Received 25 June 2018; revised 28 August 2018; accepted 2 November 2018. Date of current version 11 December 2018.

Digital Object Identifier 10.1109/JPETS.2018.2880762

Online Coordination of Plugged-In Electric Vehicles and Optimal Rescheduling of Switched Shunt Capacitors in Smart Grid Considering Battery Charger Harmonics

SARA DEILAMI (Member, IEEE)

Department of Electrical and Computer Engineering, Curtin University, Perth, WA 6102, Australia e-mail: s.deilami@curtin.edu.au

ABSTRACT This paper presents a practical solution to improve the performance and power quality of the smart grid (SG) with a high penetration of plugged-in electric vehicles (PEVs). The random, mobile, and time-variant PEV demands can overload lines, transformers, and distributed generations while the collective impacts of their battery charger harmonics may increase the overall total harmonic distortion (THD) of SG. To overcome these issues, this paper incorporates the optimal rescheduling of switched shunt capacitors (SSCs) and their day-ahead schedules in a recently developed online maximum sensitivity selection-based PEV coordination algorithm with the inclusion of harmonics. This will not only improve customer satisfaction by fully charging all vehicles before 8 A.M. for the next day travel but also reduce node voltage fluctuations, overall THD, and system losses. To check the performance of the proposed approach, detailed simulations are performed on the modified IEEE 23-kV medium voltage distribution network with seven SSCs and 22 low-voltage residential networks that are populated with PEVs with nonlinear battery chargers and industry nonlinear loads.

INDEX TERMS PEV, online coordinated charging, SSCs, THD, battery charger and nonlinear loads harmonics.

I. INTRODUCTION

The global trend to develop Smart Grids (SGs) with stylish and complex technologies such as high speed bi-directional communication networks, smart metering, real time monitoring and online control of network assets is providing opportunities for further improvement of the distribution network performance by utilizing Renewable Distributed Generation (RDG) resources, Plugged-in Electric Vehicles (PEVs) and Smart Appliances (SAs) [1]–[3]. However, there are still unsolved challenges associated with transformation from the conventional, centralized, producer-controlled and aging power networks to the sophisticated decentralized, user-controlled SG configuration. Recent investigations aim at improving the performance and power quality of the grid by implementing Demand Side Management (DSM), controlling reactive power flow and considering the applications of Load Tap Changers (LTCs) and Switched Shunt Capacitors (SSCs) as a conventional approach to deal with the effects of load variations and reduction of system losses, peak demand and voltage fluctuations [4]–[16]. Increasing PEV penetration levels requires special consideration on their impacts into distribution networks. Recent studies investigated the impact of uncoordinated charging and the effectiveness of a controlled coordinated PEV charging in SGs [17].

Many studies have shown the severe impacts of the current harmonics on SG caused by industrial nonlinear loads such as Adjustable Speed Drives (ASDs), Variable Frequency Drives (VFDs) and switching converters or residential SAs such as energy efficient lights and PEVs. The adverse effects of harmonics can cause premature aging of distribution transformers, or any power related issue in the grid such as load and voltage variations, mal-operation of control devices, power system losses or harmonic resonances [16], [18]. Some research resources use the common practice of implementing passive, active or hybrid filters or de-rating of components to resolve the power related issues and improve the power quality [18]. Further, recent studies investigated the online/offline coordination approaches to mainly increase the energy efficiency and grid performance [1]–[3], [19]. These papers introduce different practical schedules with dynamic energy prices for PEV owners to shift their charging schedule to off-peak hours. The charging algorithms are classified into distributed or centralized coordination scheduling which can successfully reduce total system losses. Reference [8] is one of the recent studies that presents an online PEV coordination based on a Maximum Sensitivity Selection (MSS) Algorithm. The approach considers the random arrival of PEVs in terms of time, location and penetrations to reduce the total cost of system losses and generating energy and regulate the voltage variations. This reference ignores the current harmonics injected by Electric Vehicle (EV) battery chargers which may result in poor power quality and grid performance.

This paper considers the harmonic current injections by EV battery chargers and industry nonlinear loads in the online PEV coordination algorithm of [8] as well as the rescheduling of SSCs. The aim is to improve the performance and power quality of SG by offline dispatch of SSCs and online PEV coordination considering battery charger and nonlinear loads harmonics. The practical approach schedules the randomly arrived PEVs such that all vehicle batteries are fully charged and ready before 8am without exceeding the transformer loading, voltage regulation and power quality limits. To do this, the online MSS based PEV coordination of [8] is enhanced to first include the injected harmonic currents by EV chargers and nonlinear loads [9]. The algorithm delays PEV charging schedule to off-peak hours while successfully charging all PEVs with low penetrations. This algorithm is also modified to incorporate the day- ahead dispatch of SSCs to ensure all PEVs with medium and moderate penetrations are fully charged before 8am for their next day trip. The algorithm is then iterated to minimize the errors associated with the forecasted PEV demands and the THDv level of the grid according to the standard [20].

II. PROBLEM FORMULATION OF PROPOSED APPROACH

A. DECOUPLED HARMONIC POWER FLOW CALCULATION

The Newton-Raphson based Decoupled Harmonic Power Flow (DHPF) algorithm of [16] is implemented for modeling and inclusion of nonlinear loads and nonlinear EV battery chargers. To apply this model, the nonlinear loads including the PEVs are modeled as current sources at fundamental and harmonic frequencies [16]. The linear loads consist of a resistance in parallel with a reactance. The DHPF is used to calculate harmonic voltages and THDv levels of system.

$$I_i^{(1)} = \left[(P_i + jQ_i)/V_i^{(1)}\right]^* \quad (1)$$

$$I_i^{(h)} = C_{(h)} I_i^{(1)} \quad (2)$$

$$Y^{(h)} V^{(h)} = I^{(h)} \quad (3)$$

Where, the ratio of the h^{th} harmonic current to its fundamental is defined as $C(h)$, P and Q are real power and reactive power, and $V^{(h)}$ is the harmonic voltage. The voltage and THDv at bus i are calculated by:

$$|V_i| = \left(\sum_{h=1}^{H} \left|V_i^h\right|^2\right)^{1/2} \quad (4)$$

$$THD_{vi} = \left[\left(\sum_{h=2}^{H} \left|V_i^h\right|^2\right)^{1/2} / \left|V_i^1\right|\right] \quad (5)$$

B. FORMULATION OF OPTIMAL SSCs DISPATCH PROBLEM

For the optimal dispatch of SSCs scheduling considering harmonic distortion, the proposed Genetic Algorithm (GA) of [16] is used. The objective function of SSCs scheduling is the minimization of energy losses over 24-hour period considering switching constraints, voltage variations and THDv limits [16], [20]. The optimal switching operations of shunt capacitors at the substation and the distribution feeders are determined based on Eqs. 6-7.

$$F_{Opt-Distpatch} = min \sum_t Eloss = min \sum_t (Ploss(Q_t))t \quad (6)$$

$$Ploss = \sum_{h=1}^{H} \sum_{i=0}^{m-1} R_{i,i+1}\left(\left|V_{i,i+1}^h - V_i^h\right| \left|y_{i,i+1}^h\right|\right) \quad (7)$$

where *Eloss and Ploss* are total energy loss and power loss of the system. Q_t is the status of SSCs and t is the time interval (one hour); H, m, i and Ri, $i+1$ are highest harmonic order, total number of nodes, node number and line resistance between nodes i and $i+1$; Here are the constraints for the optimal solution:

$$V_{i\,min} \leq V_{i\,rms} = \left(\sum_{h=1}^{H} | V_i^h |^2\right)^{\frac{1}{2}} \leq V_{i\,max} \quad (8)$$

$$THD_{vi} = \left[\left(\sum_{h=2}^{H} | V_i^h |^2\right)^{\frac{1}{2}} / \left|V_i^1\right|\right] \times 100\% \leq THD_v^{max} \quad (9)$$

$$\sum_{(t=1)}^{24} (C_{nt} \oplus C_{nt-1}) \leq K_c; \quad n = 1, 2, \ldots, nc \quad (10)$$

$V_{i\,\min}$ and $V_{i\,\max}$ are the minimum and maximum limits of *rms* voltage at bus i respectively; THD_{vi} and THD_v^{max} are the distortion at bus i and maximum distortion level; C_{nt} and K_C present the capacitor n status at hour t and maximum switching; nc is number of shunt capacitors.

C. NONLINEAR ONLINE PEV COORDINATION BY MAXIMUM SENSITIVITY SELECTION (NOL-MSSCA) CONSIDERING EV BATTERY CHARGERS, NONLINEAR LOADS AND SSCs

For the formulation of online PEV coordination, the recently implemented algorithm of [8] is enhanced to also include harmonic distortions caused by EV battery chargers as well as nonlinear loads [9]. This enhanced nonlinear online MSS based controlled charging approach is also modified to incorporate the SSCs. This approach is implemented to minimize the cost of generating energy and system losses while reducing the THDv of the network and improving voltage profile. The objective function is defined as [8]:

$$\begin{aligned} \min F_{cost} &= F_{cost-loss} + F_{cost-loss} \\ &= \sum_t K_E P_{t,loss} + \sum_t K_{t,G} D_{t,total}, \\ & \quad t = \Delta t, \quad 2\Delta t, \ldots 24hours \end{aligned} \tag{11}$$

where $P_{t,loss} = \sum_{i=0}^{n-1} R_{i,i+1} \left(|V_{i,i+1} - V_i| \, |y_{i,i+1}| \right)^2$

$F_{cost-loss}$ and $F_{cost-gen}$ are the costs associated with total system losses and total generation while i and n are referring to the node number and total number of nodes, respectively. V_i in total system losses equation are calculated by the DHPF and include fundamental and harmonic voltages. The time interval for PEV coordination is $\Delta t = 5$ minutes for this problem. $K_E = 50\$/\text{MWh}$ presents the cost per MWh of losses [2], and $K_{t,G}$ refers to the cost per MWh of generation [22] as shown in Fig. 2.The minimization of objective function is formulated based on the online MSS optimization approach. This is a precise and fast optimization technique which is used to calculate the sensitivity of $P_{t,loss}$ to PEV charging loads and Q_t to the bus voltage profile at each time steps of 5 minutes [8], [9], [21].

$$MSS_{t,i} = \partial P_{t,loss} / \partial P_{PEV,i}, \quad i = 1, \ldots, i_m \tag{12}$$

$$MSS_{ssc,i} = \partial Q_t / \partial V_i, \quad i = 1, \ldots, i_m \tag{13}$$

where $MSS_{t,i}$ is the maximum sensitivity of system losses to PEV charging load at node i at time interval t and $MSS_{ssc,i}$ is the maximum sensitivity of system reactive power to the voltage profile. The total number of PEVs is shown by i_m and the power consumption is $P_{PEV,j}$ for each PEV at node i. Note that entries of the MSS vector of Eqs. 12 and 13 are extracted from the real and imaginary entries of Jacobian matrix of DHPF (Section A) [21]:

$$J = \begin{vmatrix} Re\{\partial S/\partial \delta\} & Re\{\partial S/\partial V\} \\ Im\{\partial S/\partial \delta\} & Im\{\partial S/\partial V\} \end{vmatrix} \tag{14}$$

The following constraints are considered in the enhanced and developed PEV coordination algorithm:

$$\Delta V_k = |V_k - V_{rated}| \leq 0.1pu, \quad for\ k = 1, \ldots, n \tag{15}$$

$$D_{t_{cor,total}} = \sum_k P^{load}_{t_{cor,total}} \leq D_{t_{cor,max}} \tag{16}$$

$$V_{i\,min} \leq V_{i\,rms} = \left(\sum_{h=1}^{H} |V_i^h|^2 \right)^{\frac{1}{2}} \leq V_{i\,max} \tag{17}$$

$$\begin{aligned} THD_{vi} &= \left[\left(\sum_{h=2}^{H} |V_i^h|^2 \right)^{\frac{1}{2}} / \left| V_i^1 \right| \right] \\ & \quad \times 100\% \leq THD_v^{max} \end{aligned} \tag{18}$$

where ΔV_k is voltage variations at node k in per unit (pu) which is limited to $\Delta V_{max} = 0.1$pu. $D_{t,cor,max}$ is the maximum demand (without any PEVs) at $t = \Delta t$; $V_{i\min}$ and r are the minimum and maximum value of the harmonic *rms* voltage at bus $i(V_{irms})$; THD_{vi} and THD_v^{max} are total harmonic distortion level at bus i and the maximum harmonic distortion value, respectively. H and i are the highest harmonic order and the node number, respectively.

III. PROPOSED PRACTICAL APPROACH

The proposed approach is based on the recently implemented MSS-based PEV coordination of [8] with the inclusions of battery charger and nonlinear loads harmonics and optimal day-ahead rescheduling of SSCs. This approach is an online strategy that considers the random arrival of PEVs in 5 minutes intervals within 24 hours as well as the current harmonic distortion caused by EV battery chargers and nonlinear loads and the day-ahead schedules of SSCs. To apply this algorithm, first SSCs are scheduled over 24-hour period based on forecasted daily load curves of the residential networks populated with PEVs including their charger harmonics. Secondly, the day-ahead SSC scheduling is incorporated in the online coordination program. The flowchart of proposed practical approach is provided in Fig. 1. It is based on the following steps:

Step 1 (Execute NOL-MSSCA With Battery Charger Harmonics and Random EV Plugging): The recent online PEV coordination algorithm of [8] is developed and modified to include the nonlinearities of the EV charger and their harmonics [9]. The simulation results of this approach are used to forecast the coordinated PEV daily load curves. Note that EVs are mostly charged according to their defined priorities to fulfill customer satisfactions. Therefore, the high priority EVs are charged as quickly as possible while the service to the remaining PEVs are shifted to off-peak hours to reduce the cost and THDv. The calculated PEV load curves will be used in Step 2 as the forecasted daily EV demand to generate day-ahead SSC schedules.

Step 2 (Optimal Dispatch of SSCs Using Forecasted Daily PEV Demands): Using the forecasted EV demand of Step 1, the GA of [16] is executed to perform optimal dispatch and generate the day-ahead SSCs schedules. This algorithm checks the status of the switching capacitors at each hour and schedules the SSCs for the next 24-hour period (off-line approach).

Step 3 (Execute Nonlinear Online Approach With Battery Charger Harmonics, Random EV Plugging and Day-Ahead SSC Schedules): The day-ahead SSC schedules of Step 2 are incorporated in the proposed enhanced online PEV coordination algorithm that considers EV battery chargers and nonlinear loads. As such, the sensitivity of the reactive power to bus voltages will also be considered. The SSCs are installed and switched based on their initial day-ahead schedules to improve the node voltage profiles and grid power quality. The constraints are checked and PEVs are scheduled according to the nonlinear online PEV coordination.

Step 4 (Repeat Steps 1-2 to Generate Stable Day-Ahead SSC Schedules): Since the forecasted PEV demands of Step 1 is calculated (by nonlinear online coordination approach)

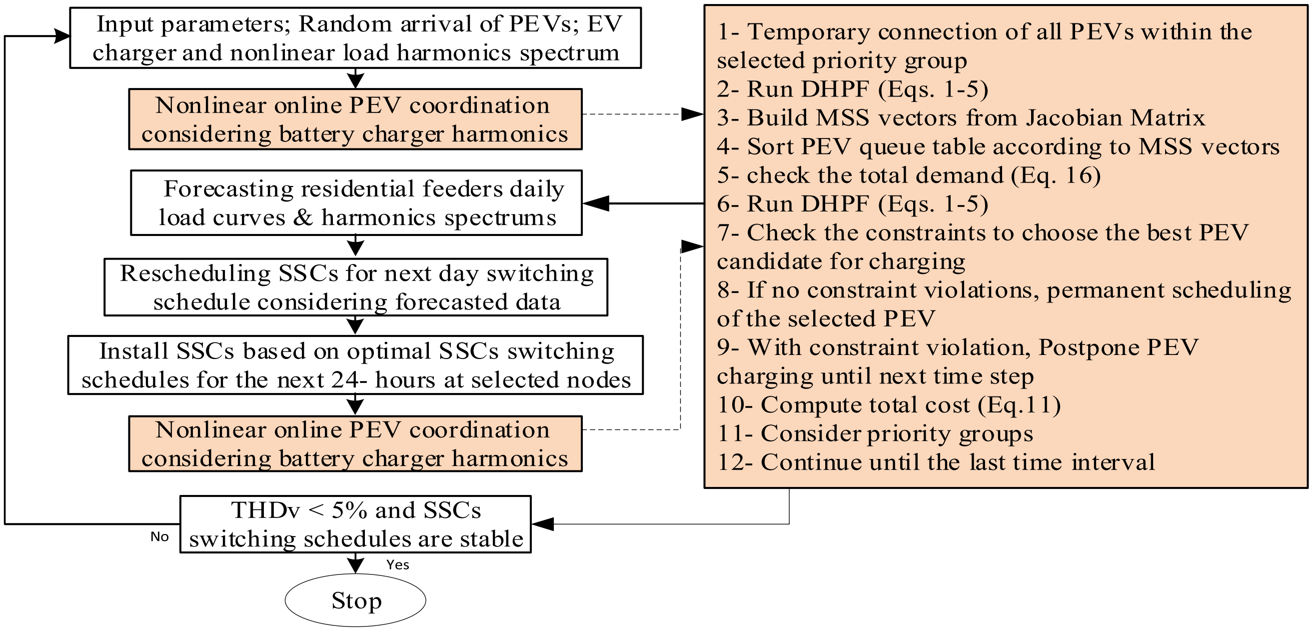

FIGURE 1. Proposed practical approach for online PEV coordination and rescheduling of SSCs in SG considering EV battery chargers and nonlinear loads' harmonics.

based on random arrivals (plugging) of EV, Steps 1-2 will be repeated until the THDv conditions are met and the SSC dispatch are almost stable (unchanged).

The proposed practical solution approach of Fig. 1 considers the following ideas:

- The proposed nonlinear online PEV coordination approach is implemented to reduce the cost of power losses and THDv levels while improving the efficiency of SG considering impacts of PEVs on grid power quality conditions.
- PEVs are charged based on their priorities when they randomly arrive to ensure customer satisfaction. The online algorithm postpones charging of some EVs (mostly low and medium priority consumers) by shifting them to off-peak hours to reduce the cost and power quality constraints.
- The incorporation of optimal day-ahead SSC scheduling of Step 2 helps to fully charge the PEVs even at high penetrations without exceeding the node voltage and grid power quality limits.
- Although the optimal day-ahead SSC schedule improves customer satisfaction, it may not be the ideal solution for keeping the THDv within the allowed standard level. This is due to the fact that random arrival and forecast of PEVs and their daily load curves are used as the initial input. The algorithm uses a random arrival combination of EVs that will change at each iteration. To reduce the abovementioned errors and possible issues associated with the day-ahead EV forecasting, an iterative approach is proposed by repeating Steps 1-2 until the ultimate solution (stable SSCs dispatch) is obtained and the THDv level is below the standard limit of 5%.

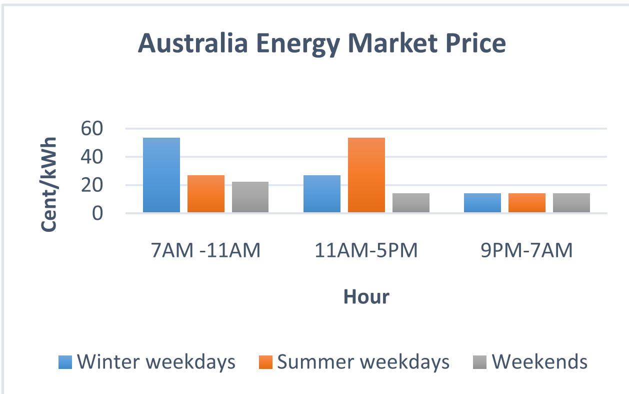

FIGURE 2. Variable short-term market energy pricing [9], [22].

IV. THE MODIFIED SMART GRID TEST SYSTEM WITH PEVs

For the simulations and analysis of this study, the IEEE 31 node 23 kV distribution test system [23] is modified to include 22 Low Voltage (LV) 19 nodes residential network. The residential networks are populated with different PEV penetration levels based on a real system data of a neighborhood in Western Australia [8]. The LV residential systems are supplied from the High Voltage (HV) main buses via 23 kV/415 V distribution transformers. The modified system under study includes 449 nodes, PEVs, nonlinear loads and SSCs as shown in Fig. 3. The daily residential load curves of [8] and energy market price of [22] have been considered for this study. Fig. 2 shows the Western Australia tariff in 2018 [9], [22].

V. PEV BATTERY CHARGERS

For realistic modeling of EV charging, a Nissan Leaf model with rated battery capacity of 24 kWh is considered.

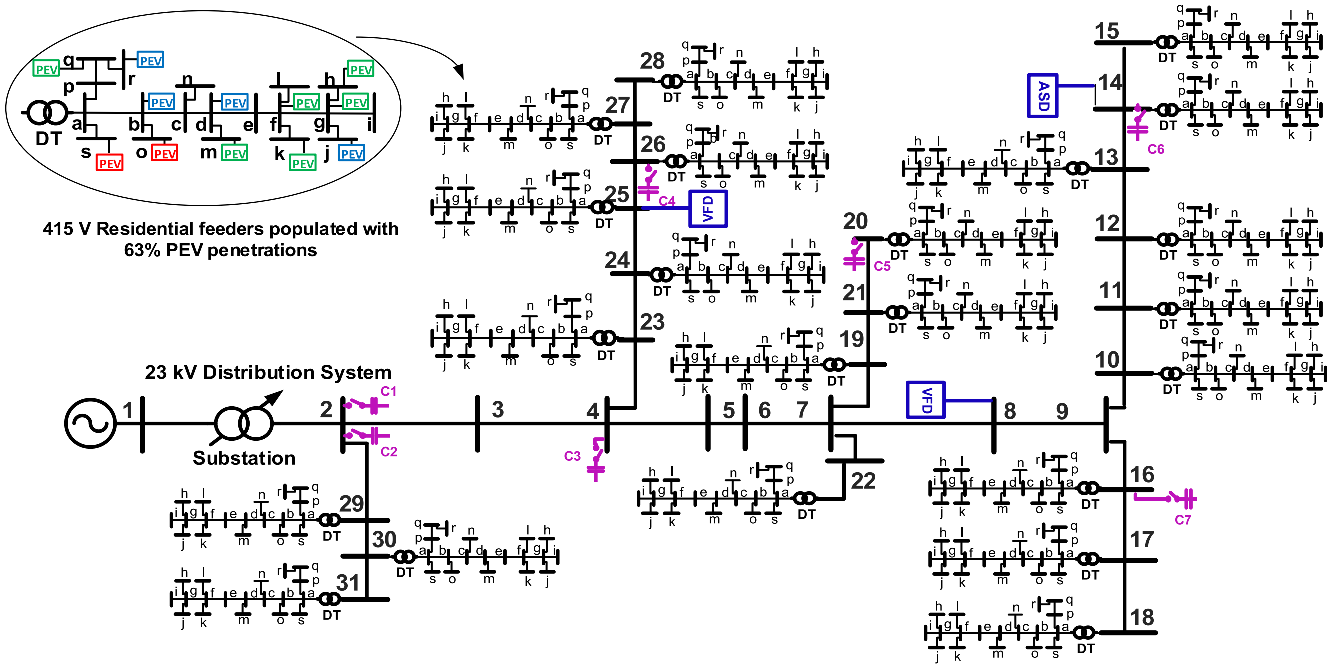

FIGURE 3. **The 449 node smart grid system includng the IEEE 31 node 23kV system with 22 low voltage 415V residential feeders, 7 switching capacitors and 63% nonlinear PEVs showing high, medium and low priority consumers in red, blue and green colors paying very high, moderate and very cheap tariff rates, respectively.**

TABLE 1. **Typical low order harmonic current spectrum of EV chargers and nonlinear loads [9], [16], [24].**

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 %**	

The charging rate is assumed 3.3 kW with level 2 charging (208 V/16 A) and efficiency of 88%. It is important to consider the impacts of nonlinear charging circuitry installed in PEVs on the power quality of SG. Recent researches have already started looking at the harmonic distortions caused by AC-DC charging circuitry but they have not considered the harmonic current injected by EV battery chargers. In this paper, harmonic current spectrum of Nissan Leaf EV chargers and nonlinear loads are included in the proposed approach to practically test and simulate the impacts of harmonics in power quality of the system as shown in Table 1 [16], [24]. The chargers are modeled as harmonic current sources (nonlinear EV loads) in DHPF algorithm. The algorithm can adapt easily to consider different harmonic spectrums.

VI. SCENARIOS AND DISCUSSIONS

The new NOL-MSSCA is performed on the modified SG system of Fig.3 considering online PEV coordination with the day-ahead SSC rescheduling. The case studies include the simulation results of the new approach with and without SSC scheduling and after number of iterations. The charging zones are defined as red zones (18h-22h), blue zones (22h-1h) and green zone (1h -8h) for low, for low, medium and high priorities respectively. The results are shown in Figs. 4-6 and Tables 2 and 3. The nonlinear online algorithm uses the maximum sensitivity selection approach (sensitivity of losses to the PEV loads and sensitivity of reactive power to the voltage profile) to sort the PEVs in MSS vectors accordingly considering their priorities (red, blue and green zones). As indicated in Figs. 4-5, this algorithm let PEV owners with high priority (red zones) to charge their vehicles as soon as they arrive home after work. Therefore, these consumers pay high tariff. Then PEVs with medium and low priorities (blue and green zones) will be charged respectively.

A. SCENARIO 1- NONLINEAR ONLINE PEV COORDINATION WITHOUT OPTIMAL DISPATCH OF SSCs

The nonlinear online approach is implemented to investigate the impacts of EV charger harmonics on SG. In this scenario, the SSCs are not installed. The algorithm can successfully keep the THDv level within the permissible standard limit by shifting the charging of PEVs to off-peak hours.

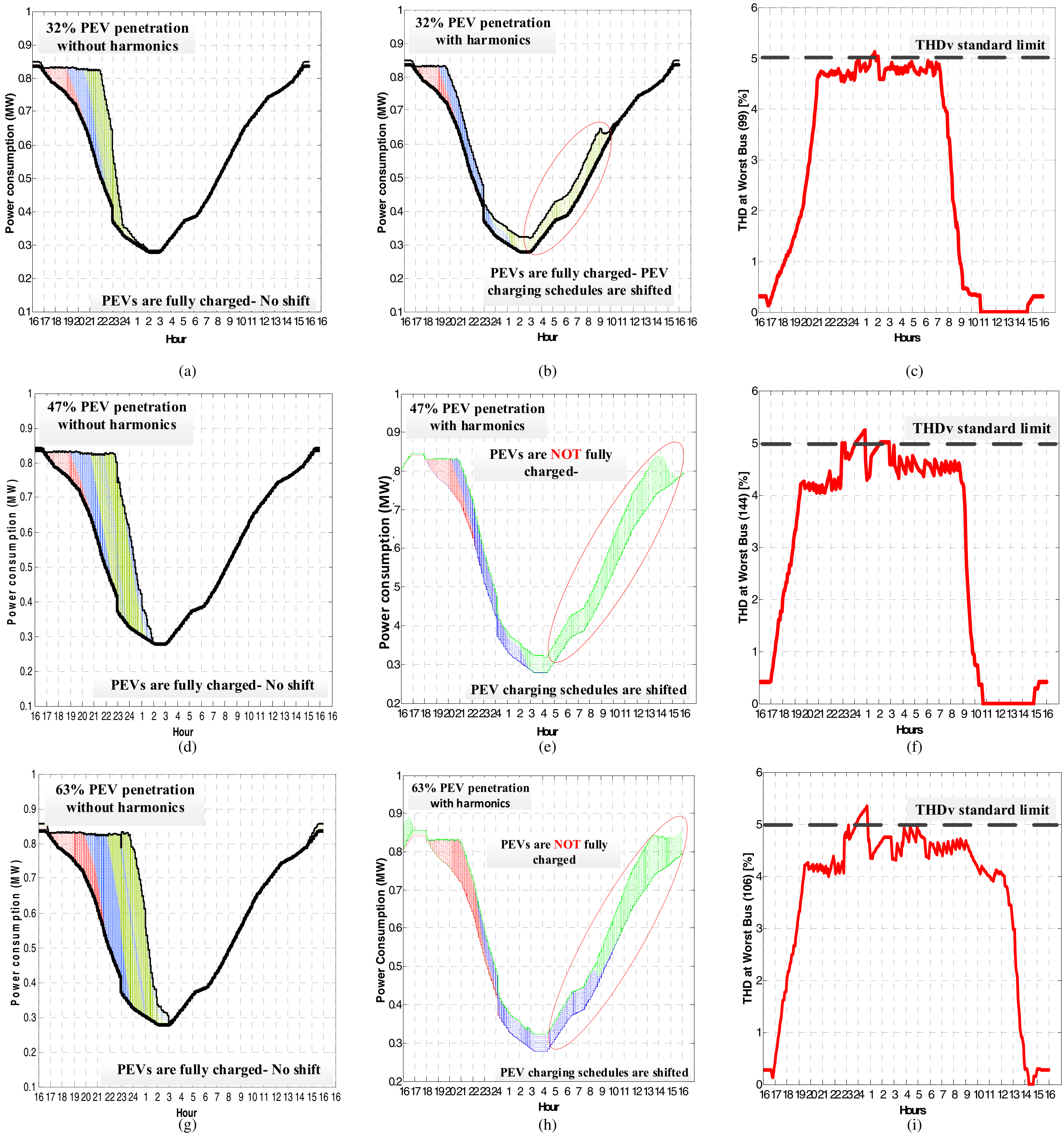

FIGURE 4. Simulation results for scenario 1– Online PEV coordination (NOL-MSSCA) without SSCs scheduling: PEV power consumption (with and without harmonics) and THDv (a-c): 32% PEV penetration; (d-e): 47% PEV penetration; (g-i): 63% PEV penetration.

As indicated by the simulation results of Fig. 4 and Table 2, the THDv levels for both medium and high PEV penetrations are almost within the allowed standard limit of 5%. However, NOL-MSSCA is not able to fully charge all PEVS before 8am. This deficiency is demonstrated in Figs. 4(e) and 4(h) for medium and high PEV penetrations of 43% and 63% (comparing controlled charging with and without THDv) indicating there are a few unattended vehicles in the PEV queue table (22 and 43 PEVs for 43% and 63% PEV penetrations). As mentioned before, this is a deficiency of Step 1 (NOL-MSSCA) which is resolved by including Steps 2-3 in the proposed solution approach of Fig. 1.

Therefore, the algorithm fails to fully charge all PEVs before 8am in the morning for medium and high PEV

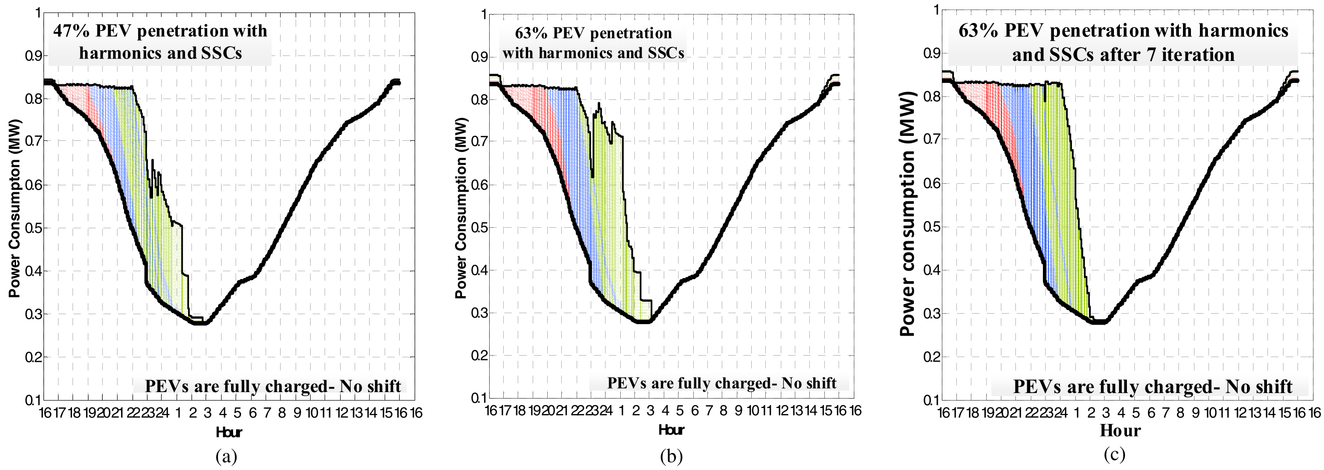

FIGURE 5. **Simulation results for scenario 2 and 3– Online PEV coordination (NOL-MSSCA) with SSCs scheduling: PEV power consumption (a): 47% PEV penetration (first iteration); (b): 63% PEV penetration (first iteration); (c): 63% PEV penetration (seventh iteration).**

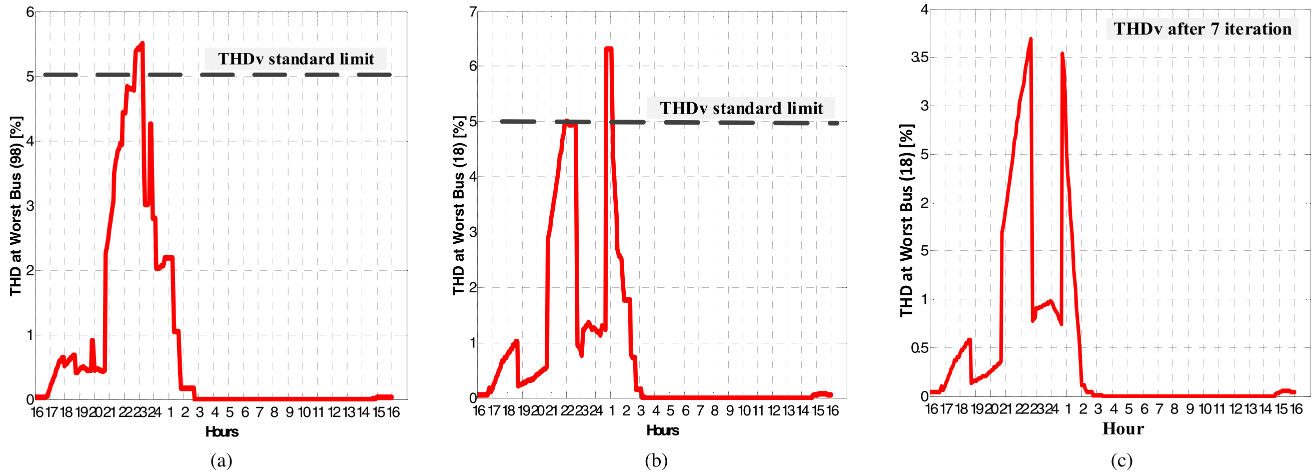

FIGURE 6. **Simulation results for scenario 2 and 3– Online PEV coordination (NOL-MSSCA) with SSCs scheduling: THDv (a): 47% PEV penetration (first iteration); (b): 63% PEV penetration (first iteration); (c): 63% PEV penetration (seventh iteration).**

TABLE 2. **Simulated case studies of online PEV coordination (NOL-MSSCA) considering harmonics without and with (SSCs).**

PEV Penetration [%]	No. of PEVs Not Fully Charged	THD [%]	Voltage Deviations [%]	System Losses [MW]
Scenario 1: PEV Coordination Without SSCs Scheduling (Fig. 4)				
32	0	5.2	7.66	0.074
47	22	5.3	7.99	0.081
63	43	5.4	8.33	0.092
Scenario 2: PEV Coordination With SSCs Scheduling (Fig. 5-6)				
32	0	4.7	7.45	0.066
47	0	5.5	9.99	0.069
63	0	6.4	9.99	0.072
Scenario 3: PEV Coordination With SSCs Scheduling and Iterations (Fig. 5-6)				
63 (2nd iteration)	0	6.3	9.98	0.072
63 (5th iteration	0	5.3	9.98	0.069
63 (7th iteration)	0	3.68	10	0.059

penetrations since it keeps postponing charging schedule to early morning hours due to voltage and THD constraint violations.

B. SCENARIO 2- NONLINEAR ONLINE PEV COORDINATION WITH OPTIMAL DISPATCH OF SSCs

In this scenario, the NOL-MSSCA of scenario 1 is implemented to calculate (forecast) the day-ahead load curves of residential feeders with different PEV penetrations. The forecasted PEV daily load curves are then incorporated in GA optimal dispatch program of [16] to generate day-ahead schedules of SSCs. This SSC rescheduling is the day-ahead dispatch and will be included in the NOL-MSSCA algorithm to improve its performance. As indicated in the results of Figs. 5-6 and Table 2, the day-ahead schedules of SSCs will significantly help NOL- MSSCA to fully charge EVs by 8am. However, they may not be able to completely keep the THDv of the entire system below the standard level of 5% for medium and high PEV penetrations.

C. SCENARIO 3- NONLINEAR ONLINE PEV COORDINATION WITH OPTIMAL DISPATCH OF SSCs AFTER ITERATION

The simulation results of scenario 2 indicate that the incorporation of optimal SSCs dispatch schedule in the online

TABLE 3. **The day-ahead schedules of SSCs for test system of Fig. 3 with nonlinear PEV coordination (After 7 iterations).**

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
C1	0	0	0	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0
C2	0	0	0	0	0	0	1	1	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0
C3	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0
C4	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
C5	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1
C6	1	1	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
C7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

PEV coordination can successfully meet the customer satisfaction by fully charge the PEVs before 8am; however, the power quality conditions are not met according to the standard limits [20]. The reason may be the random arrival of PEV and the forecast of PEVs as initial input in the optimal SSC scheduling algorithm. Therefore, in this case, Steps 1-2 of the proposed approach are repeated considering random arrival of PEVs at each iteration. This will resolve the errors associated with the initial assumptions and inputs of the algorithm by keeping the THDv within the standard limits. Simulation results show that after 7 iterations, all PEVs are fully charged (Fig. 5c), THDv levels are within the permissible level (Fig. 6c) and the SSCs schedules are almost stable (Table 3) even for high PEV penetrations.

VII. CONCLUSION

A practical approach for online PEV coordination incorporated with offline SSCs rescheduling is proposed that reduces generation cost and charges all EV batteries while designating limits for transformer loading, voltage regulation and harmonics distortions. The recently developed algorithm of [8] is first enhanced to include the harmonics, then modified to incorporate the day-ahead optimal SSC scheduling and finally iterated to properly minimize the errors caused by the random arrivals and forecast of PEVs as the initial inputs of the algorithm. Simulation results are presented in Figs. 4-6 and Tables 2 and 3. The main conclusions are:

- Inclusion of charger harmonics makes the online PEV scheduling problem more complicated due to the additional THD constraints. However, the modified algorithm can successfully charge all EV batteries at low and medium PEV penetration levels. It will keep the THDv level within the standard limit of 5% while controlling the voltage variations and minimizing the cost of generation. However, the algorithm may not fully meet customer satisfaction at high PEV penetrations and fails to fully charge all EV batteries before 8am. This is mainly due to the impacts of harmonic current injections by EV chargers that could lead to unavoidable high THDv levels and incomplete PEV charging schedule especially with medium and high PEV penetrations during peak hours.
- To avoid this, the day-ahead SSCs scheduling with the consideration of harmonics are incorporated in the online PEV coordination algorithm. Detailed simulation results demonstrate fine performance and acceptable results of the proposed algorithm at medium and moderate PEV penetrations. However, the THDv levels are still above the acceptable standard limit at high penetrations of PEVs due to errors in the forecasted next-day PEV loading.
- To resolve the issue, a simple approach is implemented by iterating the algorithm (Steps 1-2) to reschedule the optimal SSC dispatch. The idea is to re-install the SSCs based on the new rescheduling dispatch and minimize the errors by repeating the algorithm. The iterative procedure stops when the THDv level is within the standard limit of 5% and the SSCs scheduling are almost constant. The simulation results show that the algorithm stops after 7 iterations.
- Therefore, the proposed strategy of Fig. 1 can successfully resolve the harmonic distortions issues and manage the PEV charging schedules based on the PEV owners' desire.

REFERENCES

[1] W. Su, H. Rahimi-Eichi, W. Zeng, and M.-Y. Chow, "A survey on the electrification of transportation in a smart grid environment," *IEEE Trans. Ind. Informat.*, vol. 8, no. 1, pp. 1–10, Feb. 2012.

[2] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 4th Quart., 2012.

[3] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5673–5689, Dec. 2013.

[4] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244–1252, Sep. 2012.

[5] H. Liang, A. K. Tamang, W. Zhuang, and X. S. Shen, "Stochastic information management in smart grid," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1746–1770, 3rd Quart., 2014.

[6] J. Ma, J. Deng, L. Song, and Z. Han, "Incentive mechanism for demand side management in smart grid using auction," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1379–1388, May 2014.

[7] P. Samadi, H. Mohsenian-Rad, R. Schober, and V. W. S. Wong, "Advanced demand side management for the future smart grid using mechanism design," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1170–1180, Sep. 2012.

[8] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011.

[9] S. Deilami, "Online coordination of plug-in electric vehicles considering grid congestion and smart grid power quality," *Energies*, vol. 11, no. 9, 2018, Art. no. 36962, doi: 10.3390/en11092187.

[10] A. S. Masoum, S. Deilami, A. Abu-Siada, and M. A. S. Masoum, ''Fuzzy logic approach for online coordination of charging plug-in electric vehicles in smart grids,'' *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1112–11121, 2015.
[11] S. Deilami and M. A. S. Masoum, ''Optimal dispatch of LTC and switched shunt capacitors in smart grid with plug-in electric vehicles,'' in *Proc. IEEE Power Eng. Soc. Gen. Meeting (PES GM)*, Vancouver, BC, Canada, Jul. 2013, pp. 1–7.
[12] W. Zhang, W. Liu, X. Wang, L. Liu, and F. Ferrese, ''Distributed multiple agent system based online optimal reactive power control for smart grid,'' *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2421–2431, Sep. 2014.
[13] M. S. El Moursi, H. H. Zeineldin, J. L. Kirtley, and K. Alobeidli, ''A dynamic master/slave reactive power-management scheme for smart grids with distributed generation,'' *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1157–1167, Jun. 2014.
[14] Z. R. Ivanović, E. M. Adžić, M. S. Vekić, S. U. Grabić, N. L. Čelanović, and V. A. Katić, ''HIL evaluation of power flow control strategies for energy storage connected to smart grid under unbalanced conditions,'' *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4699–4710, Nov. 2012.
[15] E. Pouresmaeil, M. Mehrasa, and J. P. S. Catalão, ''A multifunction control strategy for the stable operation of DG units in smart grids,'' *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 598–607, Mar. 2015.
[16] A. Ulinuha, M. A. S. Masoum, and S. M. Islam, ''Optimal scheduling of LTC and shunt capacitors in large distorted distribution systems using evolutionary-based algorithms,'' *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 434–441, Jan. 2008.
[17] K. Clement-Nyns, E. Haesen, and J. Driesen, ''The impact of charging plug-in hybrid electric vehicles on a residential distribution grid,'' *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 371–380, Feb. 2010.
[18] E. F. Fuchs and M. A. S. Masoum, *Power Quality in Electrical Machines and Power Systems*. New York, NY, USA: Academic, 2008.
[19] *Impact of Electric Vehicles and Natural Gas Vehicles on the Energy Market*, Austral. Energy Market Commission, Sydney, NSW, Australia, 2011. [Online]. Available: http://www.aemc.gov.au/Media/docs/AECOM %20Initial%20Advice-8fff41dd-f3ea-469d-9966-e50ba2a8d17b-0.pdf
[20] *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Standard 519-1992, 1993.
[21] M. R. Khaldi, ''Sensitivity matrices for reactive power dispatch and voltagecontrol of large-scale power systems,'' *Int. J. Electron., Power Energy Syst.*, no. 6, pp. 213–489, 2004.
[22] (2018). *Price List Standard Fees and Charges*. [Online]. Available: www.synerg.com
[23] S. Civanlar and J. J. Grainger, ''Volt/var control on distribution systems with lateral branches using shunt capacitors and voltage regulators part III: The numerical results,'' *IEEE Trans. Power App. Syst.*, vol. PAS-104, no. 11, pp. 3291–3297, Nov. 1985.
[24] Nissan Leaf. *Steady State Vehicle Charging Fact Sheet*. Accessed: 2018. [Online]. Available: http/avt.inl.gov/sites/default/files/pdf/fsev/ SteadyStateLoadCharacterization2015Leaf

SARA DEILAMI is currently an Academic Member (Lecturer) with the School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University. She has published over 40 papers, including high citation journal articles and peer reviewed conferences. Her research interests are smart grid, renewable energy, power quality, and power system protection. She is currently a Committee Member of the IEEE PES/PELS and the IEEE Women in Engineering (WIE), WA Section, Australia. She acted as the Vice Chair and the Chair of the IEEE PES/PELS, WA Section, in 2015 and 2016, respectively. She was the Vice Chair and the Chair of the IEEE WIE, WA Section, in 2016 and 2017, respectively.