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Online Coordination of Plug-In Electric Vehicles Considering Grid Congestion and Smart Grid Power Quality

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Abstract: This paper first introduces the impacts of battery charger and nonlinear load harmonics on smart grids considering random plug-in of electric vehicles (PEVs) without any coordination. Then, a new centralized nonlinear online maximum sensitivity selection-based charging algorithm (NOL-MSSCA) is proposed for coordinating PEVs that minimizes the costs associated with generation and losses considering network and bus total harmonic distortion (THD). The aim is to first attend the high priority customers and charge their vehicles as quickly as possible while postponing the service to medium and low priority consumers to the off-peak hours, considering network, battery and power quality constraints and harmonics. The vehicles were randomly plugged at different locations during a period of 24 h. The proposed PEV coordination is based on the maximum sensitivity selection (MSS), which is the sensitivity of losses (including fundamental and harmonic losses) with respect to the PEV location (PEV bus). The proposed algorithm uses the decoupled harmonic power flow (DHPF) to model the nonlinear loads (including the PEV chargers) as current harmonic sources and computes the harmonic power losses, harmonic voltages and THD of the smart grid. The MSS vectors are easily determined using the entries of the Jacobian matrix of the DHPF program, which includes the spectrums of all injected harmonics by nonlinear electric vehicle (EV) chargers and nonlinear industrial loads. The sensitivity of the objective function (fundamental and harmonic power losses) to the PEVs were then used to schedule PEVs accordingly. The algorithm successfully controls the network THDv level within the standard limit of 5% for low and moderate PEV penetrations by delaying PEV charging activities. For high PEV penetrations, the installation of passive power filters (PPFs) is suggested to reduce the THDv and manage to fully charge the PEVs. Detailed simulations considering random and coordinated charging were performed on the modified IEEE 23 kV distribution system with 22 low voltage residential networks populated with PEVs that have nonlinear battery chargers. Simulation results are provided without/with filters for different penetration levels of PEVs.

Keywords: PEV; online coordinated charging; THD; battery charger harmonics

1. Introduction

1.1. Motivation

It is well-known that the current harmonic injection of nonlinear loads such as variable speed drives (VSDs), variable frequency drives (VFDs), energy-efficient lights, switching converters, smart appliances and plug-in electric vehicles (PEVs) can have damaging impacts on the power grid and cause premature ageing of its components, such as power transformers and distributed generation (DG) units. Harmonic distortion can contribute to existing grid issues such as network losses, poor voltage regulation, imbalanced operation and reactive power flows. They may also create new grid problems such as mal-operation of control devices, harmonic losses, harmonic reactive power flows and harmonic resonances [1–4]. These important issues are enough to motivate researchers, investigators and more importantly, the utilities to seek and come up with new, simple and practical strategies to resolve the power quality issues in the developing smart grids.

1.2. Literature Survey

Common practices for improving power quality and resolving voltage and current harmonic issues include de-rating of components and the installation of passive, active and hybrid filters, as well as utilization of custom power devices which tend to be expensive options [3]. An alternative and practical approach to mitigate harmonic distortion without filters has recently been implemented that is based on optimal scheduling of transformer load tap changers (LTCs) and rescheduling of the existing switched shunt capacitors (SSCs) with consideration of total harmonic distortion (THD) [2].

The number of residential, commercial and industrial customers with PEVs and electric vehicle (EV) charging stations is increasing immensely in many distribution networks. For example, the DC Fast Charging (DCFC) network in the USA has over 18,000 stations for AC, DC and wireless charging with over 40,000 connections across the country [5]. It is well-known that uncoordinated PEV charging, particularly during peak-load hours, can cause transformer and line overloading as well as voltage magnitude and voltage unbalance issues [5–8]. Besides, EV charger inverters also act like nonlinear loads and inject current harmonics that can initiate or contribute to poor power quality issues for utilities. Recent studies have started to investigate the impact of EV battery chargers on the power quality of distribution networks, and in particular, transformer life expectancy [9]. Some research works have introduced new control scheme for battery chargers or even included the power factor correction [10,11]. The negative impact of nonlinear EV chargers on the power quality of grid cannot be neglected especially under high penetration during off-peak hours.

There are two main approaches to resolving the issue: (i) motivate consumers to charge their vehicles during off-peak hours by offering dynamic energy prices, and (ii) coordinate PEV charging activities [6,7,12,13]. The second method can be implemented by an online and/or offline scheme using PEV charging/discharging coordination algorithms that are classified as decentralized (distributed) and centralized strategies [6,7,12,13]. Further, some recent researchers have presented optimal strategies for the allocation of EV parking lots and distributed renewable resources considering economic objectives [14]. In [15,16] an online approach for demand response and a control charging strategy for PEVs in smart grids are presented. Reference [17] has implemented and tested a maximum sensitivity selection-based charging coordination algorithm (OL-MSSCA) for PEVs with random arrival times, locations and penetrations. This coordination algorithm reduces the total cost, which includes the cost of generating energy and the associated grid losses while also regulating node voltages.

In this paper, the algorithm used in [17] is modified and improved to include harmonic current injections by nonlinear EV battery chargers and nonlinear industrial loads to control the individual bus voltage profiles as well as the THD of the entire smart grid. The proposed nonlinear online maximum sensitivity selection-based charging algorithm (NOL-MSSCA) is tested for different PEV penetrations and operating scenarios. For the cases with very high PEV penetration levels, some of the low priority vehicles may not be fully charged before 0800h; therefore, installations of passive power filters (PPFs) is suggested along with the proposed PEV coordination and demonstrated to ensure full service to all consumers. Figure 1 shows a schematic picture of the proposed approach and the implemented OL-MSSCA.

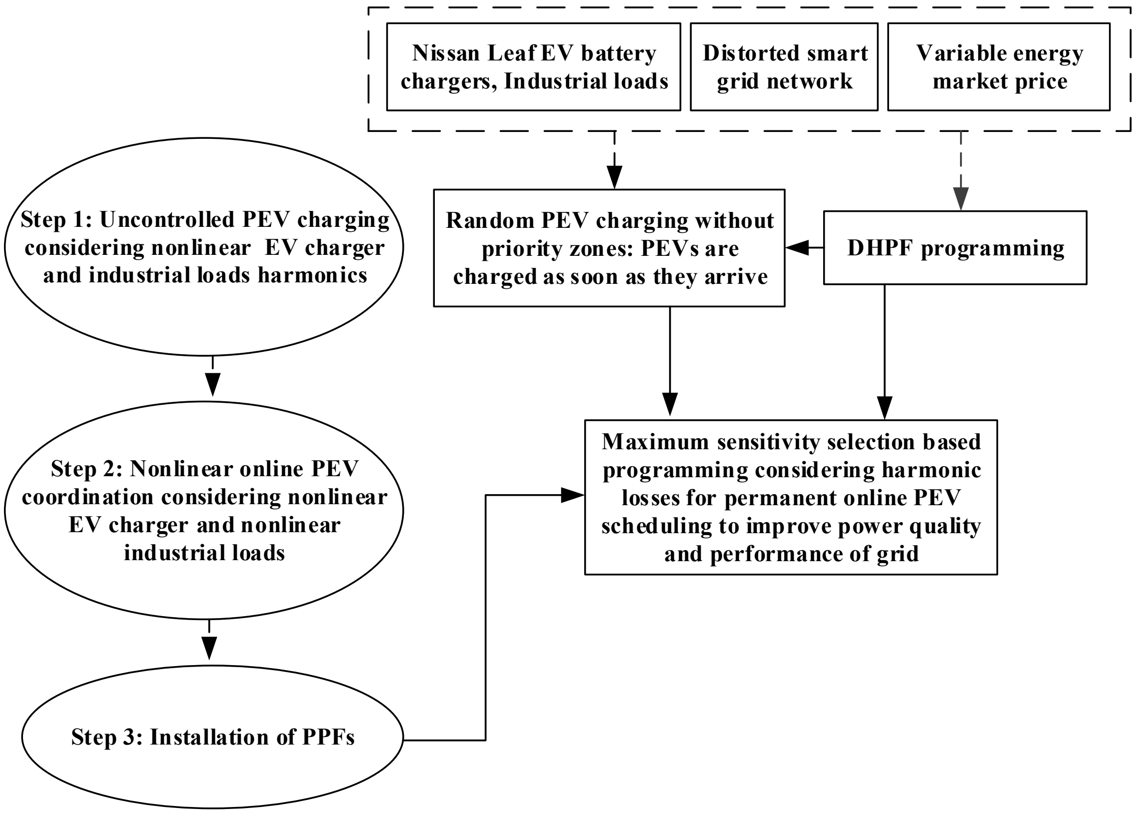


Figure 1. Schematic overview of the proposed nonlinear online plug-in electric vehicle (PEV) coordination approach considering harmonics.

1.3. Contributions

The main contributions of this paper are summarized below.

- A New Nonlinear PEV Coordination Approach. The proposed online coordination approach (OL-MSSCA) considers the nonlinearities of the EV battery chargers and industrial loads. This is due to the importance of power quality standards in the field of smart grids and online scheduling approaches. The online PEV coordination approaches available in the literature ignore the impacts of harmonics and poor power quality in the reported online scheduling programs. To consider this gap, this paper uses the application of the DHPF algorithm to model the nonlinear loads and the nonlinear EV chargers in the formulation of the objective function to minimize the total cost, improve the power quality and performance of the smart grid. Accordingly, the nonlinear OL-MSSCA will control the THDv level (considering utilities' concerns) by including the THDv in the objective cost, while also satisfying the PEV owners' preferences (considering priority zones). The new proposed objective function is formulated based on the harmonic power losses extracted from the MSS vector, which is easily extracted from the existing Jacobian matrix of the DHPF algorithm. Therefore, the proposed approach is relatively simple, fast and practical.
- A Simple and Practical Strategy to Relieve Grid Congestion. The new online algorithm can successfully keep the THDv level within the permissible standard of limit of 5% and fully charge PEVs for medium and moderate PEV penetrations. This is done by shifting some of the PEV charging activities to off-peak hours. However, the algorithm may not be able to simultaneously manage to control the THDv and customer satisfaction with high PEV penetration. This is due to the inclusion of a THDv operating condition in the objective cost function and constraints in order to avoid any THDv violations. Therefore, a simple solution consisting of PPF installation is proposed for further improvement of power quality and satisfying the demands of PEV owners.

The PPFs are designed and tuned on dominant harmonic spectrums. The new control strategy is now capable of fully charging the PEV by the next morning and controlling the THDv.

- Solution Validation and Assessment. The proposed OL-MSSCA algorithm was tested on a distorted and modified smart grid system and the results are assessed through 3 case studies. Comparison of the 3 case studies indicates that uncontrolled PEV activities (case 1) may lead to severe power quality issues (for example, for 47% PEV penetration, THDv is above 11% with high voltage deviations and losses) whereas the new proposed algorithm (case 3) can successfully keep the THDv level within the designated permissible limit, even with high PEV penetrations of 47% and 64%. Also, all PEVs are fully charged and ready for their next trip.

1.4. Organization of Manuscript

This paper is structured as follows: Section 2 includes the problem formulation/calculation and definition of the proposed solution approach. Section 3 introduces the system under study, the required load parameters and pricing lists. Section 4 explains the specifications of the PEV battery chargers and nonlinear load specifications, including their harmonic spectrums. Sections 5 and 6 present the simulation results and discussion. Finally, the conclusions are provided in Section 7.

2. Formulation of PEV Coordination Problem Considering Battery Charger and Nonlinear Load Harmonics

2.1. Decoupled Harmonic Power Flow Calculation

The formulation and solution approaches for the PEV coordination problem considering nonlinear batteries require harmonic modeling of the network. The paper uses the Newton-Raphson based decoupled harmonic power flow (DHPF) algorithm [1]. This is a common approach for modelling actual distribution networks with a large number of industrial nonlinear loads that needs a practical power-flow algorithm with fast convergence and a low memory storage requirement [1]. The nonlinear loads are modelled as a combination of passive elements and harmonic current sources at fundamental and harmonic frequencies, and the relevant admittance matrix is modified according to the harmonic frequency [1]. The linear loads consist of a resistance in parallel with a reactance while the nonlinear loads (PEVs) are modelled as current sources that inject harmonic currents into the network:

$$\begin{cases} I_i^{(1)} = [(P_i + jQ_i)/V_i^{(1)}]^* \\ I_i^{(h)} = C(h) I_i^{(1)} \\ Y^{(h)}\, V^{(h)} = I^{(h)} \end{cases} \tag{1}$$

where $C(h)$ is the ratio of the h^{th} harmonic current to its fundamental value, while P and Q are real power and reactive power, respectively. Also, $V^{(h)}$ and $Y^{(h)}$ are the voltage vector and the admittance matrix at the h^{th} harmonic frequency, respectively [1].

The admittance matrix $Y^{(h)}$ is calculated by the following equations:

$$\begin{cases} Y_{l,l}^{(h)} = 1/\left(R_{i,i+1} + jhX_{l_{i,i+1}}\right) \\ Y_{l,s}^{(h)} = 1/jhX_{c_{i,i+1}} \end{cases} \tag{2}$$

where $Y_{l,l}$ and $Y_{l,s}$ are the diagonal and the off-diagonal entries of the admittance matrix. Also, $R_{i,i+1}$, $X_{l_{i,i+1}}$, $X_{C_{i,i+1}}$ are the resistance, reactance and capacitance of the line between buses i and $i+1$, respectively.

The voltage and THDv at bus i are calculated by:

$$\begin{cases} |V_i| = \sqrt{\sum\limits_{h=1}^{H} \left| V_i^{(h)} \right|^2} \\ THD_{v,k} = \sqrt{\sum\limits_{h=2}^{H} \left| V_k^{(h)} \right|^2} / \left| V_k^{(1)} \right| \end{cases} \tag{3}$$

The harmonic power losses (including fundamental and harmonic losses) in the line between buses *i* and *i* + 1 are calculated by [2]:

$$P_{loss(i,i+1)}^{(h)} = R_{i,i+1} \left(\left| V_{i+1}^{(h)} - V_i^{(h)} \right| \left| y_{i,i+1}^{(h)} \right| \right)^2 \tag{4}$$

The total power losses of the system include the system losses at the fundamental and harmonic frequency and can be extracted from [2]:

$$P_{loss} = \sum_{h=1}^{H} \left(\sum_{i=1}^{n} P_{loss(i,i+1)}^{(h)} \right) \tag{5}$$

2.2. Proposed Nonlinear Online Maximum Sensitivity Selection Based Charging Algorithm (NOL-MSSCA) for Coordination of PEVs in a Smart Grid

A new online PEV coordination algorithm has been developed that considers the current harmonic injections of the EV battery chargers and nonlinear loads. The recently implemented OL-MSSCA of [17] uses a Newton-Raphson based fundamental power flow in order to solve the objective functions of PEV coordination without considering current and voltage harmonics. In other words, [17] ignores the nonlinearities of the EV chargers and industrial loads. This paper modifies this approach by including the harmonic currents injected by EV battery chargers and nonlinear loads in the main program and proposes a nonlinear online maximum sensitivity selection-based charging algorithm (NOL-MSSCA) for the coordination of PEVs, which also considers battery charger and industry load nonlinearities. The NOL-MSSCA is an online program and performs PEV coordination at a 5-min interval over a 24-h period (Figure 2). To implement this approach, a DHPF program was performed to calculate the harmonic bus voltages, harmonic losses and THDv of the system. The sensitivity of the total system power losses to the power consumption of each PEV at each bus were calculated using the Jacobin matrix of the DHPF algorithm to form the MSS vector. As such, the created MSS vector was used for permanent scheduling of PEVs considering the maximum total demand of the system. The proposed algorithm in Figure 2 is based on the following ideas:

1. PEV coordination is performed to reduce the costs associated with generation and losses considering the network, EVs and power quality constraints.
2. The DHPF algorithm is included in the PEV coordination approach to add the harmonic injections of nonlinear EV battery chargers and nonlinear industry loads.
3. Consumers with PEVs are classified as high, medium and low priority customers. These priorities are defined based on three different charging zones: (i) Red/high priority (1800–2200h) customers tend to charge their vehicles as soon as they return from work and pay very high tariffs. (ii) Blue/medium priority (2200–0100h) PEV owners prefer to charge their vehicles at partially off-peak periods with lower tariff rates. (iii) Green/low priority (0100–0800h) customers charge their vehicles during off-peak hours and is highly recommended because low tariffs are set for customers.
4. Most EVs users are charged based on their priorities as they are randomly plugged-in to increase consumer satisfaction.
5. Charging of the remaining EVs are postponed and shifted to off-peak hours during early-morning hours to decrease the cost and keep the power quality constraints within the permissible limits as recommended by the IEEE-519 standard [18].

6. For the scenarios with moderate and high levels of PEV penetrations, the OL-MSSCA algorithm may not be able to fully charge the EVs, especially during peak hours due to THDv violations. According to IEEE standard 519, the THDv level needs to be kept within the permissible level of 5%. Note that OL-MSSCA strictly prevents any THD and/or voltage quality violations. Therefore, no cost or penalties for THDv increases and violations are considered in the proposed PEV coordination approach. Instead, THD issues at high PEV penetration levels are resolved by the installations of inexpensive PPFs.
7. To fully charge the PEVs, a simple approach using PPF installation is considered.

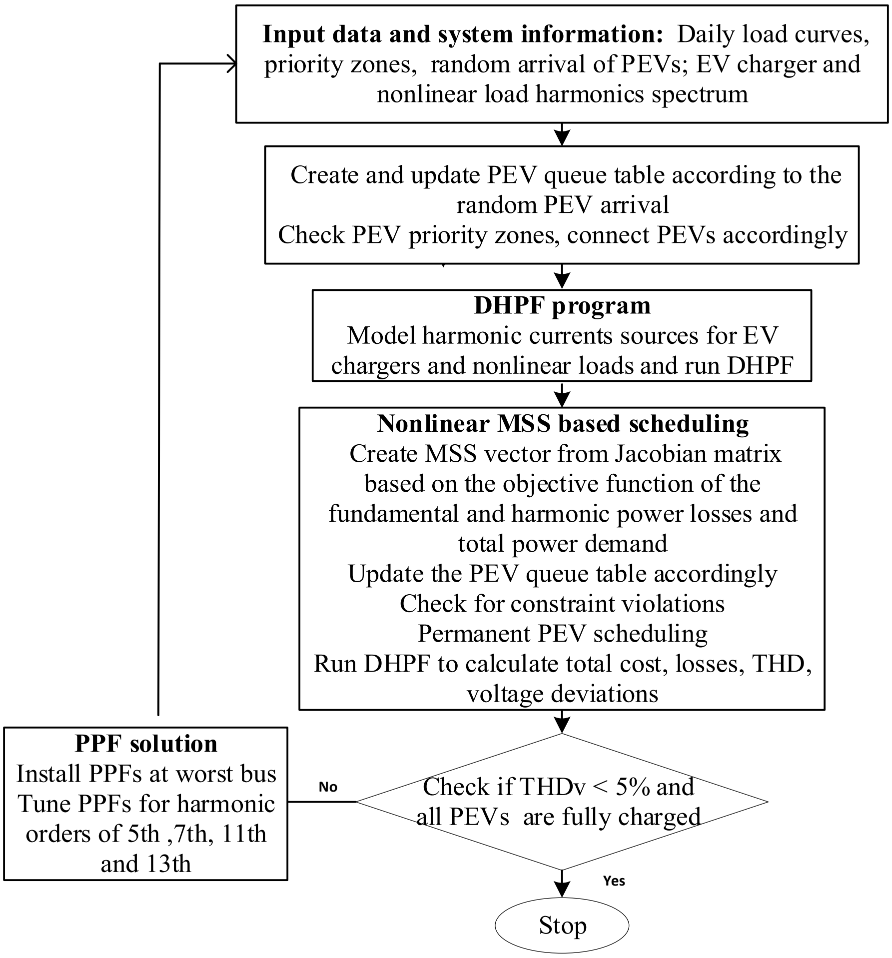


Figure 2. Proposed approach for nonlinear online PEV coordination with EV battery chargers and nonlinear industry loads' harmonics.

2.3. Formulation of Proposed NOL-MSSCA for PEV Coordination

PEV charging coordination is formulated as a nonlinear minimization problem, including the cost of losses and cost of purchasing or generating energy (total demand) [19] considering current harmonic injections by PEVs and nonlinear loads. The total power system losses of the objective function include both fundamental and harmonic voltages, which are calculated by the DHPF algorithm. The objective function is defined as:

$$\begin{gathered}\min F = \min F_{cost\ (loss+demand\ )} = \min cost(P_{t,loss} + Dt_{core,total}) = \\ \sum_{h=1}^{H} \sum_{i=0}^{m-1} K_T R_{i,i+1} \left(\left| V_{i,i+1}^{(h)} - V_i^{(h)} \right| \left| y_{i,\ i+1}^{(h)} \right| \right) + \sum_k K_G P_{t_{cor,total}}^{load}\end{gathered} \tag{6}$$

$F_{cost\ (loss\ +\ demand)}$ is the cost corresponding to total system losses and total system demand. $P_{t,loss}$ is the total power losses at hour t and $Dt_{core,total}$ is the total demand. Also, K_T is the cost per MWh of losses (for example, 50 $/MWh [20] and K_G is the cost per MWh of generation [19]. H, m and i refer to the highest harmonic order considered, total number of nodes and node number, respectively.

The objective function of the proposed nonlinear approach is formulated based on the sensitivity of the fundamental and harmonic power losses of the smart grid to the EV power consumption at fundamental frequency and the EV harmonic injections at harmonic frequencies. The MSS vectors are simply extracted from the Jacobean matrix of the DHPF algorithm. According to the mismatch power equations [21]:

$$S = \Delta(V)\ Y^{*}V^{*} \tag{7}$$

This equation includes fundamental and harmonics components. The complex power S and bus voltages V are calculated by DHPF. The equation can be expressed by the partial derivatives of S with respect to the voltage magnitudes $|V|$ and angles σ to form the Jacobian matrix [21].

The entries of the Jacobean matrix include the harmonic values of total harmonic spectrums for both nonlinear loads and the nonlinear EV battery chargers.

$$dS = \frac{\partial S}{\partial |V|} d|V| + \frac{\partial S}{\partial \sigma} d\sigma \tag{8}$$

The following constraints are considered in the newly developed algorithm:

$$\begin{cases} \Delta V_m = |V_m - V_{rated}| \leq 0.1pu, \quad for\ m = 1, \ldots, n \\ D_{t_{cor,total}} = \sum\limits_{m} P^{\,load}_{t_{cor,total}} \leq D_{t_{cor,max}} \\ V_{i\ min} \leq V_{i\ rms} = \left(\sum\limits_{h=1}^{H} |V_i^h|^2 \right)^{\frac{1}{2}} \leq V_{i\ max} \\ THD_{vi} = \left[\left(\sum\limits_{h \neq 1}^{H} |V_i^h|^2 \right)^{\frac{1}{2}} / \left| V_i^1 \right| \right] \times 100\% \leq THD_v^{max} \end{cases} \tag{9}$$

where ΔV_m is the per unit (pu) voltage deviation of bus m, which is limited to ΔV_{max} = 0.1 pu in this paper. $D_{t,cor,max}$ is the maximum demand level (without any PEVs) at time interval t (time interval is 5 min); $V_{i\ min}$ and $V_{i\ max}$ are the respective minimum and maximum limits of the harmonic *rms* voltage at bus i (V_{irms}); THD_{vi} and THD_{vmax} are the distortion at bus i and the maximum distortion allowed while H and i are the highest harmonic order considered and node number, respectively.

3. The Modified Smart Grid Test System with PEVs

The modified 449 node smart grid system, including PEVs is considered to demonstrate the proposed NOL-MSSCA of Section 2.2 for different PEV penetrations. Figure 3 shows the system under study, including the PEVs and their EV charger harmonics. The main branch is the IEEE 31 bus 23 kV system [22], which includes 22 low voltage 19 bus 415 V residential feeders with different PEV penetration levels. System and load parameters are available in [17] and [22]. The daily residential load curves of [17] and the market energy price of [19] for summer weekdays have been used for the simulations in this paper (Figure 4). Figure 4 shows the new tariff for producing and generating energy in Australia in 2018 [19]. This tariff is chosen since the LV residential feeders' data is obtained from a suburb in West Australia (WA). As indicated in this reference, the energy price changes may lead users to consume energy more efficiently. For example, the price of energy is more expensive during rush hours in summer (approximately 55 cents/kWh). Therefore, the aim is to push the PEV charging activities to a later time, so they are charged during off-peak hours. The proposed online approach (NOL-MSSCA) aims at considering both customer preference (based on priority zones) and the concerns of the utilities. In the objective function, the cost per MWh of generation (K_G) is computed based on the latest market energy price of [19].

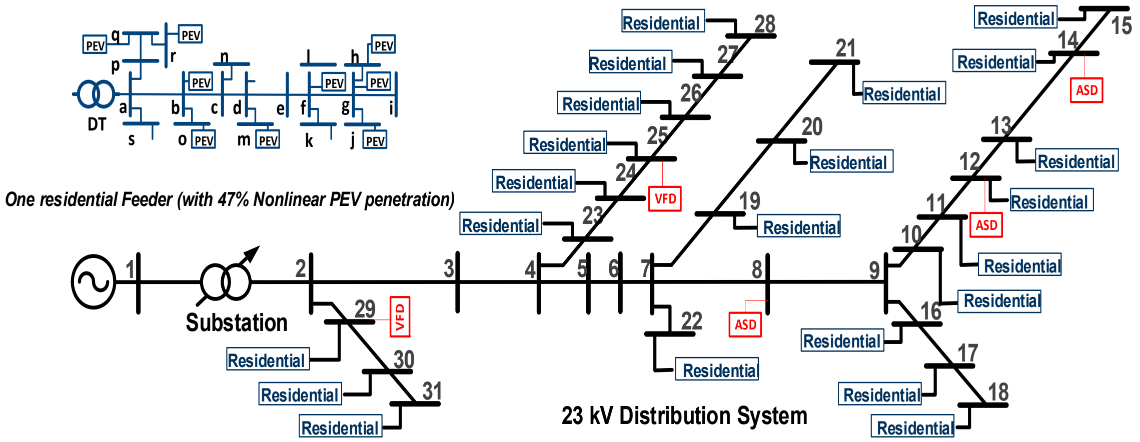


Figure 3. The 449-node smart grid system consisting of the IEEE 31 node 23 kV system with 22 low voltage 415 V residential feeders populated with 47% PEVs including nonlinear battery chargers and five nonlinear industry loads.

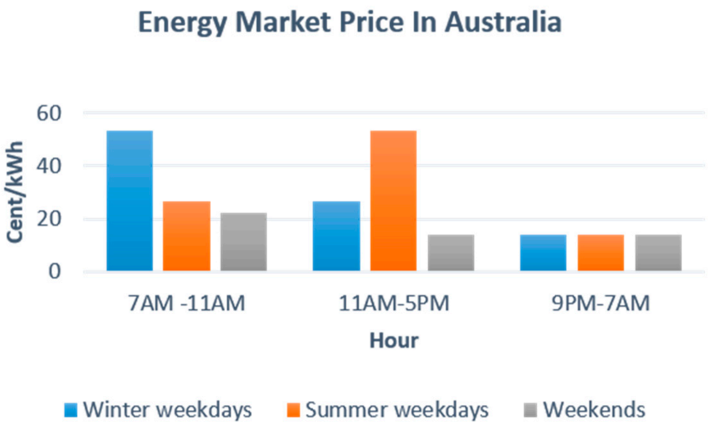


Figure 4. Variable short-term market energy pricing [19].

4. PEV Battery Charger as Nonlinear Load

PEVs are a low emission mode of transport, and therefore, they are becoming very popular in distribution systems. It is important that smart grids provide solutions to manage the energy storage options, as well as power quality impacts associated with nonlinear charging circuitry installed in PEVs. Many studies have already started to investigate the harmonic distortion created by AC-DC charging circuitry [10,23,24]. However, the impact of EV charger harmonics on grids has not been considered and included in online PEV coordination problems. In this paper, the typical harmonic current spectrum of a Nissan Leaf model is used considering a level 2 charging (208/16A) with the efficiency of 88% and rated battery capacity of 24 kWh [25]. In practice, the new EV chargers have less harmonic current contents. In the DHPF algorithm, the PEV chargers with a rating of 3.3 kW are molded as nonlinear EV charge loads with decoupled harmonic current sources based on the frequency spectrums of Table 1. To investigate the impact of harmonics on the power quality of the grid, nonlinear EV chargers as well as nonlinear industry loads were both modeled and included.

5. Simulation Results and Discussions

The new algorithm was used on the modified smart grid system of Figure 3 considering uncoordinated (random) and coordinated (NOL-MSSCA) PEV charging strategies without and with harmonics. Case studies 1–3 were simulated and the results are shown in Figures 5–7 and Table 2.

Table 1. Typical low order harmonic current spectrum of EV chargers and industry nonlinear loads [2,25].

Harmonic Order	PEV		Six-Pulse VFD		PWM-ASD	
	Mag. (%)	Phase (deg)	Mag. (%)	Phase (deg)	Mag. (%)	Phase (deg)
1	100	0	100	0	100	0
5	2	−67	23.52	111	23.52	111
7	2	−67	6.08	109	6.08	109
9	1.5	−46	4.57	−158	4.57	−158
11	1.8	−46	4.20	−178	4.20	−178
THDi	18.9%		25.2%		7.1%	

6. Discussions

The developed NOL-MSSCA was used to investigate the impacts of battery chargers and nonlinear load harmonics on uncoordinated and coordinated PEV charging. The aim is to fully charge all vehicles by 0800h for the next day's trip without exceeding the distribution transformer loading and the network power quality limits (Equation (9)). The algorithm was tested for the modified IEEE 449 bus system of Figure 3 that includes a 23 kV distribution network and 415 V residential feeders. The coordination algorithm is designed to control the node and network THDv levels within the permissible limits of 5% as recommended by the IEEE 519 Standard [18].

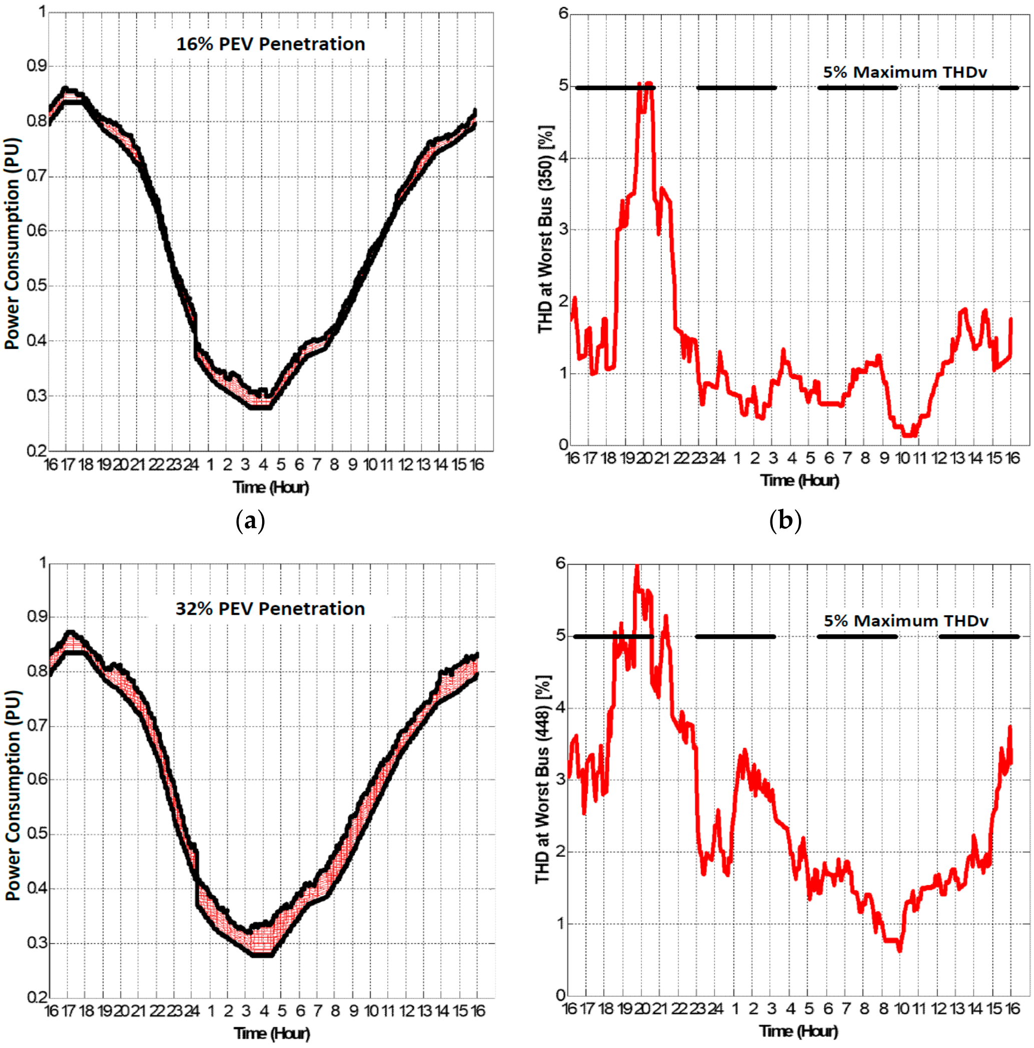
Further, Table 3 shows a comparison between the recent research and the practical coordination approach of this paper. As indicated, this paper not only addresses the need for integration of harmonics caused by nonlinear loads and EV battery chargers, but also provides solutions for further power quality improvement and customer satisfaction.

Table 2. Simulated case studies of uncoordinated and coordinated PEV charging (based on a nonlinear online maximum sensitivity selection-based charging algorithm (NOL-MSSCA) considering harmonics without/with passive power filters (PPFs).

Case	Simulation Results					
	PEVs Charging Approach	PEV Penetration (%)	Max THDv at Worst Bus (%)	Voltage Deviations (%)	System Energy Losses (MW)	Number of PEVs Not Fully Charged
1	Uncoordinated PEV Charging without PPFs	16	5.12	7.64	0.33	0
		32	6.11	8.50	0.37	0
		47	11.60	13.50	0.44	0
2	Coordinated PEV Charging without PPFs	16	5.14	0.97	0.027	0
		32	5.22	0.97	0.029	0
		47	5.36	0.98	0.032	20
3	Coordinated PEV Charging with PPFs	47	5.02	0.97	0.028	0
		63	5.02	0.98	0.029	0

6.1. Case 1—Uncoordinated PEV Charging

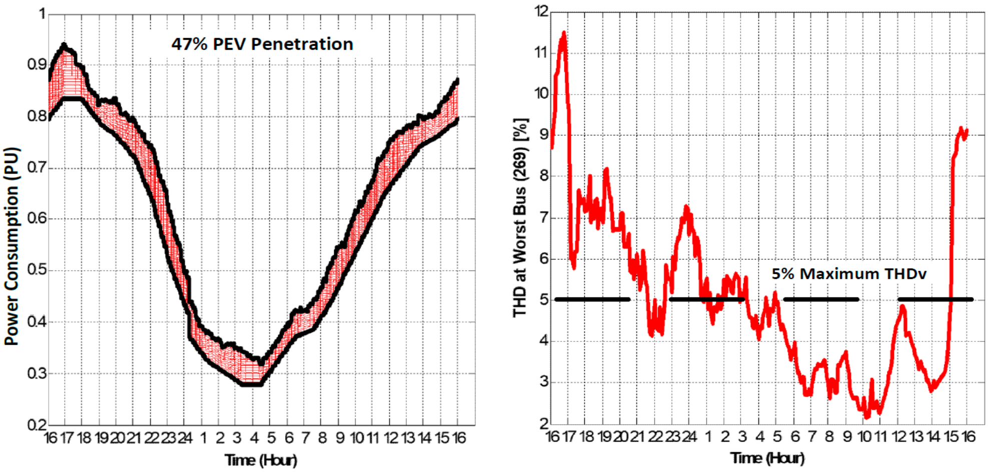
First, the uncoordinated PEV charging was tested to calculate and examine the corresponding THDv with different levels of PEV penetration. Case 1 shows the simulation results for uncoordinated charging considering voltage harmonics with 16% (includes 66 PEVs), 32% (includes 133 PEVs) and 47% (includes 198 PEVs) PEV penetrations. In this case study, the randomly arriving PEVs were selected and they were charged as soon as they plugged-in without considering the priority zones. As indicated by the results (Figure 5 and Table 2), the THDv level is very high and the impact of chargers' harmonics cannot be neglected, especially at medium and high PEV penetration of 32% and 47%, respectively.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. *Cont.*

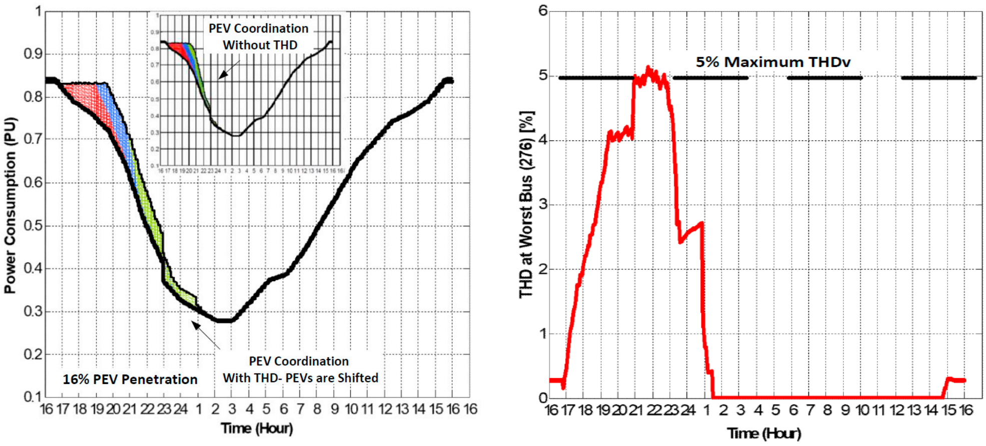


(**e**) (**f**)

Figure 5. Simulation results for Case 1—Uncoordinated PEV charging considering harmonics including power consumption and THDv of (**a**,**b**) 16% PEV charging penetration; (**c**,**d**) 32% PEV charging penetration; (**e**,**f**) 47% PEV charging penetration.

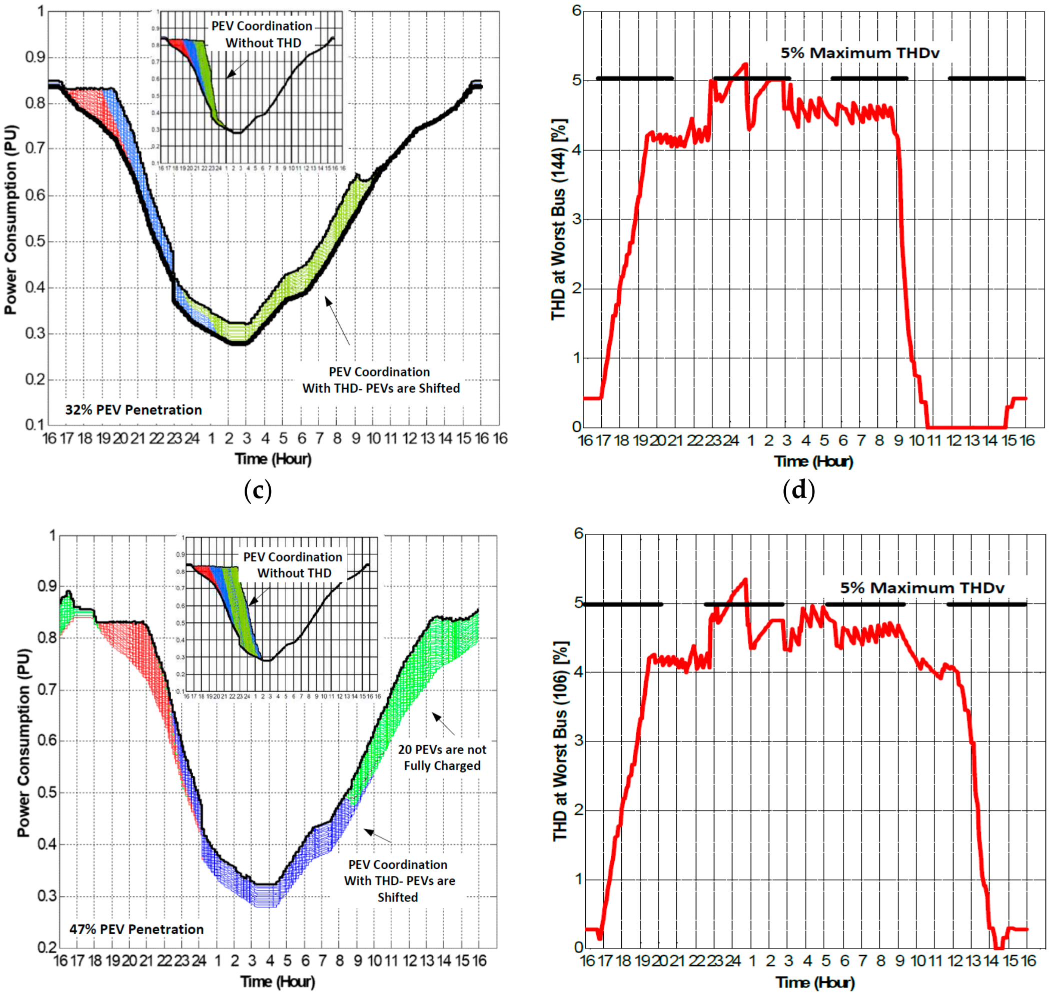
6.2. Case 2—PEV Coordination with NOL-MSSCA

In Case 2, the developed NOL-MSSCA was used to coordinate PEV charging and investigate the impact of harmonics. As the results show, the algorithm can successfully control the THDv level within the acceptable limit of 5% as defined by IEEE-519 standards for low PEV penetrations of 16%, but the THDv level is slightly over the standard limit for medium the PEV penetration of 47% (5.22%). Further, the algorithm managed to fully charge the PEVs before 0800h. This is done by shifting the PEVs to off-peak hours to reduce the effects of current harmonics injected by nonlinear battery chargers and nonlinear industry loads. Figure 6b,c show the THDv level for PEV penetrations of 16% and 32%. As expected, the THDv level is within the pre-defined allowed THD level of 5%. The simulation results for 16%, 32% and 47% PEV penetrations are shown in Figure 6 and Table 2, accordingly. The NOL-MSSCA was also used to coordinate PEV charging without considering harmonic distortion. A comparison of two PEV daily load curves (for high PEV penetration of 47%) shows that the algorithm effectively reduced the THDv level of 11.60% without constraint to the acceptable level of 5%. Additionally, the algorithm seems quite efficient in reducing the cost of generation with the proposed scenario of shifting the PEV charging schedules to off-peak hour.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

(**e**) (**f**)

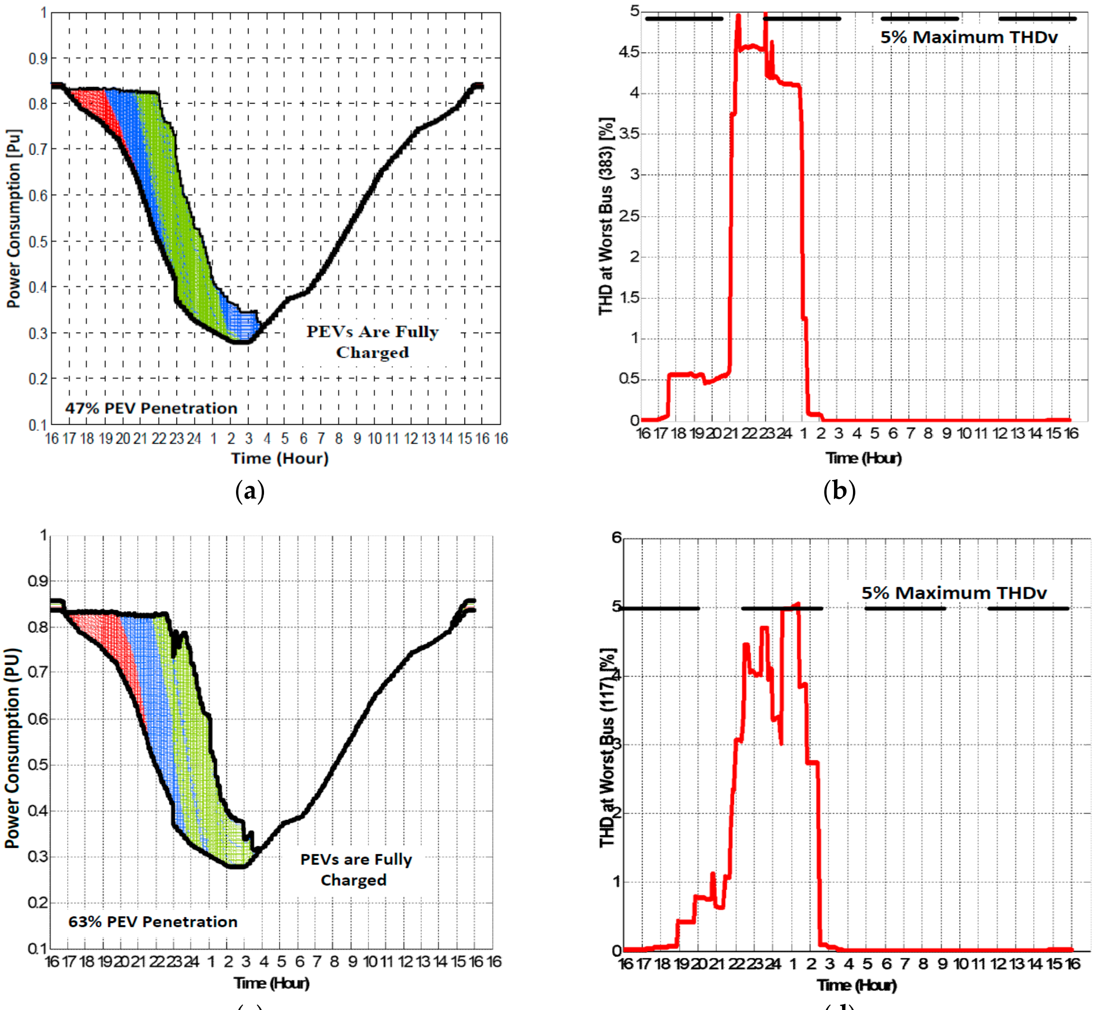
Figure 6. Simulation results for Case 2: NOL-MSSCA considering harmonics including power consumption and THDv of (**a**,**b**) 16% PEV charging penetration; (**c**,**d**) 32% PEV charging penetration; (**e**,**f**) 47% PEV charging penetration.

6.3. Case 3—Installation of Passive Power Filters (PPFs) to Improve the Performance of NOL-MSSCA with High Penetration of PEVs

The simulation results in Figure 6 for the high PEV penetration of 47% indicate that the NOL-MSSCA cannot manage to fully charge all EVs before the designated time of 0800 h for the next day's trip. This is expected since the collective effect of many vehicles with the considerable low order harmonic injections of Table 1 can create operating conditions with very high levels of overall THD distortion. To deal with the situation and prevent incontrollable harmonic pollution conditions, the NOL-MSSCA will keep postponing EV charging to the early morning hours. As a result, a number of PEVs will not be fully charged by 0800h. Case 3 demonstrates the simple possible solution of installing PPFs at the bus with the worst voltage harmonic distortion (bus 26). Simulation results are shown in Figure 7 and Table 2, accordingly. As indicated, the THDv level for the worst operating situation with 47% PEV penetrations is still within the permissible limit and the NOL-MSSCA manages to fully charge all EVs within the schedule. To assess the performance of the proposed approach, the NOL-MSSCA was also tested for very high PEV penetrations of 63% (includes 263 PEVs). As shown in Figure 7 and Table 2, even in case of very high PEV penetrations, the THDv level is still within the permitted standard limit of 5% and all PEVs are fully charged. For this purpose, PPFs are designed and tuned at four dominated harmonics of 5th, 7th, 11th and 13th. The fundamental frequency is assumed to be f_1 = 50 Hz for this study. The filter components are: $R_F = 1\ \Omega$, L_F = 100 mH, $C_{(5)F}$ = 2.07 µF, $C_{(7)F}$ = 0.84 µF, $C_{(11)F}$ = 0.6 µF, and $C_{(13)F}$ = 0.35 µF [26].

Table 3. Main findings of this study in comparison with previous work.

Item	Main Findings of This Paper (Nonlinear Online Coordination Approach) in Comparison with Previous Research	
	This Research (Nonlinear Online Approach)	**Previous Research (Online Approach)**
1	Implementation of uncontrolled PEV charging in the presence of harmonics injected by nonlinear EV battery chargers and industrial loads.	Harmonics and nonlinearities are ignored (e.g., [14,17,27]).
2	Proposing a nonlinear online PEV coordination approach (NOL-MSSCA) by using DHPF algorithm considering harmonics and THDv in the objective cost function.	Implementing a newton Raphson based power flow (PF) in the online approach. Harmonics are ignored (e.g., [17,27]).
3	Inclusion of PPFs as a practical solution to fully charge the PEVs for high PEV penetrations.	Not applicable/not used (e.g., [17,27]).



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Simulation results for Case 3: Installation of PPF with NOL-MSSCA considering harmonics including power consumption and THDv; (**a**,**b**) 47% PEV penetration; (**c**,**d**) 63% PEV penetration.

7. Conclusions

In this paper, a simple and practical approach for online PEV coordination in smart grids considering battery charger and nonlinear industrial loads is presented. The proposed NOL-MSSCA is based on the recently implemented OL-MSSCA of [17] with the inclusion of harmonics caused by EV chargers as well as nonlinear loads. The new approach uses the DHPF calculations within the online coordination algorithm to include harmonic system losses and THDv in the objective cost function. The proposed algorithm not only minimizes the cost, but also improves the power quality and performance of the grid by preventing THDv and voltage violations. Detailed simulation results for three case studies are shown in Table 2 and Figures 5–7 to assess the performance and prove the validity of the presented method. The main conclusions are:

- Uncoordinated charging of PEV batteries (case 1) could have negative impacts on the performance and power quality of a smart grid. It could result in unacceptable THDv levels beyond the permissible limits of the IEEE-519 Standard, particularly at high penetrations of EVs during peak-load hours. Table 2 and Figure 5 indicate that the system's THDv level is above 11% for a high PEV penetration of 47%.
- The proposed NOL-MSSCA managed to charge all EVs at low and moderate levels of PEV penetration without exceeding the power quality limits. The NOL-MSSCA minimizes the costs associated with generation and losses while controlling system overload and bus voltage regulations as well as the bus and network voltage THDs. Simulation results for case 2 (Table 2 and Figure 6) reveal that the proposed algorithm can manage to reduce the THDv level to approximately 5% for 16% and 32% PEV penetrations and fully charge the PEVs. However, at very high penetrations of PEVs with significant charger and nonlinear load harmonic current injections, particularly during peak-load hours, the NOL-MSSCA could not fully charge all PEVs before the designated time of 0800h for the next day's trip. As shown in Table 2 and Figure 6, the THDv level is reduced from 11.6% to 5.36% for a high PEV penetration of 47%. However, 20 PEVs were not charged by 0800h.
- To resolve the issues and meet the need for customer satisfaction, the simple approach of installing PPFs installation at the worst voltage quality buses is suggested (case 3). Simulation results show the good performance of NOL-MSSCA with passive filtering for the PEV penetration of 47%. Therefore, this practical approach successfully managed to fully charge all PEVs before their next trip in the morning, even with high PEV penetrations. According to the results of Table 2 and Figure 7, the THDv for high PEV penetrations is within the permissible standard level of 5% while all PEVs were fully charged.

In conclusion, the presented research has addressed the power quality related issues for smart grids while coordinating PEV charging activities. The power quality is one of the main factors in smart grids which has not been considered in the recent PEV coordination approaches in the literature. Many studies started to investigate the impacts of EV chargers and their harmonics. However, they have not been included in the coordination and scheduling approaches to control the THDv levels and therefore to improve the power quality.

Future works and publications could target the following research directions:

- The proposed practical approach of this paper can also be applied in other PEV coordination technologies by considering harmonics in the objective function and constraints.
- For the cases with high PEV penetrations, a more sophisticated filtering approach could be considered, such as the installation of active power filters (APFs) or custom power devices (CPDs) at selected buses with poor power quality.
- For the cases with high PEV penetrations, rescheduling of SSCs can also be investigated for further power quality improvement.

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Nomenclature

A. Acronyms

APF	Active Power Filter
ASD	Adjustable Speed Drive
CDP	Custom Power Devices
DCFC	DC Fast Charging
DHPF	Decoupled Harmonic Power Flow
DG	Distributed Generation
EV	Electric Vehicle
LTC	Transformer Load Tap Changer
MSS	Maximum Sensitivity Selection
NOL-MSSCA	Nonlinear Online Maximum Sensitivity Selection based Charging Algorithm
PEV	Plug-in Electric Vehicle
PPF	Passive Power Filter
PWM	Pulse Width Modulation
SSC	Switched Shunt Capacitor
THD	Total Harmonic Distortion
THDv	THD of Voltage
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

B. Indices, Parameters and Variables

$C(h)$	Ratio of the h^{th} harmonic current to its fundamental
$C_{(h)F}=$	Tuned filter capacitor at harmonic h
$Dt_{core,total}$	Total system demand
$D_{t,cor,max}$	Maximum demand level (without any PEVs) at time interval t
f_1	System fundamental frequency; f_1 = 50 Hz
f_h	Harmonic h frequency; $fh = h(f_1)$
$F_{cost\ (loss\ +\ demand)}$	Objective function of the proposed NOL-MSSCA algorithm
H	Highest harmonic order considered
K_T	Cost per MWh of losses (for example, 50$/MWh [19]
K_G	Cost per MWh of generation [20]
P	Real power
$P^h_{loss(i,i+1)}$	Harmonic power losses in the line between busses i and i + 1
P_{loss}	Total system power losses (including fundamental and harmonic losses)
$Pt,loss$	Total system power losses (including fundamental and harmonic losses) at hour t
Q	Reactive power
RF	Tuned filter resistor
$R_{i,i+1}$	Resistance of the line between busses i and i + 1
S	Complex power
dS	Partial derivative of S with respect to voltage
$\frac{\partial S}{\partial \lvert V \rvert}$	Partial derivative of S with respect to voltage magnitude
$\frac{\partial S}{\partial \sigma}$	Partial derivative of S with respect to voltage phase angle
t	Time interval (equal to 5 min in this paper)
$THD_{v,k}$	THD voltage of bus k
THD_{vi}	THD distortion at bus i
THD_{vmax}	Maximum allowed THD distortion at bus i
V	Voltage

$\mid V \mid$	Voltage magnitude
σ	Voltage phase angle
$V^{(h)}$	Harmonic voltage at harmonic frequency h
$V_i^{(h)}$	Harmonic voltage of bus i at harmonic frequency h
$\Delta V_{\ m}$	The per unit (pu) voltage deviation of bus m
$\Delta V_{max} = 0.1\ pu$	Selected limited of voltage deviation
$V_{i\ man}$	Maximum limit of the harmonic rms voltage at bus i
$V_{i\ mix}$	Minimum limit of the harmonic rms voltage at bus i
$X_{l_{i,i+1}}$	Reactance of the line between busses i and $i + 1$
$X_{C_{i,i+1}}$	Capacitance of the line between busses i and $i + 1$
$Y^{(h)}$	Admittance matrix at harmonic frequency h
$Y_{l,l}$	Diagonal entries of the admittance matrix.
$Y_{l,s}$	Off-diagonal entries of the admittance matrix.

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