival}^{i}$ and $\Delta SOC_{F}^{i}$ are the departure SOC, initial SOC and the required additional SOC at departure time of the $i$th EV, respectively. This equation guarantees the departure SOC of each EV to be equal or greater than the customer requirement. The required additional SOC ($\Delta SOC_F^i$) is determined by the EVs owners.

(11) Generation Limits:

$$P_{LDG}^{j,t} + SR_{LDG}^{j,t} \leqslant U^{j,t} \times P_{LDG,\max}^{j}; \forall t \quad (21)$$

$$P_{LDG}^{j,t} \geqslant U^{j,t} \times P_{LDG,min}^{j}; \forall t \quad (22)$$

where $P_{LDG,\max}^{j}$ and $P_{LDG,min}^{j}$ are the maximum and minimum generation of the $j$th generator in period $t$, respectively. The power generation of each generator always is kept between its minimum and maximum power.

(12) Minimum up/down time constraints:

$$(t_{ON}^{j,t-1} - MUT^{j}) \times (U^{j,t-1} - U^{j,t}) \geqslant 0; \forall t \quad (23)$$

$$(t_{OFF}^{j,t-1} - MDT^{j}) \times (U^{j,t} - U^{j,t-1}) \geqslant 0; \forall t \quad (24)$$

where $t_{ON}^{j,t}$ and $t_{OFF}^{j,t}$ are the duration for which the $j$th generator had been continuously up and down till time step $t$, respectively; $MUT^j$ and $MDT^j$ are the minimum up and down time of the $j$th generator, respectively.

(13) Transmitted power limits:

$$|P_{UG}^{t}| \leqslant P_{UG}^{\max} \quad (25)$$

where $P_{UG}^{\max}$ is the maximum possible value for transmitted power between MG and the upstream grid.

The proposed model is solved using mixed integer linear programming (MILP) solver CPLEX under GAMS on a Pentium IV, 2.6 GHz processor with 4 GB of RAM.

## 4. Simulation and discussion

The proposed method was applied to a typical MG illustrated in Fig. 1. Forecasting techniques based on time series method used to obtain the forecast wind speed and solar radiation of a chosen day [48]. Moreover, their forecasted errors are also considered in the proposed method. The spinning reserve requirement to accommodate RESs uncertainty is assigned to 20% of the hourly predicted output powers of renewable generation [35].

The main parameter values of the wind turbines and the PV system are taken from [49] and are illustrated in Tables 1 and 2, respectively. The forecasted wind speed and solar radiation data were taken from Iran meteorological organization and shown in Figs. 6 and 7, respectively [37]. Then the output of the wind generator can be obtained by Eq. (4) and the PV power is calculated by Eq. (5). They are shown in Fig. 8. The forecasted load is also shown in Fig. 8. The renewable power curve is the total power supplied by the PV and wind generator. There are two MTs and one FC in the MG and the details are shown in Table 3.

The intelligent parking lot is located in the MG with capacity of 200 EVs. The Arrival and departure times of EVs are assumed as random variables. The intelligent parking lot is supposed to be located in the commercial feeder. Based on a statistical study on some parking lots on weekdays in Tehran city carried out by authors, the hourly parking utilization illustrated in Fig. 9 has been obtained. However, the stochastic behavior of EVs' owners in the presence of incentives is not considered in this study and it is assumed that the EVs owners carry out charge/discharge in a

**Table 1**
The main parameter values of the wind generator.

| Gen. type | Rated power (kW) | Cut-in speed (m/s) | Rated speed (m/s) | Cut-out speed (m/s) |
|---|---|---|---|---|
| Wind | 500 | 3 | 12 | 30 |

**Table 2**
The main parameter values of the PV panel.

| Gen. type | Conversion efficiency (%) | Array area ($m^2$) | Ambient temperature (°C) |
|---|---|---|---|
| PV | 15.7 | 1500 | 25 |

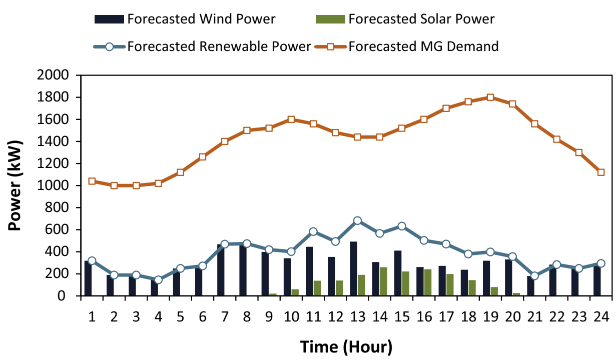


**Fig. 8.** Forecasted MG demand, wind and PV power.

**Table 3**
Local dispatchable generators data.

| Gen. | Gen. type | $a$ ($) | $b$ ($/kW) | $P^{min}$ (kW) | $P^{max}$ (kW) | MUT (h) | MDT (h) | $t_{ON}/t_{OFF}$ (h) | UDC ($) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | MT | 20 | 0.15 | 150 | 700 | 3 | 3 | 4 | 100 |
| 2 | MT | 40 | 0.25 | 100 | 450 | 2 | 2 | −6 | 20 |
| 3 | FC | 90 | 0.45 | 50 | 300 | 1 | 1 | −8 | 20 |

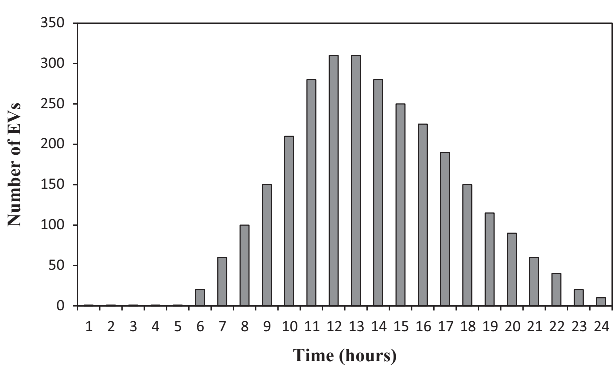


**Fig. 9.** The statistical parking utilization information.

**Table 4**
The relation of AOB and the maximum number of switching between charging and discharging.

| Age of the battery (year) | AOB < 4 | 4 ⩽ AOB < 6 | 6 ⩽ AOB < 8 | 8 ⩽ AOB |
|---|---|---|---|---|
| Maximum number of switching between charging and discharging ($N_{max}$) | 8 | 6 | 4 | 2 |

scheduled time [50]. The stochastic character of EVs' owners and probabilistic nature of arrival and departure time of EVs will be considered by the authors in a future work.

In this paper, the EVs parking lot prioritizes the charging/discharging procedure of each EV considering its arrival time, approximate duration of presence in the parking lot, open market pricing signal, and price offers of other EVs. After that the classified data sent to the MGCC and the main controller uses the received data to optimally schedule the MG resources.

**Table 5**
The hourly electricity price in the open market.

| Hour | Price ($/kW h) | Hour | Price ($/kW h) |
|---|---|---|---|
| 1 | 0.033 | 13 | 0.215 |
| 2 | 0.027 | 14 | 0.572 |
| 3 | 0.020 | 15 | 0.286 |
| 4 | 0.017 | 16 | 0.279 |
| 5 | 0.017 | 17 | 0.086 |
| 6 | 0.029 | 18 | 0.059 |
| 7 | 0.033 | 19 | 0.050 |
| 8 | 0.054 | 20 | 0.061 |
| 9 | 0.215 | 21 | 0.181 |
| 10 | 0.572 | 22 | 0.077 |
| 11 | 0.572 | 23 | 0.043 |
| 12 | 0.572 | 24 | 0.037 |

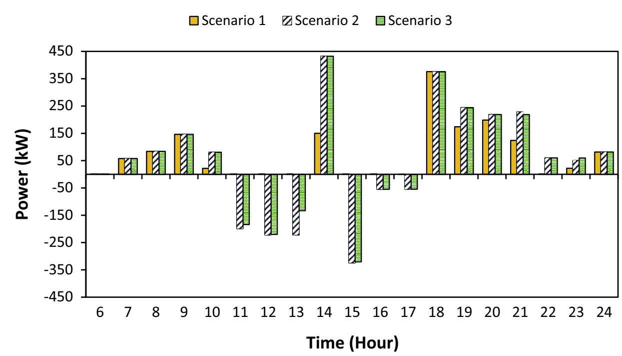


**Fig. 10.** The hourly scheduled electricity demand of the intelligent parking lot.

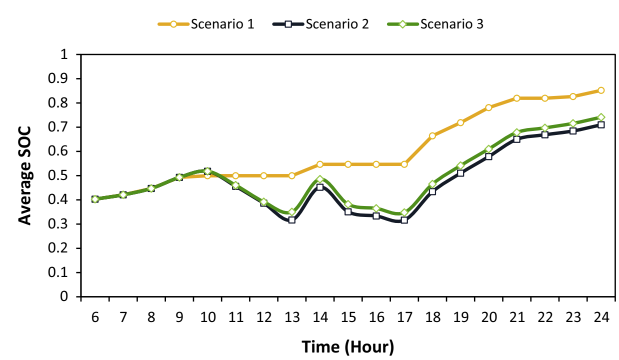


**Fig. 11.** Average SOC for existing EVs in the intelligent parking lot.

There are several types of electric vehicles in the market with various battery capacities from 8 kWh to 48 kWh [51]. In this paper, all electric vehicles supposed to be Chevy Volt [52] which it is an average electric vehicle with 16.5 kWh battery capacity. However, different types and sizes of batteries can be taken into account by the proposed method.

Table 4 presents the relationship between the age of the battery (AOB) and the number of switching between charging and discharging. For example, old batteries have the lowest number of switching between charging and discharging mode.

The initial SOC of each EV is considered as a continuous uniform random number between 0.1 and 0.7. The arrival time is assumed between 6:00 AM and 6:00 PM. Also, the approximate duration of presence in the parking lot is considered as a continuous uniform number between 2 and 8 h.

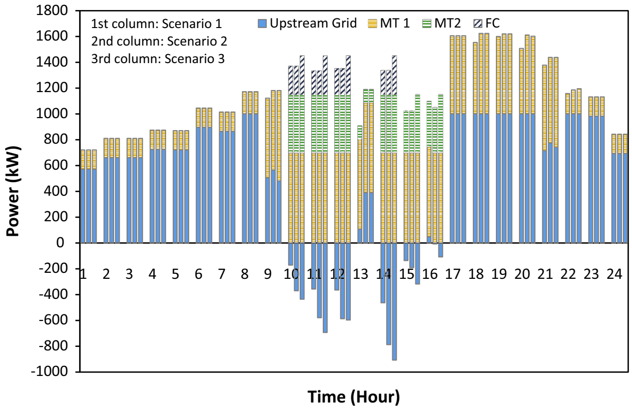


**Fig. 12.** Upstream transmitted power and local dispatchable generators outputs.

The charging price that the EV owners is willing to pay is considered as a continuous uniform random number between 0.15 and 0.3 \$/kW h. The discharging price that the EV owners is willing to sell the stored energy is considered as a continuous uniform random number between 0.25 and 0.4 \$/kW h. The sample time ($\Delta t$) is set to 1 h since it is a reasonable decision making time for 200 EVs. Table 5 provides the hourly electricity price of the open market. The spinning reserves of DGs are priced at a rate equal to 20% of their highest marginal cost of the energy production [53]. The EVs offer reserve at a price equal to 10% of their desired discharging price.

In order to analyze the robustness of the proposed energy and reserve model, the problem is addressed in three scenarios:

- Scenario 1: In this scenario the intelligent parking lot does not contribute in both energy and reserve scheduling and only plays a role as a variable load; the required spinning reserve is provided by local dispatchable generators.
- Scenario 2: In this scenario the intelligent parking lot contribute in the energy scheduling via V2G option but still doesn't participate in the reserve scheduling and the required spinning reserve provided only by local dispatchable generators.
- Scenario 3: In this scenario the intelligent parking lot contributes in both energy and reserve scheduling and the required spinning reserve provided by both the EVs and local dispatchable generators.

The intelligent parking lot scheduled power and its average SOC for existing EVs in these scenarios are shown in Figs. 10 and 11, respectively. During hours with lower electricity prices, the charging amount has been increased in scenarios 2 and 3 rather than the one in scenario 1 due to the capability of EVs in order to sell the stored energy to the upstream grid. In addition, a comparison between scenarios 3 and 2 shows that in scenario 3, the sold energy of the intelligent parking lot decreased briefly because a specific amount of energy should be stored in the EVs' batteries due to provide reserve. In scenarios 1 and 2, MT1 provides spinning reserve during off-peak hours while MT2 and FC provide spinning reserve during peak hours. So, some of the MTs and FC capacity are allocated in order to provide reserve and the required energy should be purchased from the upstream grid with high prices; it increases the MG operation costs. In the third scenario, similar to the scenarios 1 and 2, MT1 provides spinning reserve during off-peak hours. However, in peak hours, the EVs provide the required reserve for the MG with fewer prices.

Fig. 12 shows the exchanged power between the upstream grid and MG as well as scheduled power of local dispatchable generators in these three scenarios.

Table 6 shows the spinning reserve scheduling provided by the intelligent parking lot and local dispatchable generators. In scenarios 1 and 2, MT1 provides spinning reserve during off-peak hours while MT2 and FC provide spinning reserve during peak hours. So, some of the MTs and FC capacity are allocated to reserve and the required energy should be purchased from the upstream grid

**Table 6**
The spinning reserve scheduling provided by the intelligent parking lot and local dispatchable generators.

| Hour | Scheduled Spinning Reserve (kW) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Local dispatchable generators | | | | | | | | | | | |
| | MT 1 Scenario | | | MT 2 Scenario | | | FC Scenario | | | Intelligent Parking Lot Scenario | | |
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | 63.7 | 63.7 | 63.7 | – | – | – | – | – | – | – | – | – |
| 2 | 37.8 | 37.8 | 37.8 | – | – | – | – | – | – | – | – | – |
| 3 | 37.8 | 37.8 | 37.8 | – | – | – | – | – | – | – | – | – |
| 4 | 29.0 | 29.0 | 29.0 | – | – | – | – | – | – | – | – | – |
| 5 | 49.8 | 49.8 | 49.8 | – | – | – | – | – | – | – | – | – |
| 6 | 54.4 | 54.4 | 54.4 | – | – | – | – | – | – | – | – | – |
| 7 | 93.8 | 93.8 | 93.8 | – | – | – | – | – | – | – | – | – |
| 8 | 94.8 | 94.8 | 94.8 | – | – | – | – | – | – | – | – | – |
| 9 | 83.9 | 83.9 | – | – | – | – | – | – | – | – | – | 83.9 |
| 10 | – | – | – | – | – | – | 80.2 | 80.2 | – | – | – | 80.2 |
| 11 | – | – | – | – | – | – | 116.7 | 116.7 | – | – | – | 116.7 |
| 12 | – | – | – | – | – | – | 98.6 | 98.6 | – | – | – | 98.6 |
| 13 | – | – | – | 136.5 | 136.5 | – | – | – | – | – | – | 136.5 |
| 14 | – | – | – | – | – | – | 113.3 | 113.3 | – | – | – | 113.3 |
| 15 | – | – | – | 126.5 | 126.5 | – | – | – | – | – | – | 126.5 |
| 16 | – | – | – | 100.6 | 100.6 | – | – | – | – | – | – | 100.6 |
| 17 | 94.0 | 94.0 | 94.0 | – | – | – | – | – | – | – | – | – |
| 18 | 76.0 | 76.0 | 76.0 | – | – | – | – | – | – | – | – | – |
| 19 | 79.6 | 79.6 | 79.6 | – | – | – | – | – | – | – | – | – |
| 20 | 71.2 | 71.2 | 71.2 | – | – | – | – | – | – | – | – | – |
| 21 | 36.3 | 36.3 | 2.7 | – | – | – | – | – | – | – | – | 33.6 |
| 22 | 56.8 | 56.8 | 56.8 | – | – | – | – | – | – | – | – | – |
| 23 | 49.8 | 49.8 | 49.8 | – | – | – | – | – | – | – | – | – |
| 24 | 58.9 | 58.9 | 58.9 | – | – | – | – | – | – | – | – | – |

**Table 7**
MG total cost in three scenarios.

| Scenario | Total cost |
|---|---|
| 1 | 5931.18 |
| 2 | 5561.16 |
| 3 | 5472.01 |

with high prices; it increases the MG operation costs. In the third scenario, similar to the scenarios 1 and 2, MT1 provides spinning reserve during off-peak hours. However, in peak hours, the EVs provide the required reserve for the MG with fewer prices.

Table 7 shows the MG total operation cost in these three scenarios. In scenario 1 which the intelligent parking lot only plays a role as a controllable load, the total operation cost is $5931.18. In the second scenario which the intelligent parking lot allows the MGCC to use V2G option and the spinning reserves are only provided by the local dispatchable generators, the total operation cost is $5561.16. In the third scenario which the intelligent parking lot participates in the both energy and reserve scheduling, the total operation cost is $5472.01. By comparing scenario 3 with scenarios 1 and 2, the conclusion can be drawn that the total daily operation costs reductions are about 8.4% and 1.6%, respectively.

As shown in Fig. 10, in the first scenario the parking lot purchases electricity during off-peak hours while the EVs are situated in idle mode during peak hours. However in the last two scenarios the parking sells the EV's stored energy to the grid during peak hours while during off-peak hours it purchases electricity from the grid. In the last scenario, the software of the intelligent parking lot involving the EVs with older batteries in the reserve scheduling in order to reduce their switching between charging/discharging mode and with this strategy helps to increase the EVs' battery lifetime [54].

In the scenarios 2 and 3, when the electricity price is high, it is preferred to sell the electricity stored in EVs to gird. The parking load increases dramatically at 14:00 and 18:00, due to high electricity prices between 11:00−13:00 and 15:00−17. So, all of the EVs tend to sell energy to the grid and the average SOC of the existing EVs in the parking decrease significantly. On the other hand, by approaching the final hours of EV's presence in the parking lot and low electricity prices, the mode of the most EVs are changed to charging mode; therefore, a peak load is appeared at 14:00 and during hours 18:00–21:00.

In Scenario 3 comparing with scenario 2, the sold energy of the intelligent parking lot decreased because a specific amount of energy should be stored in the EVs' batteries because of providing reserve.

## 5. Conclusion

In this paper, a new energy resources scheduling for a MG consisting of renewable generation and EVs has been proposed. The intelligent scheduling and control of charging and discharging of EVs introduces a great opportunity for evolving a sustainable integration of electrical and transportation system. Through V2G, EVs' owners can make revenue while their cars are parked; it can provide valuable economic incentives for EV owners. In addition, utilities significantly support V2G capability and benefit from dispersed energy storages in the grid. Simulation results evidenced that the use of intelligent parking lot for managing of the charging/discharging of EVs has eliminated the risk of an electricity demand growth during the peak load of the network. The proposed model helps the IPL to play a role as an aggregator in order to collect the dispersed EVs in an accumulated area and manage their energy demand and provide a proper V2G infrastructure for them in order to sell the stored energy or provide the required spinning reserve. In the proposed model, the EVs charging/discharging strategy for implementing in an intelligent parking lot has been also presented. The economical and technical aspects of EVs charging/discharging were simultaneously taken into account. As, the renewable power forecasting errors led into serious risks for the power system, The proposed model scheduled reserve in order to eliminate generation and consumption mismatch. In this paper, spinning reserve is provided by local dispatchable generators and intelligent parking lot. The proposed model helps the intelligent parking lot to play a role as an aggregator in order to collect the dispersed EVs in an accumulated area and manage their energy demand to prevent unexpected overloads or power mismatch in the power system. The results showed that the charging was carried out during the hours with lower electricity prices while during the hours with higher electricity prices the proposed model preferred to discharge the EVs to sell the stored energy or provide the required spinning reserve. Also, considering the lifetime of battery as an important parameter affected the charging/discharging scheduling of EVs as well as ancillary service scheduling.

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