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Managing and Minimizing Cost of Energy in Virtual Power Plants in the Presence of Plug-in Hybrid Electric Vehicles Considering Demand Response Program

Hassan Barati† **and Farshid Ashir***

Abstract – Virtual power plants can be regarded as systems that have entered the network after restructure of power systems. In fact, these plants are a set of consumers capable of consuming and generating power. In response to widespread implementation of plug-in hybrid electric vehicles, further investigation of energy management in this type of power plants seems to be of great value. In effect, these vehicles are able to receive and inject power from/into the network. Hence, study of the effects of these vehicles on management of virtual power plants seems to be illuminative. In this paper, management of power consumption/generation in virtual power plants has been investigated in the presence of hybrid electric vehicles. The objective function of virtual power plants problem management is to minimize the overall costs including not only the costs of energy production in power generation units, fuels, and degradation of batteries of vehicles, but also the costs of purchasing electricity from the network. Furthermore, the constraints on the operational of plants, loads and hybrid vehicles, level of penalty for greenhouse gas emissions (CO_2 and NO_x) produced by power plants and vehicles, and demand response to the immediate price of market have all been attended to in the present study. GAMS/Cplex software system and sample power system have been employed to pursue computer implementation and simulation.

Keywords: Distributed energy resources, Plug-in Hybrid Electric Vehicles (PHEV), Virtual power plant, Energy costs, Demand response

1. Introduction

In response to increasing tendency towards alternative technologies and resources of energy, remarkable integration of plug-in hybrid electric vehicles (PHEVs) into electricity networks as well as widespread application of distributed energy resources (DERs) such as micro-turbines, fuel cells, photovoltaic systems, and wind turbines are expected in the ‘not too distant future’ [1]. The costs of energy production, uncertainty in production, environmental concerns about application of fossil fuels, and decrease of these resources all have resulted in reconsideration of the structure of energy resources as well as development of various clean and renewable energy resources. With application of renewable energy resources, consumers are supposed to just pay the cost of energy generation. It is worth mentioning that the costs of energy transmission and distribution, indirect costs of health problems, and environmental remediation costs are not afforded by consumers any more [2]. Furthermore, successive development of electric vehicles leads to their widespread application, as a result of which utilization of a large number of these vehicles in the future of power systems can be anticipated. Application of electric vehicles in general and plug-in hybrid electric vehicles in particular presents several advantages such as reduced emissions of CO_2, NO_x, peak loads created through increasing consumption (charging battery) when the load is low, and peak loads clipping created through injecting power (discharging battery) when the load is high. PHEVs are considered as DERs since they could provide the network with energy. Several energy generators and DERs could be brought together to satisfy the demand load. Although utilization of PHEVs as DERs has some advantages, energy scheduling becomes complicated. Furthermore, gathering several various generation units would make this challenge more intricate. Hence, energy scheduling is a crucial issue in this area.

Recently introduced VPP is responsible for integrating and scheduling distributed energy resources. VPP gathers distributed energy resources and coordinates different organizations as well as other factors in the network. VPP receives energy from DERs and contracts with users to satisfy demand load. In the process of pursuing this objective, a range of economic issues with a completely new scale would be raised [1]. The main purpose of VPP is to integrate different types of distributed energy resources and improve utilization of these resources through development of advanced communication substructures.

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† Corresponding Author: Department of Electrical Engineering, Dezful Branch, Islamic Azad University, Dezful, Iran. (barati216@gmail.com)
* Department of Electrical Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran. (ashirfarshid@gmail.com)

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There are different studies about PHEV-related subjects such as PHEV impacts on the electricity network [3,4], battery capacity analyses [5], environmental impacts [6,7], market analyses [8,9], demand analyses [10,11] and charging infrastructure [12,13].

Several studies have investigated energy scheduling in PHEV-penetrated networks [14-20]. Although energy management systems or market analysis models are presented in these studies, the impacts of pollution and cost-related issues are not addressed clearly. In a study conducted in this regard, the values of PHEVs as network resources were analyzed. Furthermore, PHEVs battery charging was modeled, which incorporated units in the power system according to ERCOT (Electricity Reliability Council of Texas) formulated as MILP (Mixed-Integer Linear Programming) [21]. The objective of the model was to minimize the overall cost of system including generation costs as well as the operation costs of PHEVs. The mentioned study addressed the financial and pollution impacts in the network area; however, DER and VPP were not attended to. The mentioned model had to be applied [22] along with another model to decide on driving and charging of PHEV by its owner. The combination of these two models contributed to the examination of the incentives of drivers of different electricity tariffs. However, the possibility of PHEV battery application as an energy supply was not considered. Ref. [23] focused on the effects of optimal integration of plug-in hybrid vehicles on economic efficiency of micro-grids. Monte-Calro simulation was used to deal with uncertainties of daily trip distance driven of the PHEVs, load values, and market price. Moreover, genetic algorithm was an optimization method, which tried to minimize total operational cost of micro-grids.

In ref. [24], a stochastic operating strategy based on teaching-learning optimization algorithm is proposed for VPPs considering different uncertainties and stochastic consumption of plug-in hybrid electric vehicles (PHEVs). Ref. [1] addressed VPP formation considering penetration of hybrid electric vehicles in the network. Furthermore, the study investigated the effects of cost-related issues and emission of pollutants. In addition, a method was suggested to schedule distributed energy resources and electric vehicles with application of the concept of virtual power plant to minimize energy cost. However, the costs of environmental pollution damages caused by plants and vehicles were not addressed in this study.

The main contribution of this paper is to propose a method for management of energy resources by VPP in the presence of hybrid electric vehicles, which minimizes the overall cost and emission of CO_2 and NO_x with consideration of penalty rate for producing environmental pollution of greenhouse gases in cost function with or without demand response. The optimization framework is mathematically modeled as Mixed Integer Programming (MIP) and solved using a CPLEX solver in the General Algebraic Modeling System (GAMS) [25].

The paper is organized as follows. In section 2, the formulation of energy management in virtual power plants considering hybrid vehicles and demand response program is explained. Section 3 contains the simulation results followed by the conclusions.

2. Formulation of Energy Management in Virtual Power Plants in the Presence of Hybrid Vehicles

The virtual power plant considered in this study consisted of micro-turbines, solar and wind farms, fuel cells, biomass units, and small hydro and geothermal plants. Furthermore, in the case of necessity, it was capable of purchasing energy from the upstream electricity network.

In the following sections, objective function and constrains of the problem are discussed in detail.

2.1 Problem formulation of scheduling virtual power plant

It is supposed that a group of people form a VPP to decrease cumulative cost and enjoy its economic benefits. First, the group receives electricity from national network for certain tariff. After formation of a VPP, the group can receive the required energy from different sets of EPs (Energy Providers) to reduce the costs. There are some small-scale plants (EP) such as micro-turbines, solar and wind farms, fuel cells, biomass units, small hydro and geothermal plants as well as national networks. The cost of obtaining energy from EPs varies through time. Each EP has an efficiency percentage and a minimum and maximum power limit. VPP is responsible to obtain the required energy level from EPs and then transmit it to a set of consumers with TE (Time Elastic) and TIE (Time Inelastic) loads. If required, the VPP can also obtain energy from PHEV batteries by discharging them.

PHEV battery has a charging efficiency, which is the percentage of the energy that can actually be stored. Furthermore, the efficiency of discharge is the percentage of stored energy in PHEV battery, which can be delivered to VPP. Each PHEV has an initial level of charge, can be charged / discharged during the day, and consumes energy. PHEV batteries require a minimum level of energy, and the level of battery charge cannot be lower than this level. As long as the level of battery charge is higher than the minimum level of charge, PHEV can travel in a charge-depleting (CD) mode. Whenever the battery charge reaches its minimum level, it switches to charge-sustaining (CS) mode and travels through consuming gasoline.

Charge and discharge scheduling is a shared decision between VPP and the owner of PHEV. The owner of PHEV decides on the time and length of connection, and mileage of travel. In fact, VPP is responsible for charge and discharge scheduling and supplies energy for PHEV considering gasoline and electricity costs. VPP fulfils the mentioned duty through dispatching EPs as required.

The study is aimed at managing VPP energy and minimizing the overall cost of energy to supply load and develop charging and discharging schedules of PHEVs. Pollution caused by units and vehicles are taken into account in the overall cost. This model considers a penalty per kilogram of produced greenhouse gases, which should be paid to the respective environmental entity. This results in a scheduling which minimizes the cost and pollution.

The objective function is defined as follows [1]:

$$\begin{aligned} C_1 = &\sum_{t\in T}\left[\sum_{u\in U} c_{u,t}^{EP} \times e_{u.t}^{EP} + \sum_{u\in U} c_u^{SU} \times s_{u,t}\right] + \\ &\sum_{t\in T}\left[\sum_{v\in V}\left(c_t^{gas} \times cs_v \times d_{v.t}^{CS} + [f(\delta_{v,t}) - f(\delta v, t-1)]^+\right)\right] \end{aligned} \tag{1}$$

where,

$$\underline{p}_v \le e_{v,t-1}^{PHEV} \le \overline{p}_v ; \forall_{v\in} V, \forall t \in T \tag{2}$$

$$\begin{aligned} e_{v,t}^{PHEV} &= e_{v,t-1}^{PHEV} + \eta_v^+ \times e_{v+t}^+ \\ &- \frac{1}{\eta_v^-} \times e_{v+t}^- - E_{v,t}^{reg} ; \forall v \in V, \forall t \in V \end{aligned} \tag{3}$$

$$e_{v,0}^{PHEV} = PO_v ; \forall v \in V \tag{4}$$

$$e_{v,t}^+ \le \rho_v^+ \times I_{v,t} \times x_{v,t} ; \forall v \in V, \forall t \in T \tag{5}$$

$$e_{v,t}^- \le \rho_v^- \times I_{v,t} \times \left(1 - x_{v,t}\right) ; \forall v \in V, \forall t \in T \tag{6}$$

$$d_{v,t}^{CD} \le \mathrm{d}_{v,t}^{total} ; \forall v \in V, \forall t \in T \tag{7}$$

$$d_{v,t}^{CD} \le \frac{\left(e_{v,t-1}^{PHEV} - \underline{p}_v\right)}{E_v} ; \forall v \in V, \forall t \in T \tag{8}$$

$$d_{v,t}^{CS} \le \mathrm{d}_{v,t}^{total} - d_{v,t}^{CD} ; \forall v \in V, \forall t \in T \tag{9}$$

$$E_{v,t}^{req} = d_{v,t}^{CD} \times E_v ; \forall v \in V, \forall t \in T \tag{10}$$

$$\delta_{v,t} = 1 - \frac{e_{v,t}^{PHEV}}{\overline{p}_v} ; \forall v \in V, \forall t \in T \tag{11}$$

$$\sum_{u\in U} \eta_u^{EP} \times e_{u.t}^{EP} + \sum_{v\in V} e_{v.t}^- = \sum_{v\in V} e_{v.t}^+ + l_t^{TIE} ; \forall t \in T \tag{12}$$

$$o_{u,t} \times G_{u,t} \le e_{u,t}^{EP} \le o_{u,t} \times \overline{G}_{u,t} ; \forall u \in U, \forall t \in T \tag{13}$$

$$o_{u,t} - o_{u,t-1} = s_{u,t} + z_{u,t} ; \forall u \in U, \forall t \in T \tag{14}$$

$$\sum_{y=t-\tau_u^+} s_{u,y} \le o_{u,t} ; \forall u \in U, \forall t \in T \tag{15}$$

$$\sum_{y=t-\tau_u^-} z_{u,y} \le 1 - o_{u,t} ; \forall u \in U, \forall t \in T \tag{16}$$

$$\begin{aligned} &\mathrm{x}_{\mathrm{v;t}}, \mathrm{o}_{\mathrm{u;t}}, \mathrm{s}_{\mathrm{u;t}}, \mathrm{z}_{\mathrm{u;t}} \in \{0,1\} ; \\ &\forall u \in U, \forall v \in V, \forall t \in T \end{aligned} \tag{17}$$

$$\begin{aligned} &\mathrm{e}_{u,t}^{\mathrm{EP}}, \mathrm{e}_{\mathrm{v},t}^{\mathrm{PHEV}}, \mathrm{e}_{\mathrm{v},t}^{+}, \mathrm{e}_{\mathrm{v},t}^{-}, \mathrm{E}_{\mathrm{v},t}^{\mathrm{req}}, d_{v,t}^{CD}, d_{v,t}^{CS}, \delta_{v,t} \ge 0 ; \\ &\forall u \in U, \forall v \in V, \forall t \in T \end{aligned} \tag{18}$$

Objective function can minimize overall cost of the system including cost of generating energy, startup of EPs, gasoline, and battery degradation which is a function of depth of discharge (DOD). Also, environmental pollution of emission of CO_2 and NO_x are considered as penalty cost, which can be defined as follows:

$$\begin{aligned} C_2 = &\sum_{t\in T}\left[\alpha_c\left(\sum_{u\in U} CO_{2u}^{EP} \times e_{u.t}^{EP} + \sum_{v\in V} CO_{2v}^{PHEV} \times d_{v.t}^{CS}\right)\right] + \\ &\sum_{t\in T}\left[\alpha_n\left(\sum_{u\in U} NO_{xu}^{EP} \times e_{u.t}^{EP} + \sum_{v\in V} NO_{xv}^{PHEV} \times d_{v.t}^{CS}\right)\right] \end{aligned} \tag{19}$$

In this equation:

α_c : Penalty coefficient per gram of generated CO_2 (\$/g)

α_n : Penalty coefficient per gram of generated NO_x (\$/g)

CO_{2u}^{EP} : Value of production of CO_2 by EP u (g/kWh)

CO_{2v}^{PHEV} : Value of production of CO_2 by PHEV v (g/mile)

NO_{xu}^{EP} : Value of production of NO_x by EP u (g/kWh)

NO_{xv}^{PHEV} : Value of production of NO_x by PHEV v (g/mile)

Objective function considered in this study is obtained from adding equation (19) to equation (1).

$$C_t = C_1 + C_2 \tag{20}$$

2.2 Modeling problem by considering demand response

In this case, it is supposed that hybrid vehicles offer a price for charging/discharging their batteries. The bidding price is per hour and per kWh of exchanged energy. Thus, the resultant of charge and discharge cost paid by VPP to owners of vehicles is calculated with application of equation (21), which is added to the objective function (20).With consideration of demand response, the overall objective function is as follows:

$$C_3 = \sum_{t\in T}\left[-\sum_{v\in V} C_t^C \times e_{\mathrm{v}.t}^+ + \sum_{v\in V} C_t^{DC} \times e_{\mathrm{v}.t}^-\right] \tag{21}$$

where,

C_t^C : Bidding price to charge vehicles' battery during period t (\$/kWh).

C_t^{DC} :Bidding price to discharge vehicles' battery during period t (\$/kWh).

$e_{v,t}^+$: Energy delivered to PHEV v during period t (kWh).

$e_{v,t}^-$: Energy obtained from PHEV v during period t (kWh).

Therefore, overall objective function is as follows:

$$C_t = C_1 + C_2 + C_3 \tag{22}$$

2.3 Constraints of the problem

Constraints (2) to (11) are related to PHEVs, in which (2) applies the minimum and maximum charge limits for PHEVs. (3) is the balance equation of battery energy between successive periods. If the battery is charged or discharged, the level of energy increases or decreases during the following period, respectively. (4) sets the initial energy level of each PHEV. (5) and (6) guarantee that charging and discharging do not take place simultaneously during each period, and either one can just occur when there is a connection between PHEV and the network. (7) and (8) make the distance traveled in CD mode (discharge) become the minimum of the 'actual trip distance' and 'possible trip distance by consuming the available energy left in PHEV battery'. (9) sets the distance of CS mode. (10) calculates the required energy for traveling the trip distance. (11) calculates DOD of each period. Constraints (12) to (16) are related to EPs. (12) is the equation of energy balance. The sum of energy obtained from EPs and discharged energy of batteries is provided for PHEV and TIE loads. (13) guarantees that minimum and maximum capacities of each EP are met, and forces the binary variable $Q_{u,t}$ to take value 1 if energy is generated by EP u in period t. (14) sets binary variables of start-up and shut-down EPs constraints. (15) and (16) apply the minimum and maximum start-up and shut-down times of EPs. (17) defines binary variables, and (18) applies non-negativity constraints to them.

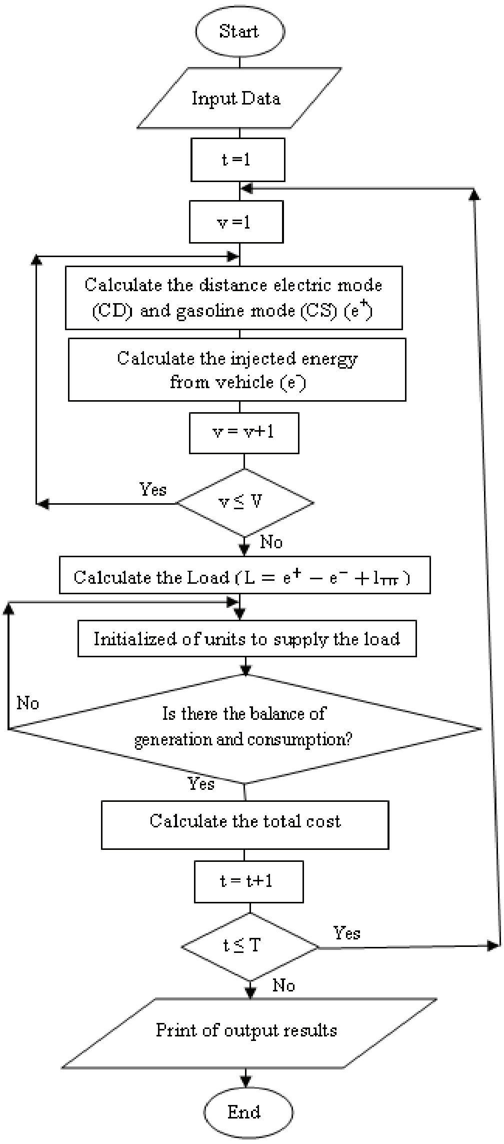

Fig. 1. Flowchart of problem solving of scheduling virtual plant energy

The MIP optimization problem of (1) to (22) is modeled in GAMS software using Cplex solver [25]. The Cplex is a GAMS solver that allows users to combine the high level modeling capabilities of GAMS with the power of Cplex optimizers. Cplex optimizers are designed to solve large, difficult problems quickly and with minimal user intervention. Access is provided to Cplex solution algorithms for linear, quadratically constrained and mixed integer programming problems [25]. The flow chart of solving problem has been presented in Fig. 1.

3. Simulation results

In this section the effects of VPP formation on the cost and level of greenhouse gas emissions will be discussed. The main objective of solving the problem is to minimize the overall cost and emission of greenhouse gases, which is included in the objective function.

3.1 The case study

The VPP consists of 213 plug-in hybrid electric vehicles (PHEV). The vehicles can be classified into 4 types. Technical specifications of the vehicles specified according to the United States Department of Transportation are provided in Table 1[1]. Table 1 presents the required energy per mile (E_v), battery capacity ($\overline{P_v}$), battery cost, and the distance traveled by vehicle in CS mode per gallon of gasoline. The minimum level of battery charge ($\underline{P_v}$) and the initial level of battery energy (P_{0v}) are considered as 10% and 30% of the battery capacity of vehicles,

Table 1. Vehicle type specifications

Vehicle class	Energy requirement [kWh/mile]	Battery capacity [kWh]	Battery cost [$]	MPG in CS-mode
Compact	0.26	8.6	3178	30.2
Mid- size	0.30	9.9	3377	26.4
Large	0.38	12.5	3776	20.6
Small SUV	0.46	15.2	4189	18

respectively. Charge and discharge efficiency of batteries (η_v^+ and η_v^-) is 90%. The charge/discharge rate of all batteries (ρ_v^+ and ρ_v^-) is 2.4 (kWh). The vehicles can travel in CD mode and CS mode. 34 small-scale plants (EP) in VPP were investigated. The data related to these units, which are gathered from California Energy Commission DER Guide, are demonstrated in Table 2. The minimum production capacity and the minimum time of start-up/shut-down of these units are 5 kW and 1 hour, respectively. In this model, VPP can obtain a portion of its required energy from the national network. The level of the received energy depends on the price of the electricity purchased from the network in comparison with the price of the same level of energy purchased from other generating units in VPP.

Table 2. EP data

Unit type	Number of units	Maximum limit [kWh]	Price [¢ /kWh]	EP Efficiency (%)
Micro-turbine	2	50	24.43	95.8
Solar	7	25	26.22	76.0
Wind	8	50	7.24	99.9
Biomass	5	28	10.83	93.0
Fuel cell	3	50	26.65	85.0
Small hydro	5	15	8.65	87.0
Geothermal	4	15	8.31	90.0

Table 3. Emission data

Technology	CO_2	NO_x	Unit
Micro-turbine	539.8	0.2223	grams/kWh
Biomass	0	0.034	
Fuel cell	385.6	0.0068	
Grid (average)	544.3	2.267	
Compact car	291.0	0.07	grams/mile
Mid-size car	335.0	0.07	
Large car	395.0	0.07	
Small SUV	480.0	0.07	

Table 4. Type and number of plant units

Type of plant	Unit
Micro-turbine	U1-U2
Solar	U3-U9
Wind	U10-U17
Biomass	U18-U22
Fuel cell	U23-U25
Small hydro	U26-U30
Geothermal	U31-U34
Network	U35

Vehicles and generating units consuming fossil fuels produce NO_x and CO_2, which are particularly harmful to people. The emission level of these gases produced by vehicles and energy generation units is shown in Table 3. The assumption is that wind and solar farms as well as small hydro and geothermal units produce very lower level of greenhouse gases. Type and number of plants are presented in Table 4. The VPP consists of 574 houses, whose consumption changes over time. Fig. 2 reveals the total load of these houses during different hours of a day [1].

During the time span of the study (24 hours), the price of gasoline was $3.049 per gallon. The distance traveled hourly by PHEVs is considered according to the actual data.

In this study, each period is 1 hour, and the calculations are made for 24 hours. $I_{v,t}$ denotes the availability/unavailability of the vehicles and is considered for 1 hour. If the vehicle is available and capable of exchanging energy, the value of this variable is 1; otherwise it would be 0.

The total cost of VPP has been considered as the objective function of the problem related to scheduling the vehicles and generating units. Furthermore, a cost function is considered for greenhouse gases, which means that VPP should pay a fine based on the penalty that is passed by the network regulator. The penalty per kilogram CO_2 and NO_x is $0.1 and $10, respectively.

3.2 Results of computer simulation without demand response (WDR)

The results of simulation in different scenarios are represented in this section. The assumption is that the vehicles are entirely controlled by VPP, and energy charge/discharge is free. The total cost of VPP for different

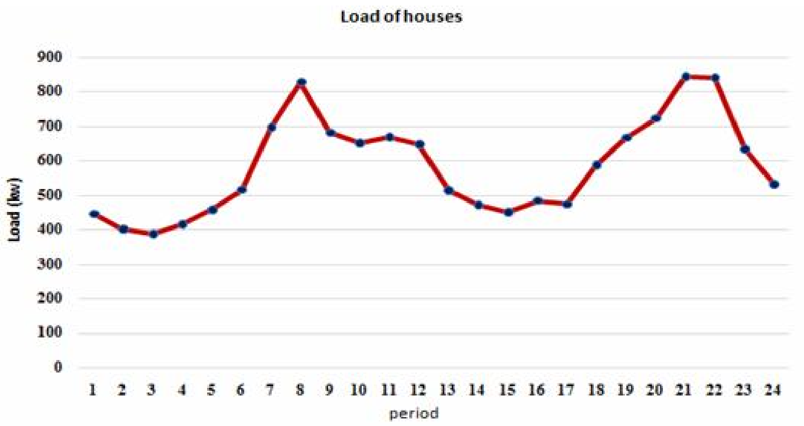

Fig. 2. Load of houses of VPP throughout the day

scenarios has been computed. The scenarios are as follows:

Scenario 1: VPP required energy is provided by the national network, and the power of VPP interior production units is not consumed. In this scenario, it is supposed that there are no PHEVs, and vehicles only run in CS mode (fossil fuel).

Scenario 2: VPP required energy is provided by the production units as well as the national network. PHEVs do not play a role in load supply. Moreover, similar to the previous scenario, the vehicles run in CS mode (fossil fuel).

Scenario 3: VPP required energy is provided by the network, and the power of VPP interior production units is not consumed. In this scenario, the assumption is that PHEVs are present; however, they can only be charged and cannot be discharged (V2G). Furthermore, they cannot inject power to the system.

Scenario 4: VPP required energy is provided by the production units as well as national network. In this scenario, it is supposed that PHEVs are present; however, they can only be charged and cannot be discharged (V2G). Moreover, they cannot inject power to the system.

Scenario 5: VPP required energy is provided by the production units and national network. In this scenario, it is supposed that PHEVs are present and can be charged and discharged (receive/inject power) (withV2G).

■ Scenario 1

In this scenario, it is assumed that the overall need of consumers is provided by the central electricity network, and the vehicles only run in CS mode (fossil fuel). This scenario is similar to the status of current electricity network, which includes no electric vehicles. Table 5 presents the results of the calculations in this regard. The VPP production units are not considered in this scenario so that the power received from the network per hour is equal to users' consumed load per hour (Fig. 2). In this scenario, the overall cost includes the cost of the electricity consumed by users, the cost of fuels used in vehicles, and the penalty price obtained for greenhouse gas emissions by the network and vehicles.

Table 5. Results of scenario 1

Item	Quantity
Total cost ($)	3939
CO_2 (kg)	9824.413
NO_x(kg)	32.211

Table 6. The results of the scenario 5 in comparison with other scenarios

Item	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total cost ($)	3939	2531	3703	2188	1952
Total cost without battery cost ($)	------	------	3422	2050	1684
CO_2 (kg)	9824.413	2495.791	8809.272	760.394	479.868
NO_x(kg)	32.211	1.361	34.862	0.633	0.269

■ Scenario 5

In this scenario, the whole model of VPP is examined with consideration of PHEV vehicles. These vehicles can be discharged and can inject power to the network (V2G). The results of simulation in this scenario have been compared with those of other scenarios (Table 6).

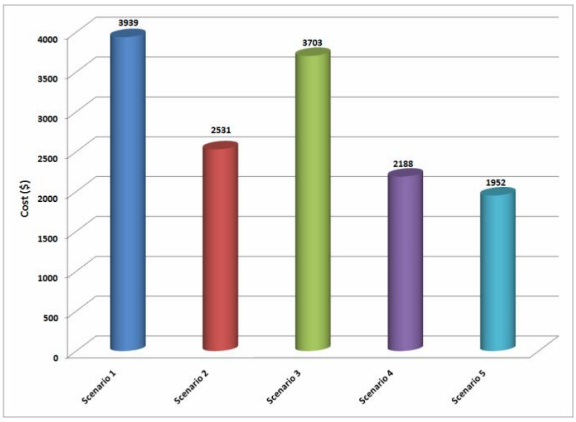

Fig. 3. The cost of scenario 5 compared with other scenarios

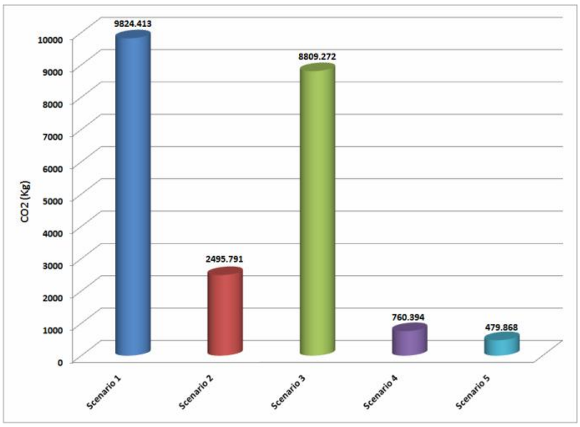

Fig. 4. CO_2 emission in scenario 5 compared with other scenarios

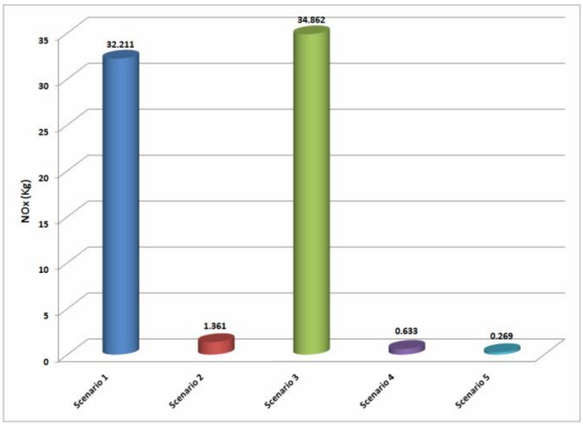

Fig. 5. NO_x emission in scenario 5 compared with other scenarios

Comparison of the simulation results reveals the efficiency of vehicles with V2G capability in decreasing the cost and pollution. As shown in Table 6, the overall cost of energy supply of scenario 5 is \$1952, which is \$236 less than that of scenario 4 (without V2G capability). The level of CO_2 and NO_x emissions has decreased 280.5 kg and 365 g, respectively. This capability plays a crucial role in decreasing environmental pollution. Comparison of the results of this scenario and those of the first one (current state of the network) reveals that the overall cost has decreased by \$ 1987 (about 50%)(Fig. 3). The obtained reduced cost is the result of applying cheap and renewable units along with lower penalty specified for greenhouse gases (Figs. 4 and 5). The capacity of contribution of units has been shown in Fig. 6.

According to Figs. 7 and 8, as a result of charging and discharging capability of vehicles, they can be charged and discharged during off-peak load and on-peak load hours,

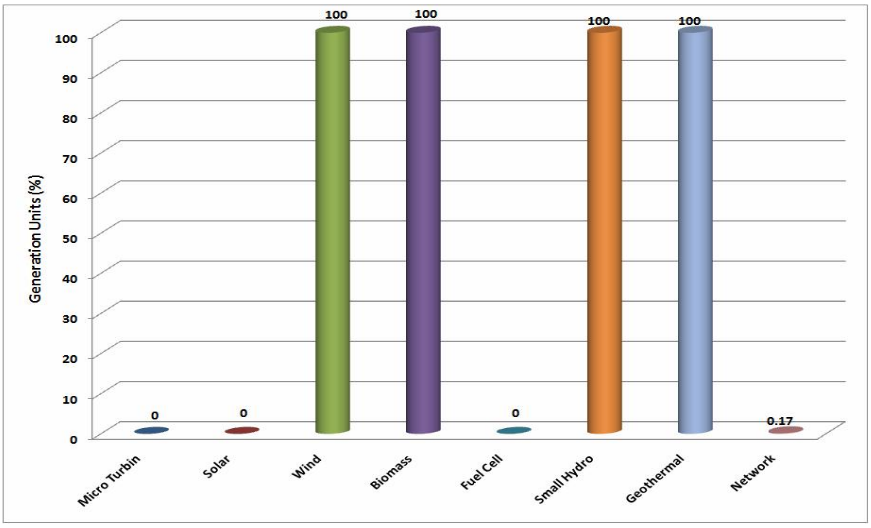

Fig. 6. The generation capacity of the units in scenario 5

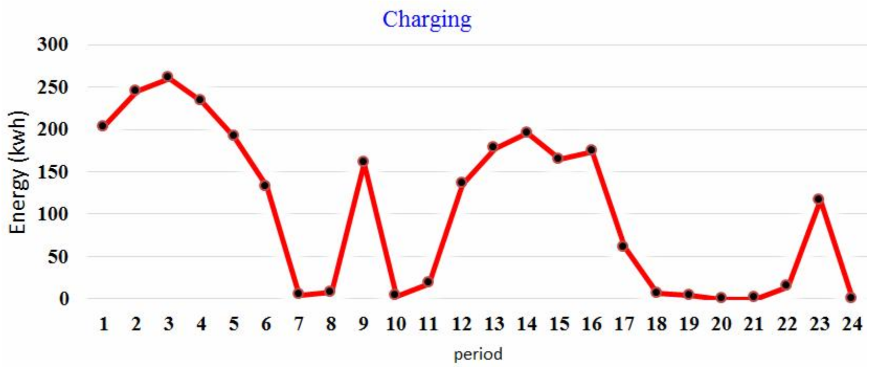

Fig. 7. Diagram of charging vehicles in scenario 5

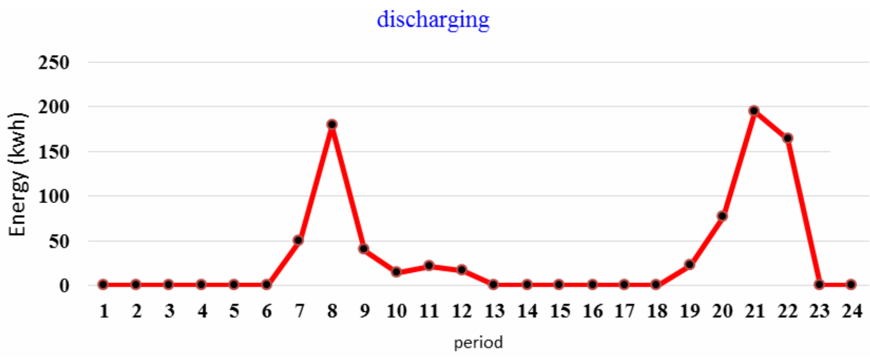

Fig. 8. Diagram of discharging vehicles in scenario 5

Table 7. Suggested price charged and discharged

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Charging price (¢/kWh)	10	10	9	8	8	8	7	7	6	6	2	2	2	1	1	1	0	0	0	0	0	8	9	10
discharging price (¢/kWh)	0	0	0	0	1	1	8	8	8	8	9	9	9	10	10	11	11	11	12	15	15	15	2	0

Table 8. Results of different simulation considering demand response

Item	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total cost ($)	3939	2531	3572	2036	1780
DR cost ($)	---------	----------	223	179	260
CO_2 (kg)	9824.413	2495.791	9491.6	902.9	1077.9
NO_x (kg)	32.211	1.361	37.703	1.386	2.775

which means the entrance of less expensive plants to the circuit and the reduced overall cost. Table A presented in the appendix shows power generation level of DER units of VPP as well as the received power from the national network throughout the day.

In the 5th scenario, units 1- 9 did not enter the circuit throughout the day. These units include micro-turbines and solar units, which supply high price electricity. Furthermore, the pollution level of micro-turbines is high, as well. Moreover, fuel cell units were shut-down and did not enter the circuit throughout the day due to their higher price and pollution level. In contrast, wind farms, geothermal, biomass, and hydro units were active throughout the day, and their energy generation was maximized. In this scenario, only at 10 p.m., power was obtained from the national network. The reason that the peak load was at 9 p.m. while the power was obtained from the network at 10 p.m. is that at 9 p.m. most of the vehicles were discharged to reduce the peak load of the network. This discharging resulted in lower power mode so that they did not possess higher power level to be discharged at 10 p.m. Hence, the generation power was decreased at 10 p.m., and VPP had to obtain power from the national network. Fig. 7 illustrates the obtained power by vehicles throughout the day. As shown in Fig. 7, the highest level of charging occurred in the early hours of the day, i.e. at 3 a.m. (household load had the least level at this time), which was 261 kW in total. Consideration of the calculated total charged/discharged power by vehicles, consumed load by the VPP per hour, and the net load reveals the consistency of the net load level per hour, i.e. 649.05 kW. The consistency prevents start-up and shut-down of units incurring a lot of cost. In fact, in this scenario, the algorithm charges and discharges the vehicles to cause the net load to be consistent so that the overall cost decreases. Note that only at 22 p.m. the net load was 27.22 kW more than that of other hours, which was precisely equal to the obtained power from the central network.

The level of transmitted energy to the network by the vehicles is shown in Fig. 8 (hourly level of discharged power of vehicles throughout the day). The mentioned figure illustrates that discharge has occurred only from 7 a.m. to 12 a.m. and from 7 p.m. to 10 p.m. As VPP consuming load was high at the mentioned hours, the vehicles were discharged to reduce the load of the network. In addition, the vehicles have traveled longer distances at some specific hours, which made them to obtain energy from their batteries. For instance, at 8 a.m., the load of the network was high and the vehicles traveled the maximum distance (577 miles) so that the maximum discharging of vehicles occurred at the first peak (178 kWh). Furthermore, the maximum discharging occurred at 9 p.m., which was the peak load (194 kWh). Comparison of the distance traveled in the electric mode and fossil fuel mode reveals that the distance traveled in CD mode is longer. In this scenario, the distance traveled in CD and CS modes was 4996 and 1331, respectively, which demonstrates that the traveled distance in CD mode was 3.75 times longer than that of CS mode. According to the results, VPP can reduce emission of greenhouse gases and the overall cost of power supply. The presence of electric vehicles, which are capable of discharging power (V2G), results in lower cost and pollution.

3.2 Results of computer simulation with demand response (DR) program

In this section, the five afore mentioned scenarios are simulated with consideration of demand response in calculations. It is assumed that the electric vehicles suggest a price for charging/discharging their batteries. The price is specified hourly and per kWh for the exchanged energy (Table 7). As the first two scenarios do not consider the electric vehicles, the results are the same as those presented in Table 6. For other scenarios, the simulations were performed again and the results are presented in Table 8.

As mentioned above, in DR program, the vehicles should pay an amount of money to VPP management so that the management system has a tendency to provide the vehicles with more charge, which results in increasing the pollution. Moreover, the VPP management has to incur more cost for purchasing electricity from the network. Therefore, an optimal point and a compromise between these two positions are required. In the process of

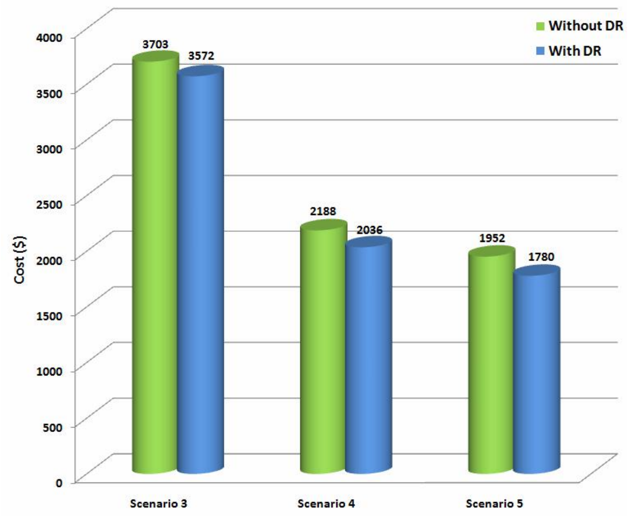

Fig. 9. Overall cost with/without demand response

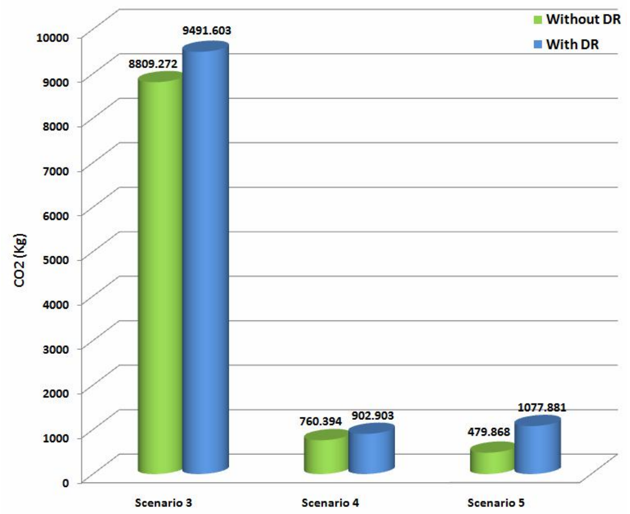

Fig. 10. CO_2 emission with/without demand response

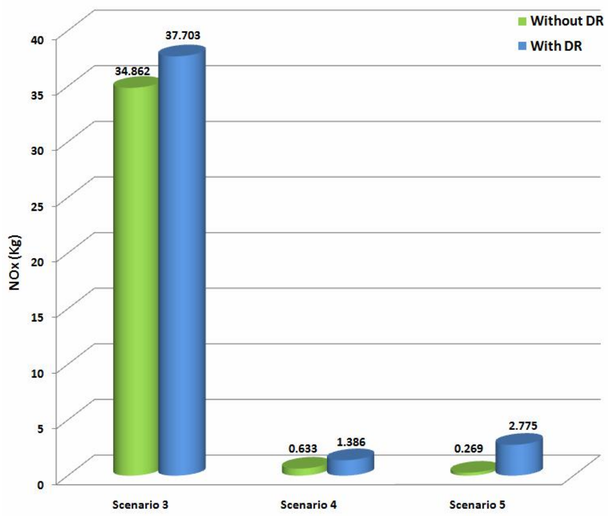

Fig. 11. NOx emission with/without demand response

performing DR program, the trend of cost and pollution reduction in all scenarios is almost the same as the previous state (without DR program). However, reduction of cost in all scenarios is greater than that of previous state (wit hout DR). This reduction is the result of cost payment to VPP for charging the vehicles.

Scenario 3: In this scenario, reduction of cost is greater than that of WDR state. Moreover, the level of CO_2 emission produced by vehicles decreases. However, the level of NO_x emission related to the increased charge of the vehicles exceeds; this increase leads to increased generation of the central network, whose pollution is high.

Scenario 4: In this scenario, the reduction level of cost is more than that of WDR state. However, the emission of pollution increases as the result of increased generation of the network and units.

Scenario 5: In this scenario, cost reduction is greater than that of WDR state. Furthermore, reduced pollution has smaller inclination. Note that in the 5th scenario, pollution level is higher than that of 4th scenario (in which the vehicles do not have the capability of V2G). In fact, the capability of vehicles to charge and inject power to the system along with their capacity to perform DR program causes more pollution. Increased pollution is due to higher tendency of vehicles to exchange energy with the system, which results in more charging and discharging cycles; and consequently, the generation of electric energy increases, as well. As the vehicles are required to pay an amount of money to VPP for charging, VPP has a tendency to provide them with more charge. Comparison of the generated energy by the central network with and without DR reveals that the generation of the network has increased, which causes a higher level of pollution. As a result, the level of pollution is higher in this scenario. The overall level of cost and pollution in all scenarios with and without Demand Response has been compared and presented in Figs. (9)-(11).

4. Conclusions

In this paper, scheduling of the generating units to minimize the overall cost of a virtual plant in the presence of PHEVs was studied. The results are as follows:

- For a group of consumers considered as a virtual power plant, the cost of electricity supply, fuel of vehicles, and penalty for pollutants would be high when they normally receive their energy from the central network.
- Formation of VPP and electricity supply by VPP units of Distributed Energy Resources (DER) results in remarkable reduction of the overall cost as well as decreased level of produced CO_2 and NO_x. Therefore, formation of VPP and application of DG units lead to reduced cost and environmental pollution level.
- Application of hybrid vehicles in a power system without VPP structure results in decreased overall cost

and CO_2emission. However, as the mentioned vehicles consume electricity, increased production of electric energy by the central network, whose pollution is high, leads to release of more NO_x.

- Application of DER and renewable energy resources in the presence of PHEV vehicles through V2G technology in power systems managed by VPP leads to substantial decrease of cost and emission of greenhouse gases, e.g. CO_2 and NO_x.
- Contribution of PHEVs to supply power due to charging during off-peak load periods and discharging (injecting power to the system) during on-peak load periods results in reduction of peak load during peak hours without any need to insert expensive units into the circuit. Furthermore, the profile of the load network will be flat, and hence less on/off cost would be required for balancing the power.
- Demand response results in lower overall cost when the vehicles are charged and discharged. However, due to increased production of electric energy caused by increased charge and discharge cycles, a number of issues related to environmental pollution will be faced.

Appendix

Table A shows power generation level of the DER units of VPP as well as the received power from the national network throughout the day.

Table A: Level of generating power of the DER units of VPP

period	1	2	3	4	5	6	7	8	9	10	11	12
u10	50	50	50	50	50	50	50	50	50	50	50	50
u11	50	50	50	50	50	50	50	50	50	50	50	50
u12	50	50	50	50	50	50	50	50	50	50	50	50
u13	50	50	50	50	50	50	50	50	50	50	50	50
u14	50	50	50	50	50	50	50	50	50	50	50	50
u15	50	50	50	50	50	50	50	50	50	50	50	50
u16	50	50	50	50	50	50	50	50	50	50	50	50
u17	50	50	50	50	50	50	50	50	50	50	50	50
u18	28	28	28	28	28	28	28	28	28	28	28	28
u19	28	28	28	28	28	28	28	28	28	28	28	28
u20	28	28	28	28	28	28	28	28	28	28	28	28
u21	28	28	28	28	28	28	28	28	28	28	28	28
u22	28	28	28	28	28	28	28	28	28	28	28	28
u26	15	15	15	15	15	15	15	15	15	15	15	15
u27	15	15	15	15	15	15	15	15	15	15	15	15
u28	15	15	15	15	15	15	15	15	15	15	15	15
u29	15	15	15	15	15	15	15	15	15	15	15	15
u30	15	15	15	15	15	15	15	15	15	15	15	15
u31	15	15	15	15	15	15	15	15	15	15	15	15
u32	15	15	15	15	15	15	15	15	15	15	15	15
u33	15	15	15	15	15	15	15	15	15	15	15	15
u34	15	15	15	15	15	15	15	15	15	15	15	15
u35	---	---	---	---	---	---	---	---	---	---	---	---
period	13	14	15	16	17	18	19	20	21	22	23	24
u10	50	50	50	50	50	50	50	50	50	50	50	50
u11	50	50	50	50	50	50	50	50	50	50	50	50
u12	50	50	50	50	50	50	50	50	50	50	50	50
u13	50	50	50	50	50	50	50	50	50	50	50	50
u14	50	50	50	50	50	50	50	50	50	50	50	50
u15	50	50	50	50	50	50	50	50	50	50	50	50
u16	50	50	50	50	50	50	50	50	50	50	50	50
u17	50	50	50	50	50	50	50	50	50	50	50	50
u18	28	28	28	28	28	28	28	28	28	28	28	28
u19	28	28	28	28	28	28	28	28	28	28	28	28
u20	28	28	28	28	28	28	28	28	28	28	28	28
u21	28	28	28	28	28	28	28	28	28	28	28	28
u22	28	28	28	28	28	28	28	28	28	28	28	28
u26	15	15	15	15	15	15	15	15	15	15	15	15
u27	15	15	15	15	15	15	15	15	15	15	15	15
u28	15	15	15	15	15	15	15	15	15	15	15	15
u29	15	15	15	15	15	15	15	15	15	15	15	15
u30	15	15	15	15	15	15	15	15	15	15	15	15
u31	15	15	15	15	15	15	15	15	15	15	15	15
u32	15	15	15	15	15	15	15	15	15	15	15	15
u33	15	15	15	15	15	15	15	15	15	15	15	15
u34	15	15	15	15	15	15	15	15	15	15	15	15
u35	---	---	---	---	---	---	---	---	---	22/27	---	---

Nomenclature

Parameters

V, U, T : Set of PHEVs, EPs, and time intervals

$I_{v\,t}$: 1 if PHEV v is available during period t and 0 otherwise

l_t^{TIE} : Required energy to satisfy TIE loads during period t (kWh)

$\bar{G}_{u,t}, \underline{G}_{u,t}$: Maximum and minimum energy generated by EP u during period t (kWh), respectively

$\bar{P}_v, \underline{P}_v$: Maximum and minimum capacity of battery energy of PHEV v (kWh), respectively

PO_v : Initial energy stored in battery of PHEV v (kWh)

p_v^+, p_v^- : Total energy transferable to/from PHEV v during one time period (kWh), respectively

${}^{+}_{u}, {}^{-}_{u}$: Minimum up and down times of EP u

${}^{EP}_{u}$: Efficiency of EP u based on plant side and transmission system losses

${}^{+}_{v}, {}^{-}_{v}$: Battery charge and discharge efficiency of PHEV v, respectively

$C_{u,t}^{EP}$: Price of gaining energy from EPu during period t (paid by VPP to EP u)

C_t^{gas} : Price of gasoline during period t (¢/gallon)

CS_V : Average cost of using gasoline by PHEV v (gallon/miles)

$d_{v,t}^{total}$: Total traveling distance during period t by PHEV v (miles)

E_v : Required energy to run PHEV v on electricity for one mile (kWh)

Variables

$e_{u,t}^{EP}$: Provided energy value by EP u during period t (kWh)

$e_{v,t}^{PHEV}$: Battery energy level of PHEV v at the end of period t (kWh)

$e_{v,t}^{+}, e_{v,t}^{-}$: Transmitted energy to/from PHEV v during period t (kWh)

$X_{v,t}$: 1 if PHEV v is charged during period t and 0 otherwise

$d_{v,t}^{CD}, d_{v,t}^{CS}$: Traveled distance in CD (charge - depleting) mode and CS(charge - sustaining) mode during period t by PHEV v (miles)

$E_{v,t}^{req}$: Required energy for PHEV v during period t (kWh)

$\delta_{v,t}$: DOD (depth of discharge) for PHEV v during period t

$f(\delta)$: Required cost to replace battery as a function of DOD

$o_{u,t}$, $s_{u,t}$, $z_{u,t}$: 1 if EP u is online, started-up or shut-down, respectively in period t and 0 otherwise

$r_{v,t}$: The cost variable of battery deterioration of PHEV v during period t (applied in modeling of battery degradation cost function).

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Hassan Barati was born in Dezful, Iran, in 1969. He received the B.Sc. degree in electronic engineering from the Isfahan University of Technology, Isfahan, Iran, in 1993, the M.Sc. degree in electrical engineering from the Tabriz University, Tabriz, Iran, in 1996 and the Ph.D. degree in Electrical Engineering from the Islamic Azad University, Science and Research Branch, Tehran, Iran, in 2007. Currently, he is an Assistant Professor in the Electrical Engineering Department, Dezful Branch, Islamic Azad University, Dezful, Iran. His research interests are power systems operation & Reliability, restructured power systems, Micro-grids and Smart Grids, FACTS devices. received B.S degree in electrical engineering from Yonsei university. His research interests are robust control, filtering and signal processing.

Farshid Ashir was born in Shoushtar, Iran, in 1977. He received the B.Sc. degree in Electrical Engineering from the Shoushtar Branch, Islamic Azad University, Shoushtar, Iran, in 2009, the M.Sc. degree in electrical engineering from the Ahvaz Branch, Islamic Azad University, Ahvaz, Iran, in 2015. His research interests are power systems operation, Micro-grids and Smart Grids, FACTS devices.