

Impact of plug-in hybrid electric vehicle charging/discharging management on a microgrid

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Abstract: Plug-in hybrid electric vehicles (PHEVs) may replace conventional vehicles in most urban areas and populated cities due to their lower levels of air pollution compared to internal combustion engine (ICE) vehicles. PHEVs can increase the ability of residential complexes to participate in demand-side management, as well. This paper explores the potential of PHEVs as a flexible load in order to satisfy 2 main issues: increasing the penetration rate of renewable energy in a microgrid and increasing the load factor. In this study, 3 scenarios for managing PHEV charging and discharging are considered. The first scenario connects PHEVs to the grid as plug-and-forget demand. In the second and third scenarios, PHEVs are connected vehicle to grid (V2G). This means that both charging and discharging are possible in an interface. For each scenario an algorithm is defined to manage the charge and discharge of vehicles. Load factor, rate of renewable energy penetration, and total costs are 3 factors we tried to improve in these algorithms.

This study was performed for the Ekbatan residential complex in Tehran, Iran. There are many regions around the world with similar situations where this work could be expanded.

Key words: PHEV, renewable energy, demand side management, charging, discharging

1. Introduction

According to a study by the Iran Air Quality Control Company, in 2011 air pollution was at an unhealthy level on more than 250 days in Tehran, and the main source of pollution was internal combustion engine (ICE) vehicles. The government decided to reduce alarm level days to 20 by improving vehicle electrification in the public transportation system and replacing ICE vehicles with electric vehicles [1]. A PHEV is a hybrid electric vehicle (HEV) with the ability to charge the grid it is connected to. This feature of PHEVs will make it possible to improve energy resources for domestic consumption and decrease car exhaust fumes in business and residential areas.

Two important renewable resources, photovoltaic (PV) and wind turbines, are intermittent. Vehicle to grid (V2G) is technology that can use PHEVs to support renewable energy resources as an energy storage system. Conventional methods of load management can cover the intermittency of renewable energy at a low level of penetration and supply its fluctuations. However, if renewable energy increases to 10%–30% of the power generation system, power fluctuation in renewable units should be amended by additional resources. This

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intermittency can be managed by either conventional power plants or storage. Storage has another advantage; it can absorb the surplus power of renewable units while adding the constraint that this power is given back for a limited duration [2]. On the other hand, PHEVs can increase the reliability of power systems significantly and inexpensively compared to other storage systems, especially in microgrids that have variable and unpredictable generation from renewable sources. In [3] prospective PHEVs and the benefits of them for their owners, the environment, the power grid, and the government were presented, and the control and communication equipment required were given. In reference [4] the best time for PHEV charging and discharging is found by PSO method. In this paper different tariffs for hours of the day are considered. Past studies suggested that the existing power generation units had the capacity to supply the increased load of PHEVs if their market share increased up to 25% [5]. PHEVs can be considered responsible loads, and they are appropriate loads to charge whenever electrical demand is low. They can participate in demand-side management (DSM), which leads to an improved load duration curve [6–12].

In [13], charging PHEVs as vehicle-to-grid technology is considered. It is an opportunity to create flexible load as a part of DSM based on network operation. The method presented in [14] was performed to analyze and obtain applicable data about the influence of PHEVs on the grid system. In [15], a residential grid-connected PV system is designed to supply PHEV charging. Reference [16] presents an energy model and studies the economic and environmental impact of a personal ecosystem for residences and transportation based on renewable energy sources and PHEVs. The main objective of [17] is to consider a residential photovoltaic system to supply a plug-in hybrid electric vehicle load, in addition to regular residential requirements. In [18] the capability of electrical vehicles (EVs) and PHEVs are presented as dynamic, configurable energy storage appliances that can be used in transportation and power systems.

There is negligible electrical storage in existing power grids; therefore, power plant generation should follow demand. Energy storage is the system that can be used to increase the superposition of demand and generation. Batteries of PHEVs have the capacity to serve as energy storage if the number of PHEVs increases significantly [19,20].

One study showed that a considerable number of vehicles are parked in a parking area most of the time. Since vehicles should be connected to the grid after they are completely charged to utilize their energy storage capacity, it could be beneficial to pay incentives to vehicle owners who are committed to this project. Vehicles follow a significant traffic schedule most days of the week that does not change remarkably from week to week [21,22].

In addition to the management algorithms and data gathering regarding wind, sun irradiance, and PHEV behavior in traffic, the novelty of this paper is in studying PHEV charge and discharge management over a long time period; the economic and systematic impact of this management can be used in energy planning in a residential complex. Recent papers on PHEV charge and discharge management have been short studies, but here a period of 1 year is considered in simulation. This management algorithm can use PHEV charging, which is a remarkable part of the future power grid load as a storage system. It can improve the power grid with less investment when compared with conventional storage systems.

In real cases charging process management should be dynamic. Input data from management programs can be achieved through metering instruments installed on equipment such as wind turbines, feeder outputs, and some counter sensors installed on entrance and exit gauges. In this paper offline management is used; however, we tried to use databases derived from local data gathering in order to produce a case resembling the real world case as much as possible.

The remaining part of this paper is structured as follows. Basic assumptions regarding the electrical energy source and electrical load of the Ekbatan complex are presented in the first section. Then charging load of PHEVs is studied. Three scenarios of PHEV load management are defined in the next step. For each scenario we used an algorithm to improve some characters of the power system such as load factor, rate of renewable energy penetration, and total cost. Finally we conclude with a discussion of the results and one scenario is chosen as the best solution for the air pollution problem in our case study.

2. Power sources and load of the Ekbatan complex

Ekbatan is a residential complex whose owner wants to convert it to a green complex. A study is done to find the best combination of electrical resources, and those are used to gain maximum possible renewable electrical energy after 20 years. As a result, 30 MW wind turbines and 35 MW photovoltaic panels are chosen. The capacity of these resources is more than the load of the Ekbatan complex; however, because they usually produce less energy than their nominal capacity, additional production can be sold to the electrical grid. The Ekbatan complex decides to use as much renewable energy as they can.

The electrical energy sources of Ekbatan considered are wind turbine, photovoltaic panel, and connection to a distribution network, after 20 years. There will be 20 wind turbines in this hypothesis with a rated power of 1.5 MW: cut in speed of this wind turbine is V_{cut-in} , 3 m/s; rated speed is $V_{cut-rated}$, 7 m/s; and cut off speed is $V_{cut-out}$, 20 m/s. These data are from a Vestus V-60 (tower length 80 m, blade length 2.4 m). The distribution network connected to this complex grid has a capacity of 35 MW.

3. Wind turbine outlet energy

The electrical power production of each wind turbine can be calculated from its power–speed curve. Such a curve is illustrated in Figure 1. Eq. (1) represents the outlet power of the wind turbine versus the wind speed [23]:

$$P_w = \begin{cases} 0 & V < V_{cut-in}, V > V_{cut-out} \\ P_{rated} \times ((V - V_{cut-in}) / (V_{rated} - V_{cut-in}))^3 & V_{cut-in} < V < V_{rated} \\ P_{rated} & V_{rated} < V < V_{cut-out} \end{cases} \quad (1)$$

in which P_w is the outlet power of wind turbine (kW), V_{cut-in} is the cut in wind speed (m/s), $V_{cut-out}$ is the cut out wind speed (m/s), V is wind speed (m/s), V_{rated} is nominal wind speed (m/s), and P_{rated} is the maximum power of the wind turbine (kW).

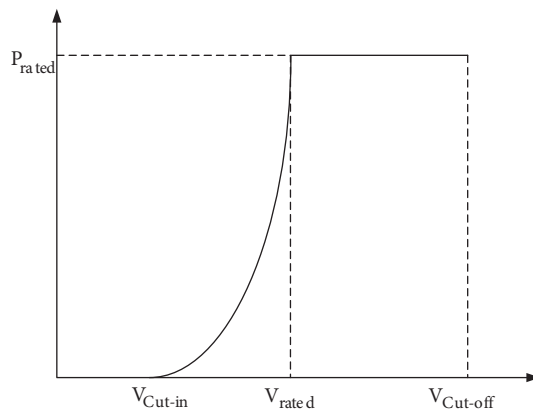


Figure 1. Power–speed curve of wind turbine.

Annual speed of the wind is recorded in west Tehran. These data are recorded at 3 different heights (10, 30, and 100 m) by the Iran Renewable Energy Organization. They estimate wind speed for each height by a conversion equation and interpolation. The estimated data for 80 m height is shown in Figure 2. The maximum wind speed recorded in that year is 29.9 m/s and the average was 4.9 m/s. Standard deviation of annual wind was 4.1 m/s, which shows high variation of wind and, as a result, high variation in wind turbine production. If this wind blew into Vestus V-60 blades, its electrical production would have been used in simulation. In this paper the 10th week of the year is considered the sample week for more visibility. Wind speed and wind turbine production for the 10th week of the year are shown in Figure 3. Mean value of 30 MW wind turbine production is 10.2 MW in the year of sampling.

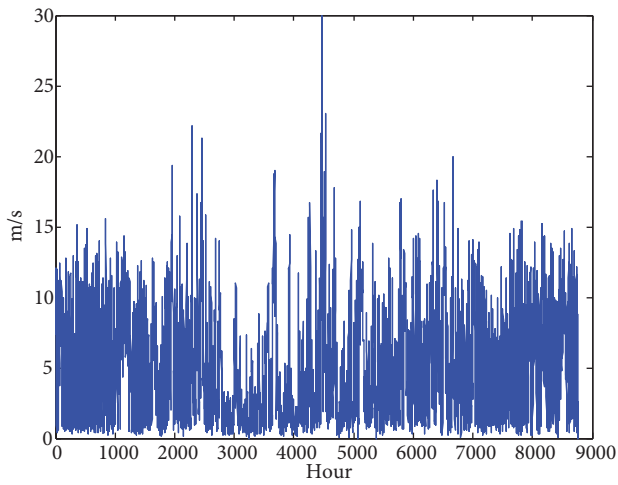


Figure 2. Annual recorded speed of wind for west Tehran.

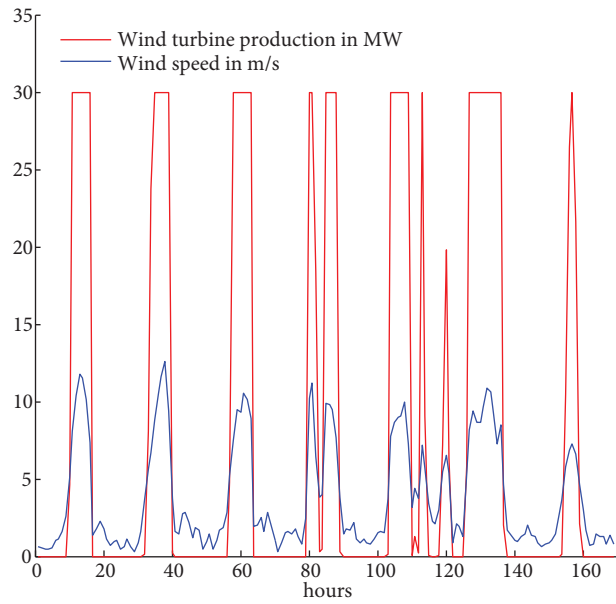


Figure 3. Wind speed and turbine electrical production in the 10th week.

3.1. Photovoltaic outlet energy

A photovoltaic (PV) is a combination of several photovoltaic modules that convert sunlight irradiance into electricity. The output power of the PV units (P_{pv}) can be calculated according to Eq. (2):

$$P_{PV} = \eta_g \times N \times A_m \times G_t \tag{2}$$

where η_g is the PV generator efficiency, A_m is the area of a single module used in a system (m^2), G_t is the global irradiance incident on the titled plane (W/m^2), and N is the number of modules [24].

After 20 years 35 MW photovoltaic panels are considered as installed. One year of irradiance is recorded at that site and shown in Figure 4. The mean value was $173 W/m^2$, and maximum irradiance recorded in that year was $990 W/m^2$. The standard deviation of recorded data was $248 W/m^2$. The sun irradiance and electrical power of photovoltaic panels for the 10th week are shown in Figure 5. Mean value of annual photovoltaic panel production was 6 MW.

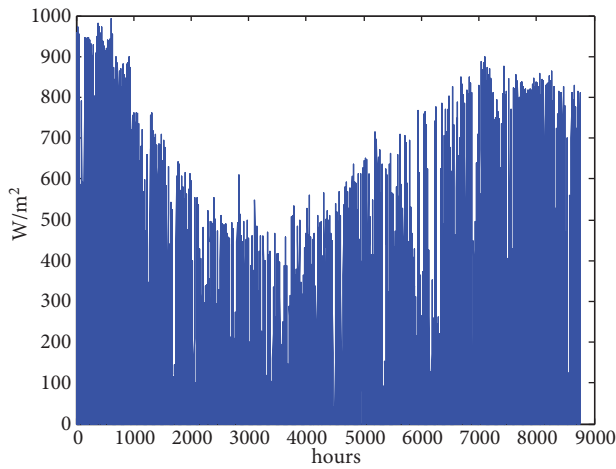


Figure 4. Annual sun irradiance.

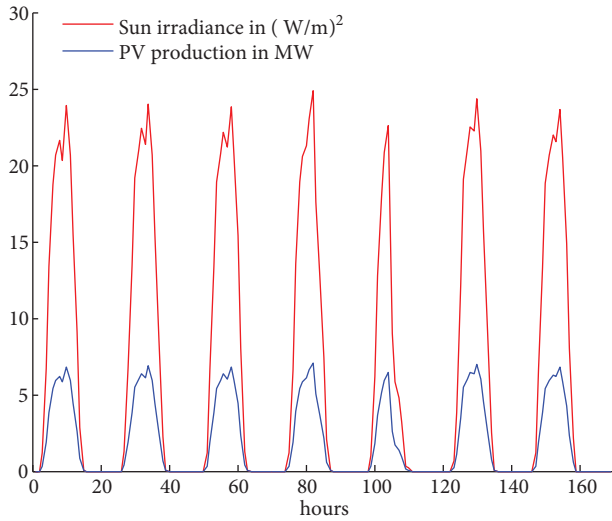


Figure 5. Sun irradiance and PV panel electrical power production in the 10th week.

3.2. Ekbatan conventional load

Ekbatan is the large residential complex in Tehran considered as a case study in this research. According to the recorded distribution system data, the maximum demand of the Ekbatan complex is 22.5 MW. Residential electrical load per user in Iran from 1988 to 2011 is shown in Figure 6 [25]. Curve fitting of these data represents 0.039 as the annual growth in Iran of the residential electrical load of each user. If this rate were fixed after 20 years, the maximum residential load of Ekbatan complex would increase from 22.5 MW to 30 MW.

There are conventional load curves for residential complexes. The IEEE Subcommittee on the Application of Probability Methods has developed a reliability test system and has represented a unique load curve for 1 year [26], which is shown in Figure 7. The annual load of Ekbatan is 30 MW multiply IEEE standard load curve. This load curve is considered a conventional load for the Ekbatan complex without charging demand. In this hypothesis the minimum conventional load of Ekbatan complex is 9 MW and the average is 18.6 MW.

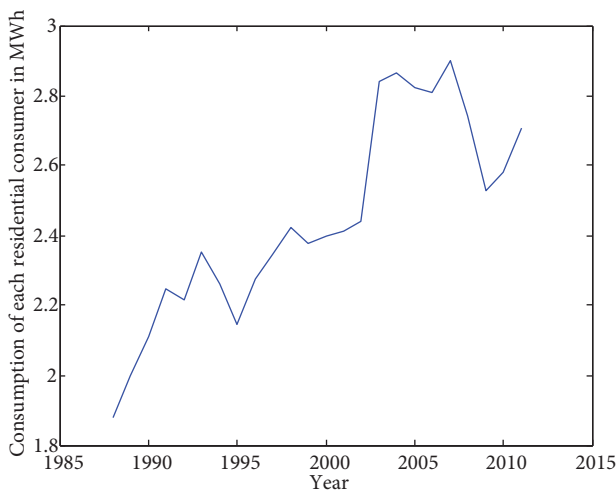


Figure 6. Residential electrical load of each user per year.

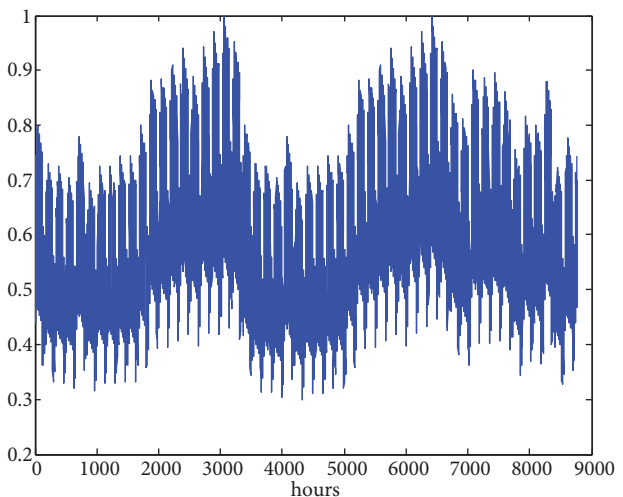


Figure 7. IEEE unique load curve.

4. Charging load of PHEVs according to their traffic behavior

4.1. Traffic curves

In order to manage the charge and discharge of PHEVs, their traffic behavior should be studied first. The traffic behavior contains data about the number of vehicles in the parking area and the number of those entering parking and exiting. Based on this a database of energy required to charge PHEVs is calculated. It assumes that the battery of each vehicle that enters the parking is empty, and it should be charged over a predetermined time depending on the charging scenario. Additionally, the energy that is stored in batteries can be discharged to the grid and contribute to energy production. In order to find the above curve, a block of a building with 100 residential units is considered. Statistics concerning the movement of vehicles to and from parking is recorded for a week. A questionnaire was completed by residents to check whether the recorded data were acceptable for 1 year or good only over the sampling period. The statistical data are a cyclic curve due to special traffic requirements such as going to the office, shopping, and sightseeing on the weekend. This data gathering showed that weekday traffic curves resemble each other, but Thursday and Friday (the 2 weekend days in Iran) have different curves. Exit and entrance curves from Monday, Wednesday, Thursday, and Friday are shown in Figure 8.

From this database exit and entrance numbers of PHEVs for all 8760 h of 1 year are estimated. Exit and entrance of vehicles in the 10th week of the year are shown in Figure 9. There are 27 nonweekend vacations in Iran, and their curves are considered Fridays and added to the annual curves by a randomized calculation.

These curves are estimated because in this study the charging and discharging process is managed offline; however, in real cases management is dynamic, and data can be achieved by sensors installed at the entrance and exit of each parking area.

4.2. PHEV-charging electrical load curve

The Ford Escape PHEV 2013 is the PHEV considered as a case study in this paper. It has a 10 kWh, 400 V, and 25 Ah battery [27]. It takes 3 h to charge an empty battery completely. In this research, state of charge (SOC) of the PHEV battery is considered zero (battery is empty) upon entering the parking area. If each PHEV was connected to a charger without any management of the start time of charging mode, it would start charging for the next 1 h period. The sampling time in this case study is 1 h, and the energy transferred to the battery during this 1 h period is 10 kWh/3. In a real-case charging curve, voltage versus current is a descendant curve. In this study it is considered fixed, because this study is a review over time and its aim is energy planning, and so instantaneous load has less importance than cumulative load. At the end of this charging mode (CM), SOC will be changed by one-third. The same condition is considered for discharging mode (DM).

Ekbatan is a residential complex with about 15,000 units. Each unit has approximately 1 car, so there are 15,000 cars in this complex [28]. If penetration of PHEVs increased to 20% after 20 years there would be 3000 PHEVs in this complex.

According to sample recording data of vehicle traffic behavior and number of PHEVs, vehicle exit and entrance and parked PHEVs are estimated for 3000 PHEVs. The charging demand curve for the 10th week of the year is illustrated in Figure 10.

5. Scenarios of PHEV load management

Three scenarios are considered in this paper. The first scenario, plug and forget, does not have management of the charging process of PHEVs, and each vehicle receives its needed charge when it is connected to the plug.

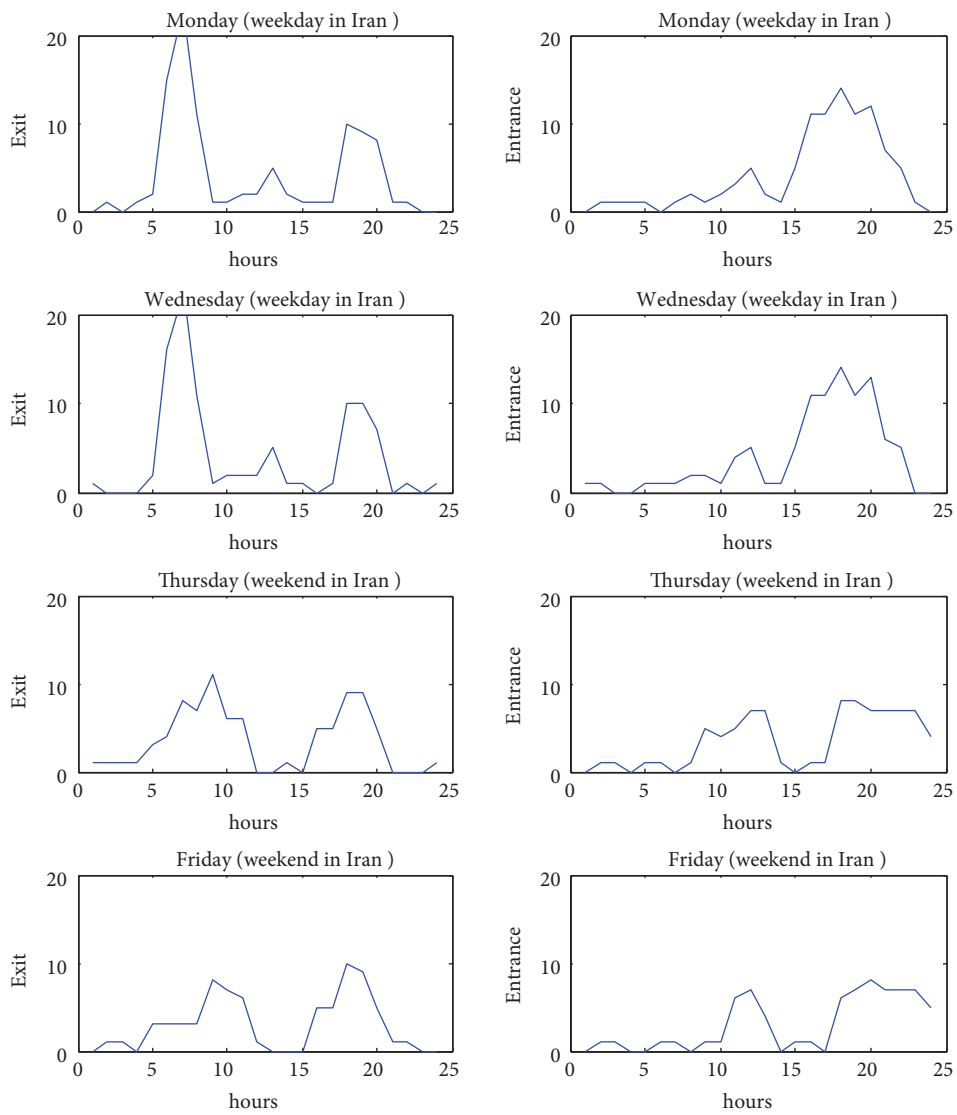


Figure 8. Exit and entrance curves of vehicles to and from their parking area on different days.

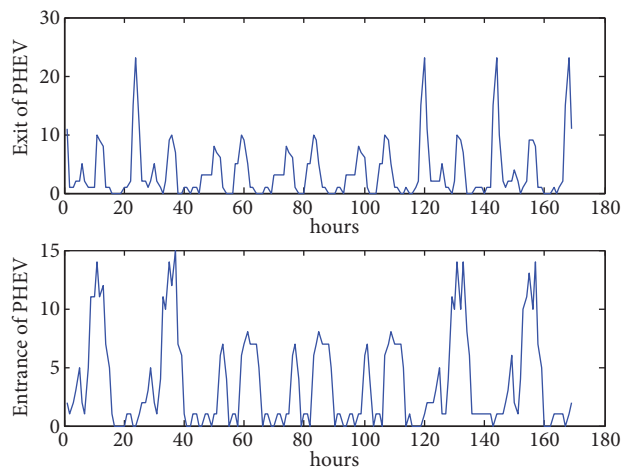


Figure 9. Exit and entrance number of PHEVs in the 10th week of the year.

They do not discharge to the grid in the first scenario. The second scenario is a management process to increase the renewable energy penetration rate in Ekbatan complex electrical consumption. As these units are owned by this complex, with a greater penetration rate the owners pay lower prices for electrical energy from the Electrical Distribution Network Company. The final scenario is allocated to improve the load factor in Ekbatan complex load by using PHEV charge and discharge management. The charging and discharging process management in these 3 scenarios is represented briefly in Table 1.

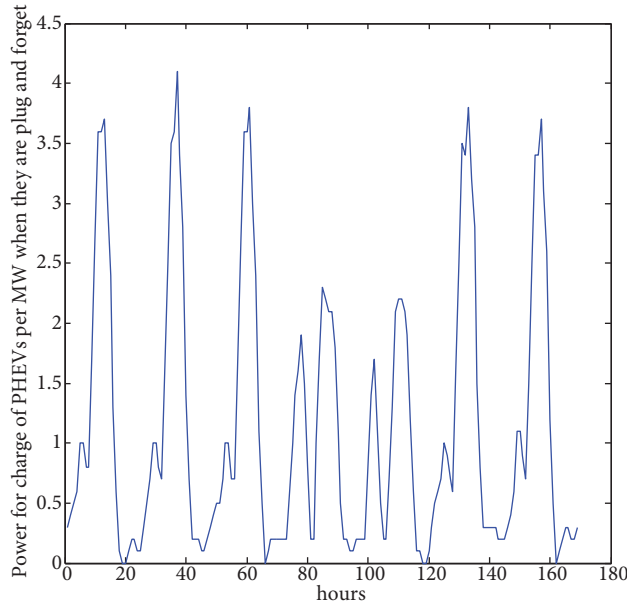


Figure 10. PHEV charging electrical load curve for the 10th week.

Table 1. Charging and discharging process management.

	Scenario title	Charging and discharging management process
1	Plug and forget	No management
2	Reducing electrical costs and increasing the penetration rate of renewable energy	If renewable unit production is more than conventional load of the Ekbatan complex, charge PHEVs as much as they need. If renewable unit production is less than conventional load of the Ekbatan complex, discharge PHEVs as much as possible.
3	Improving load curve and reducing electrical costs	If the load curve is less than the daily mean value of load, charge PHEVs as much as they need. If the load curve is more than the daily mean value of load, discharge PHEVs as much as possible.

5.1. First scenario: plug and forget

According to the first charging scenario, each PHEV that is connected to the charger receives the required charge without any management. Charging demand is added to the conventional load of the Ekbatan complex to make a total load. The distribution network supplies the difference in power between total load and renewable generation in each hour of simulation.

In Iran the electrical price of a distribution network is a single tariff, and it has been fixed at 200\$/MWh, but recently change to a 3 states tariff was discussed to include high, medium, and low consumption hours. In

this system, for high consumption hours the tariff is doubled and in low consumption hours it is halved. In this scenario the annual cost of electrical energy bought from the distribution network is 16.6 M\$, using the 3 tariff calculation. Load factor is 0.59, and renewable energy units produce 51.6% of the electrical demand of the Ekbatan complex. Power that should be supplied to the Ekbatan complex by the distribution network is shown in Figure 11 for the 10th week of the year.

5.2. Second scenario: reducing electrical costs and increasing the penetration rate of renewable energy

The second scenario represents management of PHEV charging and discharging in order to increase the penetration rate of renewable energy and reduce the cost of electrical energy purchased from the distribution network.

PHEVs are parked for longer than the time required to charge completely. As a result, they can be charged whenever the production of renewable energy is greater than the conventional load requirement of the Ekbatan complex, and they can discharge to supply the load of Ekbatan when renewable energy units produce less energy than required. The possible discharge capacity of PHEVs per hour is considered 10% of the charge in their batteries. Most people prefer to have a fully charged vehicle in the morning and so management should cover this condition. Although the conventional load of primary hours of the day is low, PHEVs will be charged 3 h before 0700 hours in order to guarantee fully charged PHEVs every morning.

The algorithm used to manage PHEV charging and discharging in this scenario is shown in Figure 12. For each next 1 h period, this algorithm determines whether to place PHEV batteries in CM or DM.

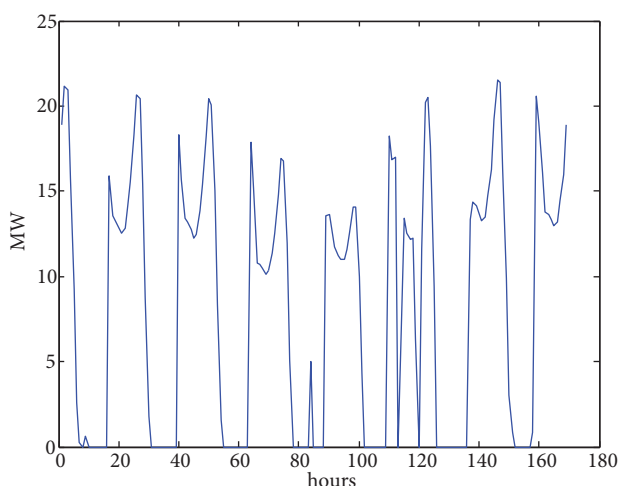


Figure 11. Power that should be supplied by the distribution network for the 10th week.

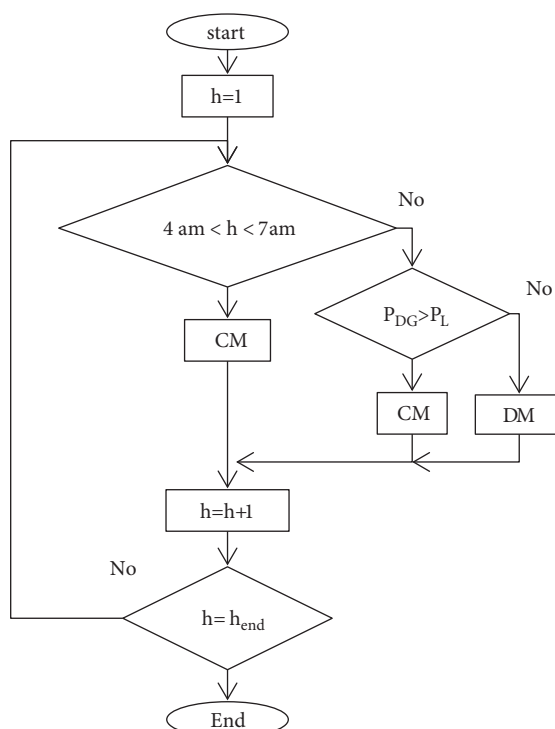


Figure 12. Flowchart 1, second scenario for PHEV CM and DM.

CM: PHEVs are in charging mode for the next hour
 DM: PHEVs are in discharging mode for the next hour
 P_{DG} : distributed generation power production
 P_L : Ekbatan conventional power load
 h: index of time during which PHEVs are in CM or DM
 h_{end} : the final index of time
 For all 8760 h in 1 year (in second and third scenarios):

1. The surplus of renewable energy plant production is sent to the distribution network.
2. If renewable energy plant production is less than the conventional load plus PHEV charging demand, the additional required power is supplied by the distribution network.

In this scenario the annual cost of electricity that should be paid by the Ekbatan complex is 14.0 M\$. This decreases considerably from the first scenario. Renewable energy produces 57.7% of electrical demand. In this case the charge and discharge of PHEVs is shown in Figure 13 for the 10th week of the year (sampling week). The energy that should be supplied by the distribution network is shown in Figure 14. In this case the load factor is 0.52.

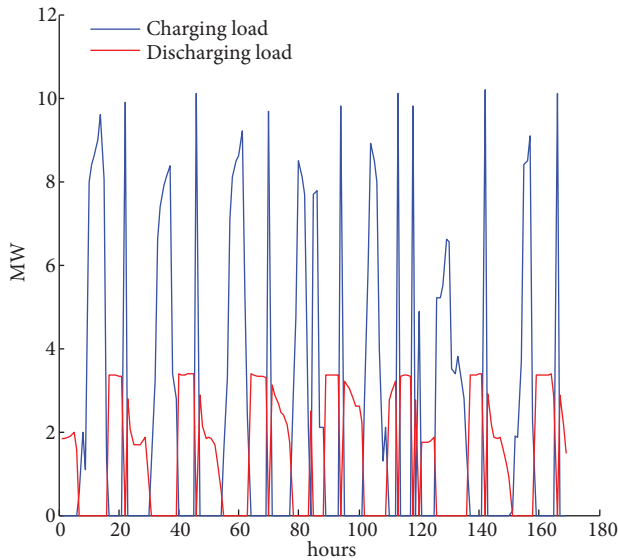


Figure 13. Charge and discharge of PHEVs for 10th week.

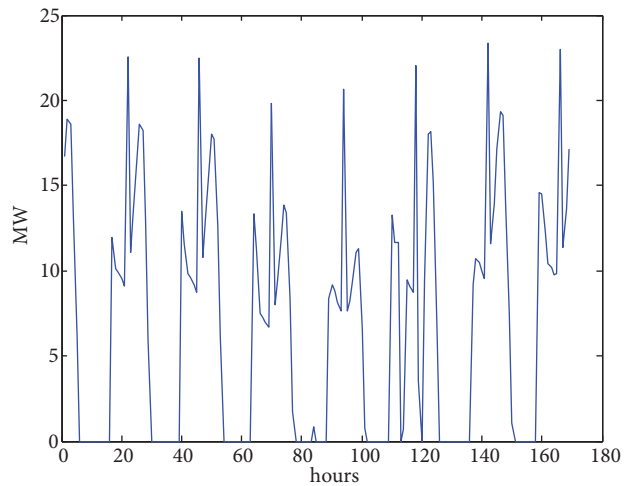


Figure 14. Power which should be supplied by the distribution network.

5.3. Third scenario: improving load curve and reducing electrical costs

In this scenario the charge and discharge process of PHEVs is managed in order to increase the load factor by making the load curve smoother while reducing electrical costs that should be paid to the distribution network by the Ekbatan complex owner. The factor used to decide when PHEVs should be in charge or discharge mode is the load. If each day has a certain load curve that can be predicted several days in advance, the curve is used as a decision-making guide. In this study the mean value of each day's conventional load is the comparison point for each time. If the conventional load is higher than this value, it is better to discharge PHEVs as much as possible to make the load curve smoother. In the first step, the mean value of each day's conventional load is calculated from a hypothetical load curve. PHEV charge and discharge are managed according to this value.

The algorithm used to manage PHEV charging and discharging in this scenario is shown in Figure 15.

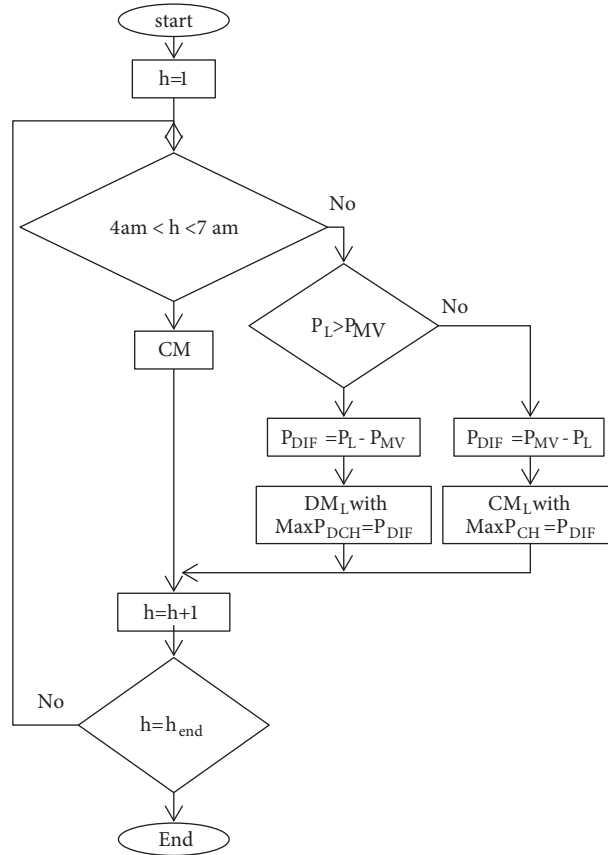


Figure 15. Flowchart 2, third scenario for PHEV CM and DM.

P_{MV} : mean load value of a particular day in the Ekbatan complex

$MaxP_{CH}$: max value of power that PHEVs can be charged in related charging mode

$MaxP_{DCH}$: max value of power that PHEVs can be discharged in related discharging mode

CM_L : limited charging mode of PHEV value up to $MaxP_{CH}$ in next hour

DM_L : limited discharging mode of PHEV value up to $MaxP_{DCH}$ in next hour

For all 8760 h in 1 year:

1. If conventional load of Ekbatan is more than the mean load value of that day, discharge PHEVs as much as possible up to the difference between mean load value and conventional load of the Ekbatan complex.
2. If conventional load of Ekbatan is equal to or less than the mean load value of that day, charge PHEVs as much as they require up to the difference between mean load value and conventional load of the Ekbatan complex.

The result of the simulation in the charging and discharging curve for the 10th week of the year is shown in Figure 16. The energy that should be supplied by the distribution network for the sample week is shown in Figure 17. The cost of energy that should be bought from the distribution network is 15.9 M\$, and the load factor increased to 0.69. In this algorithm daily load curve variation is reduced considerably, as well. In order to evaluate this improvement, the mean square error of daily load (MSEL) of the Ekbatan complex is calculated according to Eq. (3).

$$MSEL = \frac{1}{365} \sum_{n=1}^{365} \frac{1}{24} \sum_{i=1}^{24} (P_{in} - P_{mean\ n})^2 \tag{3}$$

P_{in} : load of Ekbatan complex in i th h of n th day

$P_{mean\ n}$: mean value of the Ekbatan complex load on n th day

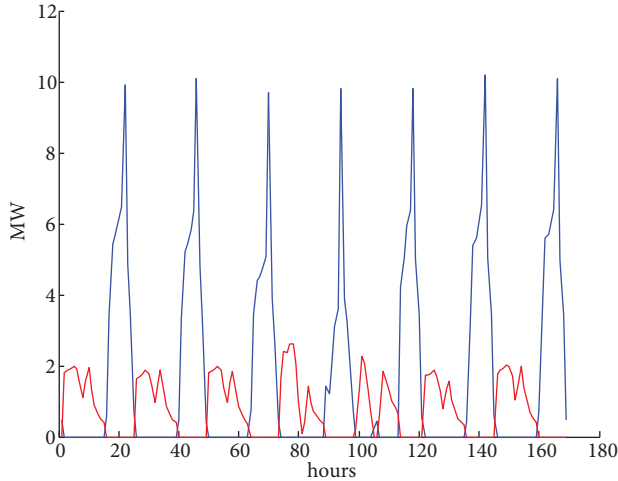


Figure 16. Charge and discharge of PHEVs for the 10th week.

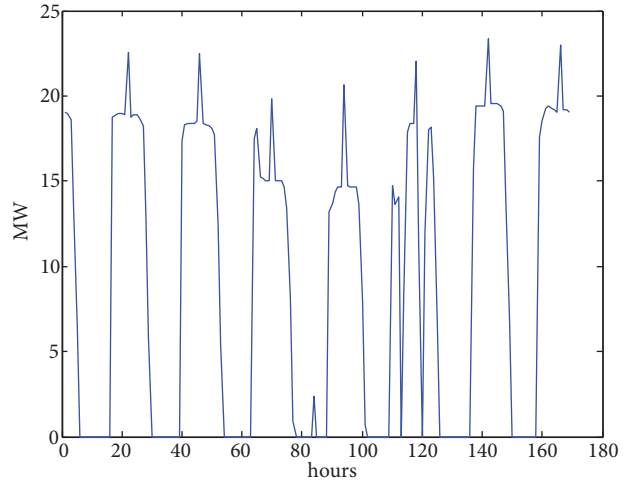


Figure 17. Power that should be supplied by the distribution network for the 10th week.

The MSEL decreases from 1596 in plug-and-forget charging to 334 in this scenario. As a result, the load curve becomes smoother compared to the first scenario.

6. Results and discussion

The characteristics of grid and renewable energy production in these 3 scenarios are presented in Table 2.

Table 2. Characteristics of grid and renewable energy production.

No.	Scenario	Load factor	Mean square error of daily load (smoothness of daily load)	Renewable unit production part	Purchased electricity cost
1	Plug and forget	0.59	1596	51.6%	16.6 M\$
2	Reducing electrical costs and increasing the penetration rate of renewable energy	0.52	1936	57.7%	14.0 M\$
3	Improving load curve and reducing electrical costs	0.69	334	49.5%	15.9 M\$

As seen in Table 2, by using the second scenario in PHEV load management, renewable energy units produce 8% more of the Ekbatan load than the first scenario (plug and forget); penetration of renewable energy increased in the second scenario. Regarding the environmental challenges, this can be a good sign for decreasing air pollution. In addition, the price the Ekbatan complex will pay to the distribution network for electrical energy is 19% lower than in the first scenario. In the third scenario the load factor increased by 6%, and the load

curve became obviously smoother than in the first scenario. Using this scenario, the spinning reserve capacity of the network will decrease, and electrical costs paid to the distribution network by the Ekbatan complex owner should decrease by 4%.

In a system with a high penetration rate of renewable energy, as intermittent renewable energy resources are high, the load factor has less importance than in conventional generation systems, and whenever renewable energy resources have high generation it is best to use it as much as possible. These calculations are made according to current electrical costs. Oil prices will increase in the coming decades; therefore, electrical costs will increase, as well, and it will be more essential to increase the penetration of renewable units. The second scenario is the best.

7. Conclusions

In this paper PHEV load management is presented over a long time period. In order to manage the electrical load of PHEVs, traffic behavior of vehicles was considered to determine how much charging load is needed at each time point and how much capacity the PHEVs discharge to the grid as electric storage. This was determined by computing the number of cars exiting and entering parking on different days of the week. Three scenarios for PHEV load management are presented in this paper. The first scenario is plug and forget; PHEVs start charging whenever they are connected to grid until their batteries are completely charged. In this scenario, no management is performed and the capacity of discharging is neglected. In the second scenario, management of charging and discharging of PHEVs is based on renewable energy resource production. In this scenario, we tried to increase part of the renewable energy plants in producing the required electrical demand in order to decrease the energy bought from the power distribution network. If this specified amount of energy is produced in thermal power plants, use of this management algorithm and elimination of this amount will decrease total air pollution produced by thermal power plants as well. In the third scenario, PHEV load management is used to decrease load curve variation in order to improve the load factor and decrease electrical costs. In this scenario, the variation in load decreases so that the turning spins reserve decreases. This scenario can be used in a grid where the rate of renewable energy plants is low and turning spins reserve has more importance. The second scenario can increase renewable energy penetration and decrease the costs of electricity purchased from the power grid. Therefore, the second scenario is the best for future power systems, because it can increase the penetration of renewable plants and cover their weakness: intermittency. If the price of fuel increases, this capability will be important.

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