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On the application of plug-in hybrid electric vehicle to compensate network harmonics: A multiobjective approach

H. Feshki Farahani[a,*], M. Khalili[b], A. Rabiee[c] and M.S. Ghazizadeh[b]

a. *Department of Electrical Engineering, Ashtian Branch, Islamic Azad University, Ashtian, P.O. Box 39618-13347, Iran.*
b. *Power and Water University of Technology, Tehran, P.O. Box 1719-16765, Iran.*
c. *Department of Electrical Engineering, Shahrekord University, Shahrekord, P.O. Box 115, Iran.*

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Abstract. One of the important capabilities of Plug in Hybrid Electric Vehicles (PHEVs) is the injecting/absorbing of harmonic current to/from the grid. In this paper, a multiobjective framework is proposed to improve the power quality of the grid by PHEVs. In this study, each PHEV is modeled as an injected harmonic current source, including different harmonic orders. The objective functions are: Total Harmonic Distortion (THD) of network nodes and the Total PHEV Current (TPC) index, both to be minimized. The multiobjective optimization problem is solved using the ε-constraint method. The best compromise solution among various non-dominated (Pareto optimal) solutions is chosen based on a fuzzy approach. A typical 14-node microgrid test system is considered in the case study to examine the effectiveness of the proposed method.

1. Introduction

Nonlinear loads, such as AC/DC converters, arc furnaces, and switching power supplies have significantly grown in power systems and smart grids. These kinds of loads may inject harmonic current into the power system, leading to distorted network voltage and also an increase in the total losses of the network [1]. Active filters are one of the solutions to eliminate these harmonics to the range of harmonic standards, such as IEEE-519 [2]. Among the active power filters, Active Power Line Conditioners (APLCs) have been widely used to suppress the harmonics of a network. In fact, the APLC injects harmonic current to the Point of Common Coupling (PCC), equal but opposite to the harmonic current of the nonlinear load in order to neutralize the PCC harmonic current. The basic principles of APLCs compensation have been introduced in [3-5]. Depending on the number of nonlinear loads and THD levels, one or multiple APLCs are installed to eliminate harmonics.

Some papers have been published in the area of APLCs sizing and location. In [6], only one APLC was selected from a set of candidate nodes to reduce voltage distortion. In [7], the installed locations for multi-APLCs were determined by a set of re-evaluated indices for all candidate nodes, because the smallest feasible size of one APLC has been considered at each iteration. In [8], it has been concluded that the algorithm presented in [7] did not necessarily yield the best APLC locations or optimum current injections in the case of a multiple-harmonic elimination approach.

*. *Corresponding author. Tel.: +98 86 37222500; Fax: +98 86 37222627*
E-mail addresses: hfeshki@yahoo.com (H. Feshki Farahani); khm66@yahoo.com (M. Khalili); rabiee@iust.ac.ir (A. Rabiee); ghazizadeh@pwut.ac.ir (M.S. Ghazizadeh)

In [8], a nonlinear programming model, based on a generalized reduced gradient algorithm, has been used to find the optimal size and location of one APLC to reduce the harmonics.

PHEV technology is a promising solution that can lead to decreased greenhouse gas emissions and air pollution in urban areas, and can totally be considered an environmentally clean technology [9]. PHEVs/PEVs hold a lot of promise in terms of higher energy efficiency, lower carbon emissions, energy independency and environmental responsibility. There are approximately 250 million cars in the United States. By the year 2020, if 10% of US vehicles are some form of PHEV or PEV, and each vehicle has a storage capacity of 20 kWh and 500 GWh, it will be both a threat to today's utilities and an opportunity [10].

Several simulations were presented in order to illustrate the potential impacts/benefits of the connection of PHEVs integration into the grid. In [11], the impact of electricity rates, based on time-of-use, on distribution load shapes with PHEV penetration has been analyzed. The load demand due to EV battery charging in distribution systems was modeled and analyzed in [12]. In [13], a real-time wide area controller was designed and implemented to improve the stability of the power system with PHEVs. Mitra and Venayagamoorthy [13] evaluated the impact of charging PHEVs on a residential distribution grid. The impact of the integration of PHEVs/PEVs on power grids was evaluated under a variety of charging scenarios in [14]. In [15], the authors presented an investigation into various aspects of how PHEVs could influence the electric power system and focused on such an infrastructure. Dyke et al. established a series of well-defined EV loads that were subsequently used to analyze their electrical energy usage and storage in the context of more electrified road transportation [16].

In [17], the authors evaluated the impact of different levels of PEV penetration on the distribution network's investment and incremental energy losses. The integration of EVs into power systems has been studied in terms of the technical operation of the grid and the electricity market [18].

Recently, a few studies have undertaken the challenge of optimization problems for power system studies [9,19-22]. A multiobjective fuzzy self adaptive PSO algorithm has been proposed in [9] to solve multiobjective optimal operation management, considering fuel cell power plants in the distribution network. A new day-ahead joint market clearing framework was proposed in [19], a stochastic multiobjective model, taking into account power system uncertainties and considering the dynamic security of power systems in market clearing. A new multiobjective model for electricity market clearing, considering both the voltage and dynamic security aspects of the power system is proposed in [20]. Aghaei et al. [21] proposed a multiobjective mathematical programming formulation, which has been implemented for simultaneous clearing of energy and ancillary service markets. In [22], an Improved Particle Swarm Optimization (IPSO) method has been introduced for the multiobjective Optimal Power Flow (OPF) problem.

From the above mentioned papers, it can be concluded that all aspects of the PHEV applications have been considered. However, to the best of the authors' knowledge, no research work in this area considers the potential of PHEV as a harmonic compensator in the present network, which includes many nonlinear loads. It should be noted that the harmonic compensation of PHEV does not degrade the battery life of a vehicle compared to the peak power saving by PHEV. Since the harmonic current (power) can be provided by a DC link capacitor and AC/DC converter, the battery is not engaged in harmonic power transfer [23-24]. Accordingly, the owners of PHEVs can take advantage of these electric vehicles and use them as sources of harmonic current injection. This matter is, in fact, the main contribution of this paper.

The compensation of harmonic current can lead to a decrease in the THD of grid nodes. In other words, the harmonic current can be provided based on minimization of the THD of the system. In this manner, the system required harmonic power is provided in order to reach minimum THD, not regarding the magnitude of harmonic current injected by PHEV. On the other hand, if a PHEV is considered a harmonic compensator, the capacity of PHEV in the active or reactive power compensation is decreased. So, the THD of grid nodes should be minimized with the least magnitude of injected harmonic current. This results in a multiobjective optimization problem, in which the injected harmonic current of PHEV is minimized, while, at the same time, the THD of grid nodes is minimized. The proposed multiobjective harmonic compensation of PHEVs is modeled by a ε-constraint method to find various non-dominated (Pareto optimal) solutions. The best compromised solution is selected based on a fuzzy decision-making approach. The contributions of this paper are:

a) Considering PHEV as a harmonic compensator;
b) Compensation of the grid harmonic by PHEVs in a multiobjective framework, in order to decrease the THD of grid nodes with the least magnitude of injected harmonic current by PHEVs.

The remainder of this paper is organized as follows: The problem formulation in the form of a Non-Linear Programming (NLP) problem is proposed in Section 2. In the next section, the validity of the proposed multiobjective scheme is studied based on a typical 14-node microgrid.

2. Problem formulation

In this part, first, the considered model of PHEV is investigated and then formulation of the multiobjective optimization problem, as well as objective functions and their constraints, are presented. It should be noted that PHEV is considered a current injection model.

2.1. PHEV harmonic model

PHEV behavior is similar to APLC, and can eliminate harmonics by injecting/absorbing harmonic current into/from the grid opposite to the harmonic currents of nonlinear loads. Hence, the model of PHEV in harmonic studies is approximately the same as that of APLC. Inspired by the APLC model used in the literature [6,25-30], the PHEV current injection model to PCC can be expressed as:

$$I^h_{\text{phev},m} = \left|I^h_{\text{phev},m}\right| \angle\theta^h_{\text{phev},m}, \tag{1}$$

where:

$I^h_{\text{phev},m}$	PHEV hth harmonic of current at mth node of grid;
$\left\|I^h_{\text{phev},m}\right\|$	Amplitude of PHEV hth harmonic of current at mth node of grid;
$\theta^h_{\text{phev},m}$	Angle of PHEV hth harmonic of current at mth node of grid.

Another form to express the injected current can be written as:

$$I^h_{\text{phev},m} = I^{h,r}_{\text{phev},m} + jI^{h,i}_{\text{phev},m}, \tag{2}$$

where:

$I^{h,r}_{\text{phev},m}$	Real part of $I^h_{\text{phev},m}$;
$I^{h,i}_{\text{phev},m}$	Imaginary part of $I^h_{\text{phev},m}$.

Indices r and i represent the real and imaginary parts of the APLC current, respectively. The interested readers are referred to [31] to find more details about the harmonic model of APLC, which is similar to that of PHEV.

2.2. Objective functions

In order to incorporate PHEVs in the harmonic compensation, two objective functions are considered as follows:

Objective functions:

$$\begin{cases} \text{Min} \quad F1; \\ \quad \text{Total Harmonic Distortion (THD)} \\ \text{Min} \quad F2; \\ \quad \text{Total PHEV Current (TPC)} \end{cases} \tag{3}$$

To reduce THD, the injected current of PHEV is increased, which causes an increase in the required harmonic power, leading to an increase in the cost of harmonic compensation and also a reduction in the capacity of PHEV to inject active or reactive power into the grid. The first objective function aims at minimizing the THD of grid nodes by the injected harmonic currents of PHEVs. On the other hand, minimization of THD ($F1$) deteriorates another objective function, $F2$. So, this problem can be expressed as a multiobjective optimization framework. The flowchart of the multiobjective optimization algorithm is depicted in Figure 1.

The first objective function, $F1$ (THD), can be written as:

$$F1 = \text{Minimize}\left(\text{Max}\{\text{THD}_m, m \in M\}\right),$$

$$\text{THD}_m = \frac{\sqrt{\sum_{h=2}^{H} |V^h_m|^2}}{|V^1_m|}, \tag{4}$$

where:

M	Number of grid nodes;
H	Maximum considered harmonic order h;
V^h_m	Voltage at node m for harmonic order h;
V^1_m	Fundamental component of voltage at node m.

Another objective function, $F2$ (TPC), can be written as:

$$F2 = \text{MinimizeTPC},$$

$$\text{TPC} = \sum_{m=1}^{M} \sqrt{\sum_{h=2}^{H} |I^h_{\text{phev},m}|^2}, \tag{5}$$

where, $|I^h_{\text{phev},m}|$ is the amplitude of PHEV injected current at node m for the harmonic of order h. The proposed multiobjective framework is subjected to the following constraints:

1. The individual harmonic voltage distortion constraint:
$$\frac{|V^h_m|}{|V^1_m|} \le V^h_{\max}, \tag{6}$$
where, $V^h_{\max}$ is usually 3%.
2. Total harmonic distortion constraint:
$$\frac{\sqrt{\sum_{h=2}^{H} |V^h_m|^2}}{|V^1_m|} \le \text{THD}V_{\max}, \tag{7}$$
where, $\text{THD}V_{\max}$ is usually 5%.
3. Load flow equations:

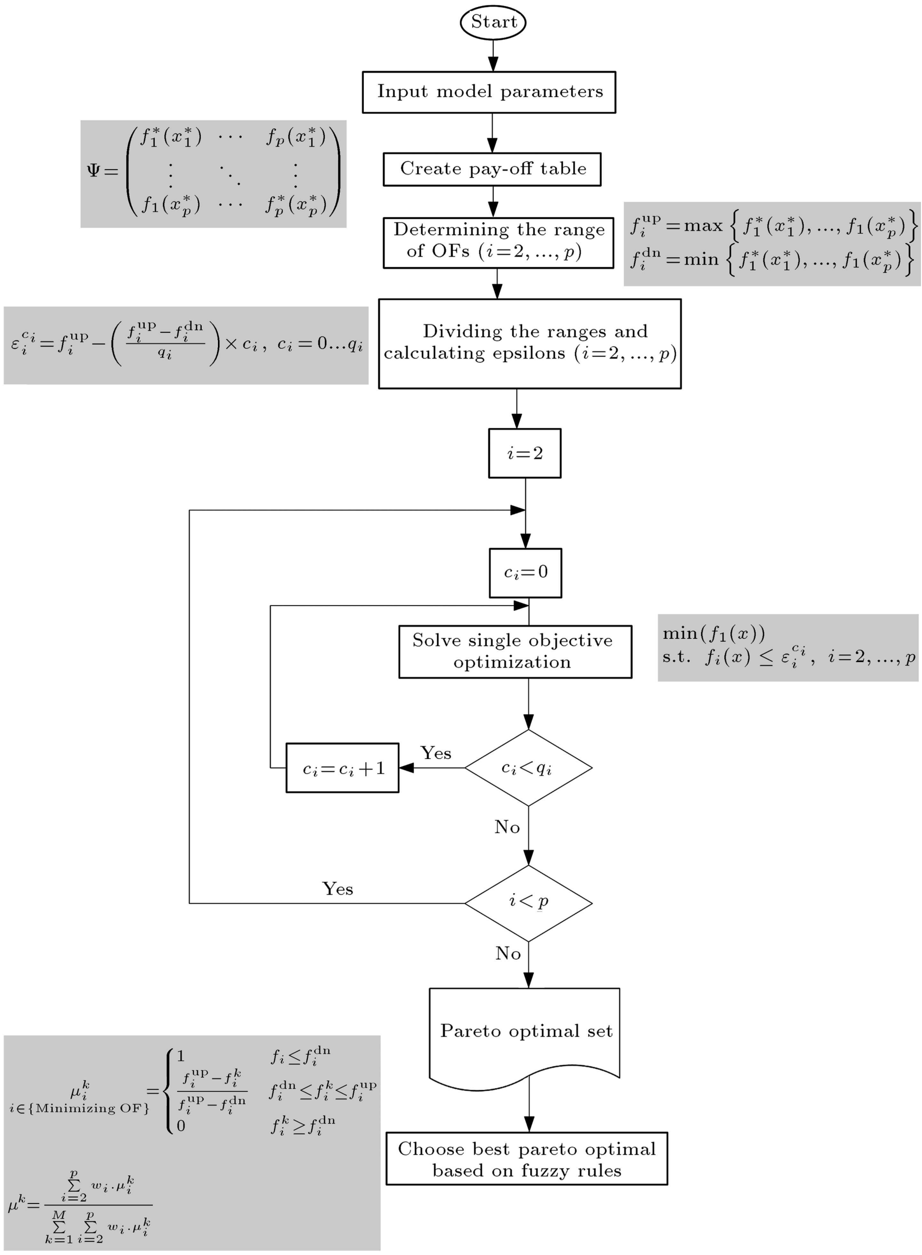

Figure 1. Flowchart of multiobjective optimization.

$$P_m^{\text{gen}} - P_m^{\text{load}} + P_m^{\text{phev}} = \sum_j V_m V_j Y_{mj} \times \cos\left(\delta_m - \delta_j - \theta_{mj}\right), \tag{8}$$

$$Q_m^{\text{gen}} - Q_m^{\text{load}} + Q_m^{\text{phev}} = \sum_j V_m V_j Y_{mj} \times \sin\left(\delta_m - \delta_j - \theta_{mj}\right), \tag{9}$$

where, m and j are the nodes indices; P_m^{gen} and Q_m^{gen} are active and reactive power generations of the ith node, respectively; P_m^{load} and Q_m^{load} are active and reactive power demands at node I, respectively; P_m^{phev} and Q_m^{phev} are generation/absorption active and reactive power at node i, respectively; V is the magnitude of voltage; δ is the angle of voltage; Y_{mj} is the magnitude of elements m and j of the admittance matrix, and θ_{mj} is the angle of elements m and j of the network admittance matrix.

4. PHEV injection current limitation:

$$|I_{\text{phev},m}| \leq I_{\text{phev},m}^{\max}, \tag{10}$$

$$|I_{\text{phev},m}| \geq I_{\text{phev},m}^{\min}, \tag{11}$$

where, $I_{\text{phev},m}^{\max}$ and $I_{\text{phev},m}^{\min}$ are maximum and minimum total PHEV current. TPC is obtained from

Eq. (12):

$$I_{\text{phev},m} = \sqrt{\sum_{h=2}^{H} \left[(I_{\text{phev},m}^{h})^2 \right]}. \tag{12}$$

Each component of the current and voltage harmonics can be expressed in the form of real and imaginary parts as:

$$I_{\text{phev},m}^{h} = I_{\text{phev},m}^{h,r} + jI_{\text{phev},m}^{h,i}, \tag{13}$$

$$V_m^h = V_m^{h,r} + jV_m^{h,i}. \tag{14}$$

2.3. Calculation of voltage harmonic components

To calculate the objective functions (the fundamental and harmonic components of PHEVs current and nodes), the voltages should be available. The fundamental components of the voltage and current are obtained from the load flow calculation by neglecting the nonlinear load. The nodes voltages can be calculated as:

$$\left[V_{\text{node}}^{h}\right] = \left[Y_{\text{node}}^{h}\right]^{-1} \cdot \left[I_{\text{node}}^{h}\right], \tag{15}$$

where, V_{node}^{h} and I_{node}^{h} are the node voltages and injecting current vectors for harmonic order, h, respectively. Y_{node}^{h} is the node admittance matrix for harmonic order h. Assuming that a PHEV is located at each node, the node injecting current is obtained as:

$$\left[I_{\text{node}}^{h}\right] = \left[I_{\text{phev}}^{h}\right] - \left[I_{\text{nload}}^{h}\right], \tag{16}$$

where, I_{phev}^{h} and I_{nload}^{h} are the PHEV and nonlinear load current vectors for harmonic order, h, respectively.

3. Case study

A typical 14-node Low Voltage (LV) network is considered as the case study, which is shown in Figure 2 [32-33]. The network comprises four feeders. This network

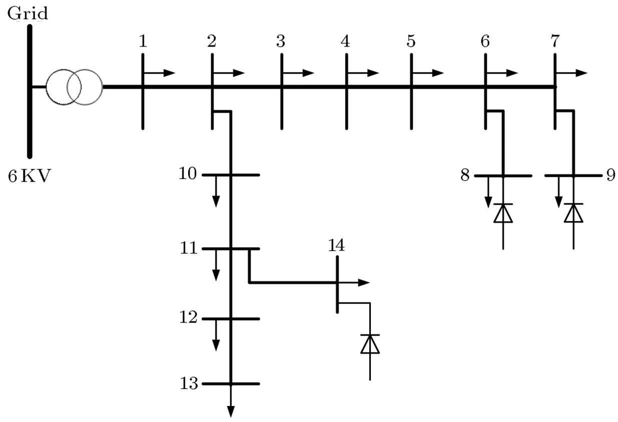

Figure 2. 14-node microgrid.

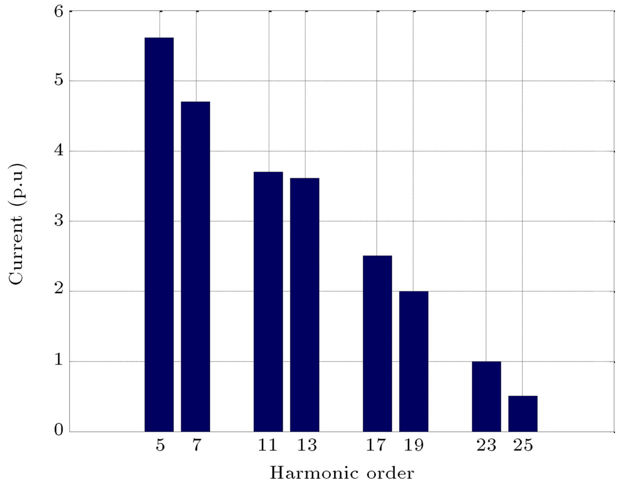

Figure 3. Harmonic contents of the nonlinear loads in the test system.

is modified by adding three nonlinear loads (six-pulse line-commutated converters) at nodes 8, 9, and 14 of the network, and the sizes were identical and equal to 30 kW.

Three identical harmonic current sources are employed as nonlinear loads in this power system. These nonlinear loads include different orders of harmonics (harmonics 5, 7, 11, 13, 17, 19, 23, 25) per unit, which are shown in Figure 3 [31]. All three nonlinear loads are alike, and inject only harmonic current to the network.

The line data and bus data of this network for fundamental frequency are taken in [33]. Six PHEVs are installed in the network to compensate harmonics in two different cases as follows:

Case 1: PHEVs are installed at nodes 6, 7, 8, 9, 13, 14 (three of the PHEVs are installed at a nonlinear load location).

Case 2: PHEVs are installed at nodes 5, 6, 7, 10, 11, 13 (none of the PHEVs is installed at a nonlinear load location).

The problem of PHEVs harmonic compensation is a nonlinear programming problem (NLP), and is modeled in GAMS software using CONOPT solver. The optimization solution algorithm is based on the ε-constraint method, which is explained, in detail, in [34-36].

The THD of buses without participation of PHEVs is plotted in Figure 4. According to this figure, the THD of buses reaches 30%, which cannot meet the harmonic standard, such as IEEE 519.

3.1. Case 1: PHEVs are installed at nodes 6, 7, 8, 9, 13 and 14

The results of the payoff table for Case 1 are shown in Table 1. According to this table, the PHEVs harmonic compensation can decrease the THD of the system from about 25% (base case without harmonic compensation by the PHEVs) to 0.1995% ($F1^* = 0.1995$) by injecting 0.18058 per units of harmonic current compensated by the PHEV. In this case, the PHEVs installed only at nonlinear load locations, i.e. nodes 8, 9 and 14, are chosen for harmonic compensation, and the other PHEVs, installed at nodes 6, 7 and 13, are not selected for harmonic compensation, which can verify the validity of the proposed method. The local harmonic sources are selected rather than the remote sources and, as a result, it prevents flowing harmonic current into the network.

On the other hand, if the minimization of TPC is interested, 0.03313 per unit of harmonic current is injected by the PHEVs, but, in this case, THD reaches 8.483%. These results verify the conflicting nature of two objective functions, $F1$ and $F2$.

Table 2 shows the results of the proposed multi-objective framework in Case 1 with different weighting factors. In this table, (n14) refers to the node of the network with the worst THD (node 14).

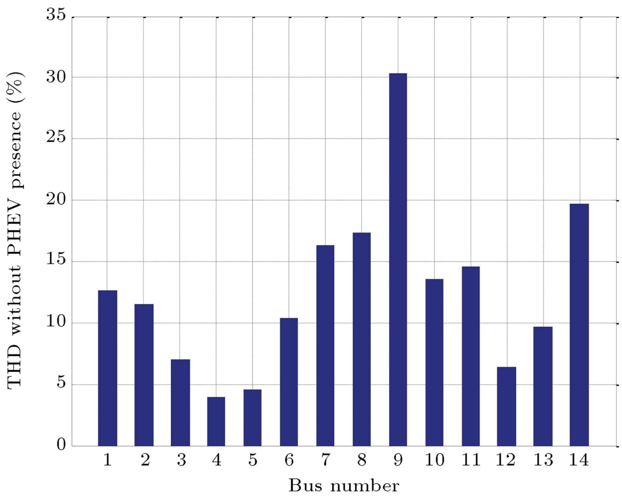

Figure 4. THD of buses with absence of PHEVs.

Table 1. Payoff table for Case 1.

	Case 1: Single objective	
$F1$ (%)	$F1^*$ =0.1995	8.483
$F2$	0.1806	$F2^* = 0.0332$

Table 3. Payoff table for Case 2

	Case 1: Single objective	
$F1$ (%)	$F1^*$ =2.3	9.899
$F2$	0.2078	$F2^* = 0.02194$

3.2. Case 2: PHEVs are installed at nodes 5, 6, 7, 10, 11 and 13

In this case, some of the PHEVs are installed at the nodes, not including nonlinear loads. The results of the payoff table for Case 2 are shown in Table 3.

According to this table, the PHEVs harmonic compensation can decrease the THD of the system to 2.3% ($F1^*$ =2.3) by injecting 0.2078 per units of harmonic current compensated by the PHEVs. Although more harmonic current is injected by the PHEVs in this case, in respect to Case 1, the THD of the system (2.3%) is more than that of Case 1 (0.1995%). This is because, in Case 2, the harmonics of the network are compensated by a remote harmonic compensator. The flow of harmonic current in the network distorts. Also, Table 3 shows that the THD of the system can reach 9.899% with the minimum amount of injected harmonic by the PHEVs. It is noted that in this case, the PHEVs located at nodes 5, 6, 7, and 13 are selected for harmonic compensation.

Table 4 shows the results of the proposed multi-objective framework in Case 2 with different weighting factors. In this table, (n7) refers to node 7 of the network with the worst THD. According to this table, one can see that the weighting factor can manage the harmonic compensation strategy. With the goal of decreasing THD, a greater value is assigned to $w1$, whereas a lower value is considered for $w1$ if total PHEV current is of the main concern in the harmonic compensation process.

Finally, the injected harmonic currents of PHEVs in Case 1, for different harmonic order, are listed in Table 5, indicating that the PHEVs inject harmonics of all orders compensate the nonlinear load harmonics and decrease the THD of the network loads as much as possible.

4. Conclusions

In this paper, a multiobjective framework is proposed for harmonic compensation of the network by PHEVs.

Table 2. The results of Case 1 with different weighting factors.

	Single objective	Multiobjective		
		$w1 = 0.7$ $w2 = 0.3$	$w1 = 0.5$ $w2 = 0.5$	$w1 = 0.3$ $w2 = 0.7$
$F1$ (%)	$F1^*$=0.1995	0.397 (n14)	2.395 (n14)	5.213 (n14)
$F2$	$F2^*$=0.0332	0.166	0.136	0.102

Table 4. The results of Case 2 with different weighting factors.

	Single objective	**Multiobjective**		
		$w1 = 0.7$ $w2 = 0.3$	$w1 = 0.5$ $w2 = 0.5$	$w1 = 0.3$ $w2 = 0.7$
$F1$ (%)	$F1^*$ =2.3 (n7)	5.1 (n7)	5.584 (n7)	7.5 (n7)
$F2$	$F2^* = 0.022$	0.115	0.0963	0.041

Table 5. The magnitude of injected harmonic current per unit by PHEVs in Case 1 with $w1 = w2 = 0.5$.

	PHEV location node					
Harmonic order	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 13**	**Node 14**
5	–	–	0.021	0.03	–	0.013
7	–	–	0.021	0.026	–	0.016
11	–	–	0.019	0.021	–	0.017
13	–	–	0.019	0.021	–	0.018
17	–	–	0.014	0.015	–	0.013
19	–	–	0.011	0.012	–	0.011
23	–	–	0.006	0.006	–	0.006
25	–	–	0.003	0.003	–	0.003

The THD of network nodes and Total PHEV Current (TPC) indices are minimized in the form of a multiobjective optimization problem. The proposed method, in fact, promotes the owner of the PHEVs to compensate the harmonics of the network. In this study, it has been shown that in the case of no PHEV participation in harmonic compensation, the THD of the buses was increased and could not meet the harmonic standards. The other advantage of PHEVs is their mobility and, therefore, they can be easily installed at nodes, including nonlinear loads, to compensate the harmonic of the network. So, the PHEVs owner can incorporate them in harmonic compensation in addition to their participation in the energy market, reserve market or reactive power market. The research work underway is to consider PHEVs in the reactive power market while compensating the harmonics of the network.

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Appendix

The line and bus data are listed in Tables A.1 and A.2.

Table A.1. Line data (per unit).

Line no.	Start bus	End bus	R	X	B
1	1	2	0.0119	0.0414	0.0045
2	2	3	0.0119	0.0414	0.0042
3	3	4	0.0135	0.04211	0.0064
4	4	5	0.0167	0.0845	0.0
5	5	6	0.01938	0.05917	0.0
6	6	7	0.0224	0.12	0.0
7	6	8	0.03181	0.0845	0.0
8	7	9	0.0342	0.17038	0.0
9	2	10	0.0167	0.042	0.0085
10	10	11	0.01938	0.05917	0.0264
11	11	12	0.06701	0.17103	0.0173
12	12	13	0.09498	0.1989	0.0
13	11	14	0.08135	0.15581	0.0

Table A.2. Bus data (per unit).

Bus no.	Real load demand	Reactive load demand
1	–	–
2	0.2	0.065
3	0.85	0.279
4	0.4	0.1312
5	0.2	0.065
6	0.2	0.065
7	0.076	0.016
8	0.1	0.03
9	0.061	0.016
10	0.112	0.075
11	0.61	0.09
12	0.016	0.061
13	0.09	0.059
14	0.135	0.061

Biographies

Hassan Feshki Farahani was born in Farahan, Tafresh, Iran, in 1979. He received a BS degree in electronic engineering from Shahed University, Tehran, Iran, in 2002, and an MS degree in power systems engineering from the Iranian University of Science & Technology (IUST), Tehran, Iran, in 2005. He received the Ph.D. degree in power engineering from the Islamic Azad University, Science & Research Branch, in 2012. He was a lecturer in Islamic Azad University, Ashtian Branch from 2005 to 2012 and has been an Assistant Professor since 2012. He is the author of more than 60 journal and conference papers. His current research interests include the analysis of Plug-in Hybrid Electric Vehicles (PHEVs) in the power system, analysis and control of power electronic multilevel converters and FACTS devices.

Mohammad Khalili received his MS degree in 2012 from the Power and Water University of Technology, Tehran, Iran, where he is currently working towards a PhD degree. His research interests are in the fields of power system economics and optimization, stochastic programming and electricity markets.

Abdorreza Rabiee was born in 1979. He studied Electrical Engineering at Shahid Chamran University, Ahwaz, Iran, and received MS and PhD degrees, in 2005 and 2010, respectively in Electrical Engineering from the Iran University of Science & Technology (IUST), Tehran, Iran. Currently, he is Assistant Professor in the Electrical Engineering Department of Shahrekord University, Shahrekord, Iran. His research interests include power system operation and planning, power markets, smart grids, and distribution system operation.

Mohammad Sadegh Ghazizadeh received a BS degree from Sharif University of Technology, Tehran, Iran, in 1982, an MS degree from Amirkabir University of Technology, Tehran, in 1988, and a PhD degree from the University of Manchester (UMIST), Manchester, U.K., in 1997, all in Electrical engineering. He is currently Associate Professor in the Department of Electrical Engineering at the Power and Water University of Technology, Tehran, Iran. He is also advisor to the Iranian Ministry of Energy, and Head of the electricity regulatory board in Iran. His research interests include power system dynamics and control, restructuring and electricity market design, and energy economics.