Optimal Scheduling of Load Tap Changer and Switched Shunt Capacitors in Smart Grid with Electric Vehicles and Charging Stations

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***Abstract*- Random charging of plug-in electric vehicles (PEVs) particularly during the peak load hours could impairment the performance of future smart grids. This paper presents genetic algorithms (GAs) for optimal scheduling of LTC and switched shunt capacitors (SSCs) to improve the performance of smart grid with PEV charging at consumer premises in residential feeders and PEV charging stations (PEV-CSs) in distribution networks. The forecasted daily load curves associated with PEV-CSs and residential feeders populated with PEVs are first generated and then incorporated in the GA-based optimal LTC and SSC scheduling solution. Simulation results without and with optimal scheduling are presented for a 449 node smart grid system with 5 PEV-CSs considering random and coordinated charging of 264 PEVs in 22 low voltage residential networks.**

***Index Terms*- Smart grid, plug-in electric vehicle, charging stations, coordinated charging, LTC, optimal dispatch and GA.**

I. Introduction

PLUG-IN electric vehicle (PEV) charging activities are expected to intensely increase at consumer premises and charging stations (PEV-CSs) in residential and distributions networks, respectively [1-2]. PEVs have numerous advantages over the conventional fuel-based vehicles including more efficient motors, low emissions, less reliance on fossil fuels, energy storage for grid surplus and vehicle-to-grid (V2G) capability for supporting grid during peak times. However, random PEV charging particularly during the peak load hours can have detrimental impacts on voltage profiles and losses of smart grids, as well as the operation of the distributed renewable energy resources [3].

The vast majority of existing studies shows that there is sufficient surplus grid generation capacity to fuel large number of PEVs provided that vehicle charging are coordinated during the off-peak hours [4]. However, the current challenges are related with the battery cost, size and capacity, as well as necessary alternative solutions for fast charging such as public charging stations to alleviate the public acceptance of PEVs. It is anticipated that vehicle charging at fast rates in PEV-CSs will affect supply quality and grid capacity, even at small PEV penetration levels.

The rapidly growing number of studies on PEV performance and impacts can be classified in four categories; (i) vehicle performance, (ii) supply adequacy, (iii) V2G technology and (iv) PEV charging impacts on distribution system. There are a number of studies and comprehensive results particularly for the first three categories. However, there is very limited research work done to investigate impacts of fast charging at PEV-CSs on distribution grid such as poor voltage profile and increased power losses. At this stage, electric utilities need good decision tools to help with the evaluation of their investments in the distribution infrastructure to support future smart grid networks that will soon feed an increasing number of PEVs.

The widely accepted approach to overcome the voltage regulation problem in conventional distribution networks while minimizing system losses is the optimal scheduling (coordination) of LTC and switched shunt capacitors (SSCs) based on forecasted active (P) and reactive (Q) daily load curves [5-7]. The volt/var control by optimal scheduling of LTC and SSCs is a multi-phase decision-making problem with discrete variables and nonlinear objective function [5-7]. The value of the objective is determined from power flow solutions given the settings of control variables. Furthermore, it is necessary to attain the objective value in the least possible number of control steps (e.g., LTC operation and/or SSC switching). There are also a few documents considering impacts of non-sinusoidal operation and nonlinear loading on the optimal volt/var control problem [8-9].

This paper presents a relatively simple and practical solution to mitigate potential issues associated with the PEV charging activities in residential and distribution networks. The proposed approach consists of first calculating (or forecasting) the daily load curves of charging stations and residential feeders with PEV charging activities, and then incorporating them in the optimal LTC and SSCs scheduling problem. The approach is implemented and evaluated on a 449 node smart grid system with five charging stations and 22 residential networks populated with 264 PEVs.

II. Problem Formulation

A. Optimal Dispatch of LTC and SSC

The objective function of LTC/SSCs scheduling problem is minimization of energy loss over a 24-hour period [9]:

$$min \sum_{t=1}^{24} P_{loss}(Q_t, T_t) * \nabla t \tag{1}$$

$$P_{loss}(Q_t, T_t) = \sum_{h=1}^{H} \sum_{i=0}^{m-1} R_{i,i+1}\left(\left|V_{i,i+1}^{h} - V_{i}^{h}\right|\left|y_{i,i+1}^{h}\right|\right) \tag{2}$$

where P_{loss} is total power loss at hour t as a function of Q_t (status of SSCs) and T_t (LTC tap position), $\Delta t = 1$ *hour* is the time interval, while H, m, i and $R_{i,i+1}$ are highest harmonic order considered, total number of nodes, node number and line resistance between nodes i and $i+1$, respectively.

The following constraints will be considered:

- Voltage constraint

$$V_{i\,min} \leq \quad V_{irms} = \left(\sum_{h=1}^{H} \left| V_i^h \right|^2 \right)^{1/2} \leq V_{i\,max} \tag{3}$$

where $V_{i\ min}$ and $V_{i\ max}$ are the respective minimum and maximum limits of *rms* voltage at bus *i* (V_{irms}).

- Maximum switching operation of LTC

$$\sum_{t=1}^{24} \left| TAP_t - TAP_{t-1} \right| \leq K_T \tag{4}$$

where TAP_t and K_T are LTC tap position at hour *t* and maximum LTC switching, respectively.

- Maximum switching operation of shunt capacitors

$$\sum_{t=1}^{24} \left(C_{nt} \oplus C_{nt-1} \right) \leq K_c; \quad n = 1, 2, \ldots, nc \tag{5}$$

where C_{nt} and K_C are the status of capacitor *n* at hour *t* and maximum switching allowed, respectively; and *nc* is the number of shunt capacitors.

B. Formulation of PEV Charging Coordination Problem

The PEV charging coordination problem is formulated with an objective function subjected to two system constraints necessary to improve smart grid performance and economy. The selected objective function is based on the minimization of total cost of purchasing or producing the energy for charging PEVs plus the associated grid energy losses [3]:

$$\min F_{cost} = F_{cost-loss} + F_{cost-gen}$$
$$= \sum_{\Delta t} K_E \, P_{\Delta t}^{total\ loss} + \sum_{\Delta t} K_{\Delta t,G} \, P_{\Delta t}^{total\ demand} \tag{6}$$

where $F_{cost-loss}$ and $F_{cost-gen}$ are the costs corresponding to total system losses and total generation, respectively; Δt is the time interval (e.g., Δt =5 min), K_E is the cost per *MWh* of losses (e.g., K_E =*50 \$/MWh*, [3, 8-9]) and $K_{\Delta t,G}$ is the cost per *MWh* of generation at time interval Δt based on the variable price of purchasing or producing the energy (e.g., Fig. 1, [3]). $P_{\Delta t}^{total\ loss} = P_{loss,\Delta t}^{h=1}$ (Eq. 2) is the total power losses of distribution system for time interval Δt .

The voltage constraints of the distribution system will be considered by setting upper and lower voltage limits:

$$0.9\,pu = V^{min} \leq V_k \leq V^{max} = 1.1\,pu \quad for \;\; k = 1,..,n. \tag{7}$$

where *k* and *n* are the node number and total number of nodes, respectively. The second constraint is for setting a ceiling limit for the total maximum system demand to prevent an overload condition from PEV charging:

$$P_{\Delta t}^{total\ demand} = \sum_{k} P_{\Delta t,k}^{load} \leq D_{\Delta t,max} \tag{8}$$

where $P_{\Delta t}^{\text{total demand}}$ is total power consumption at time interval Δt within the 24 hours, $P_{\Delta t,k}^{load}$ is the power consumption of node *k* at Δt and $D_{\Delta t,max}$ is the maximum demand level at Δt that would normally occur without any PEVs.

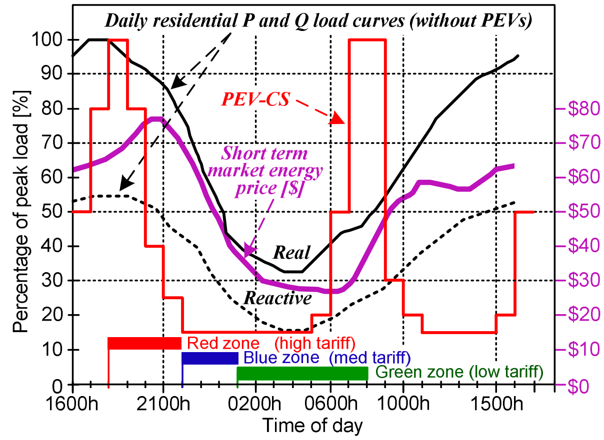


Fig. 1. Subscription options of charging time zones for PEV owners, variable short term market energy pricing [3], typical PEV-CS daily load curve [10] and active/reactive daily residential load curves [9].

III. Problem Solution

A. Optimal Load Interval Division using GA

For the linear loads, a typical P and Q load interval curve over the 24-hour period is assumed (Fig. 1), the number of load intervals is selected and a genetic algorithm [9] is employed to determine the optimal load curve intervals.

B. Optimal Dispatch of LTC and SSCs using GA

For the optimal dispatch of LTC and SSCs, the GA of [9] with sinusoidal operating conditions and linear loads is used.

C. Online PEV Charging Coordination with Random Plug-In of Vehicles Considering Consumer Priority

The online PEV charging coordination algorithm of [3] that considers random plug-in (arrivals) of vehicles, provides consumer priority (e.g., the red, blue and green charging time zones of Fig. 1) and utilizes the maximum sensitivities selection (MSS) optimization is used.

D. Proposed Practical Solution Approach

The aim of this paper is to perform GA optimal scheduling of LTC and SSCs [9] in smart grid consisting of MV distribution system with PEV-CSs and residential feeders populated with PEVs (E.g., Fig. 2). To simplify the problem and reduce computing time, a practical four step approach is taken as follows:

- Step 1- Calculate (or forecast) the daily load curves of each residential network with uncoordinated and coordinated (e.g., the MSS-based coordination algorithm of [3]) PEV charging.
- Step 2- Forecast (or calculate) daily load curves associated with the PEV charging stations (e.g., Fig. 1).
- Step 3- Simplifying the smart grid by replacing each residential network with a single node demanding the calculated/forecasted daily load curve of Step 1.
- Step 4- Perform the GA optimal dispatch of Section III for the simplified smart grid.

IV. Simulation Results

A. Smart Grid System with PEVs, PEV-CSs, LTC and SSCs

To perform optimal dispatch of LTC/SSCs with PEV charging activities and PEV-CSs, the 449 node smart grid topology of Fig. 2 is considered. It consists of the IEEE 31 node 23 kV distribution system [3] with 5 PEV-CSs and 22 low voltage 19 node 415 V residential feeders populated with 264 PEVs. System and load parameters are provided in references [3, 8-9].

B. Calculated (Forecasted) Residential Daily Load Curves Without and With PEV Charging Activities

The online PEV charging coordination algorithm of [3] is used to calculate (forecast) daily load curves of the 22 low voltage residential feeders of Fig. 2. The residential networks are assumed to have identical forecast daily load curves. The forecasted daily load curves are shown in Fig. 3. These curves are used in the next section to quickly perform optimal LTC/SCCs scheduling for different PEV charging scenarios.

C. Optimal Scheduling of LTC and SSCs with PEV Charging Considering Harmonics

The forecasted daily load curves of Fig. 3 are used to perform optimal scheduling of LTC and SSCs using GA [9] for the 449 node SG of Fig. 2. Simulation results before and after optimization including system losses, voltage profile at the worst node and THD over the 24 hour period are provided for 63% PEV penetration with uncoordinated PEV charging activities in the green (Fig. 4) and blue (Fig. 5) time zones, as well as coordinated PEV charging (Fig. 6) based on the proposed MSS algorithm of [3].

According to Figs. 4(a) and 5(a) with 5 PEV-CSs and random charging of 264 PEVs in green and blue time zones, optimal dispatch of LTC and SSCs will have significant impacts on system voltage regulation and can control the voltage profile of all nodes including the worst node within permissible limits of Eq. 7. For the case of MSS coordinated PEV charging, the voltage profile of worst node is already within permissible limits; however, the GA optimal dispatch will provide further improvements as illustrated in Fig. 6(a).

According to Figs. 4(b), 5(b) and 6(b), optimal dispatch of LTC and SSCs will also considerably reduce total system losses for both uncoordinated and coordinated PEV charging activities. Note that the optimal LTC operation and capacitor bank switching will also compensate for the fast charging demand of the five PEV-CSs. This is clearly verified by comparing the voltage profiles of the charging stations (Figs. 4(c), 5(c) and 6(c)) before and after the GA-based optimal dispatch. Daily loading pattern of the substation transformer supplying the 449 node smart grid with PEV charging activities is also investigated in Figs. 4(d), 5(d) and 6(d). As expected, optimal dispatch will also reduce daily transformer loading that will help to prevent overloading, premature aging and failure problems.

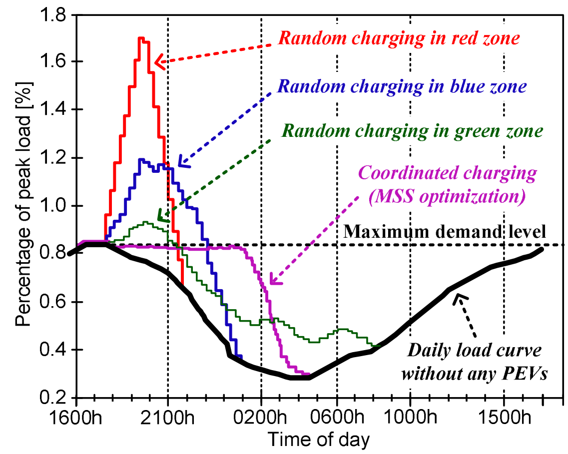


Fig. 3. Calculated (forecasted) daily load curves for one residential network of Fig. 2 at 63% PEV penetration for uncoordinated (random) PEV charging in red, blue and green time zones (Fig. 1), as well as MSS-based coordinated charging of PEVs [3].

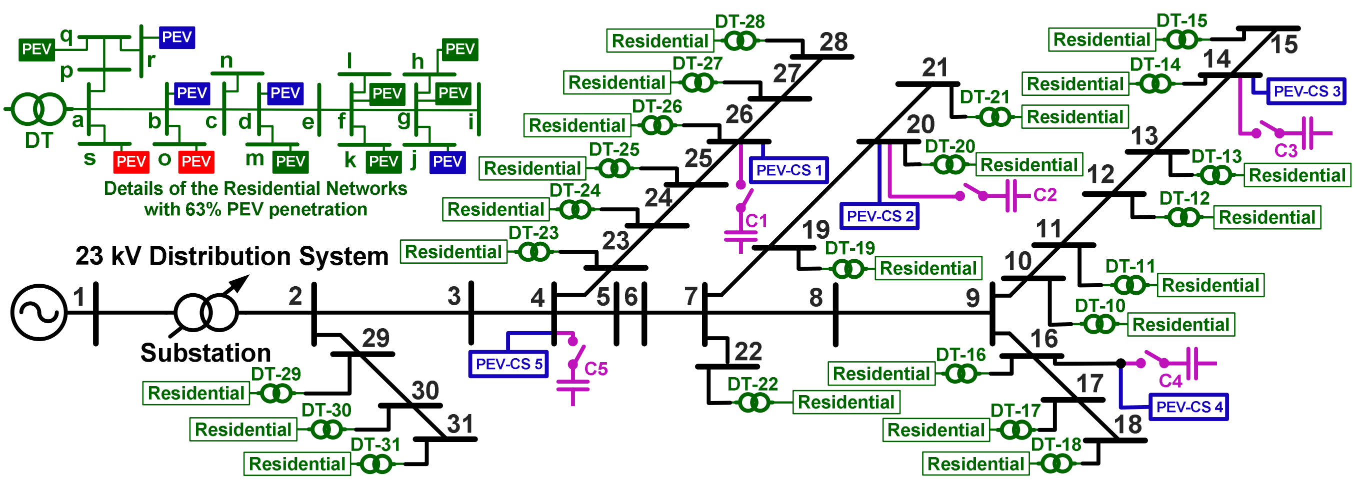


Fig. 2. The 449 node smart grid system consisting of the IEEE 31 node 23 kV system with five PEV-CSs and 22 low voltage 415 V residential feeders. The top left had side diagram presents details of one residential feeder with 63% PEV penetration showing high, medium and low priority consumers in red, blue and green colours paying very high, moderate and very cheap tariff rates, respectively (Fig. 1).

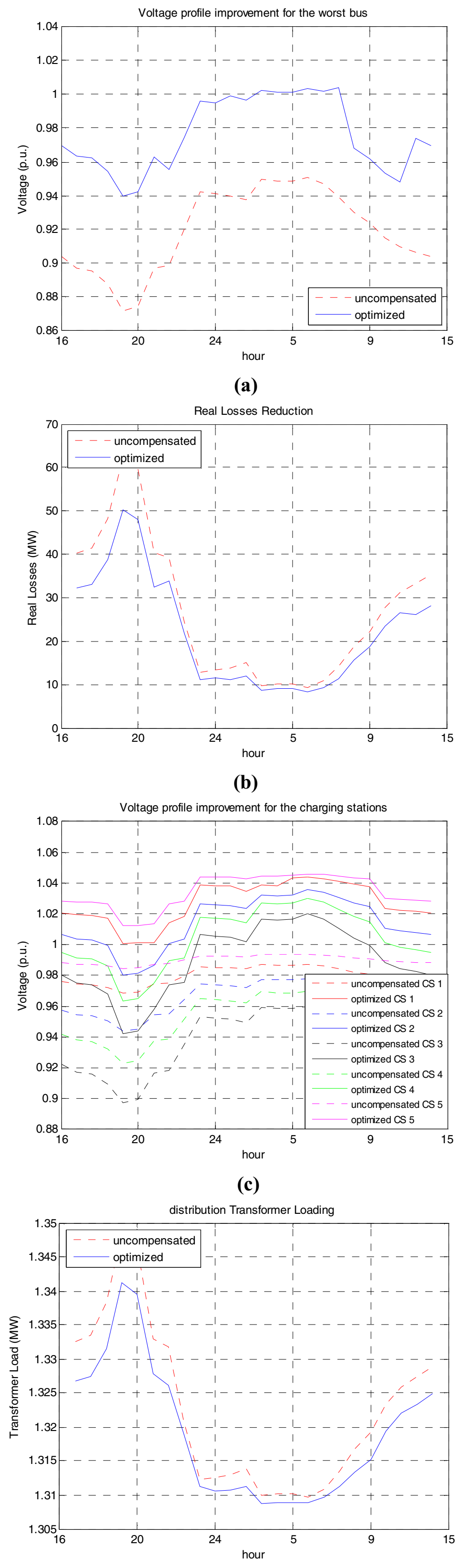


Fig. 4. Optimal scheduling of LTC and SSCs using GA for the 449 node smart grid of Fig. 2 with random PEV charging in the green time zone (Fig. 1, 01:00h to 08:00h); (a) voltage profile of the worst node (bus 15), (b) total system losses, (c) voltage profiles of the five PEV-CSs, (d) substation transformer loading.

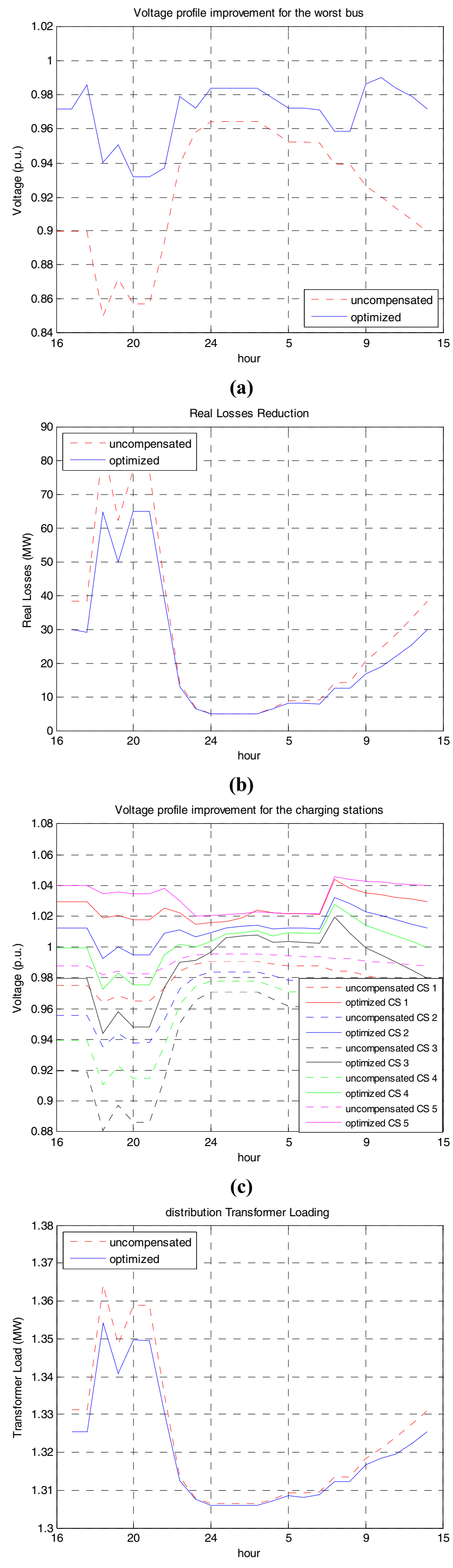
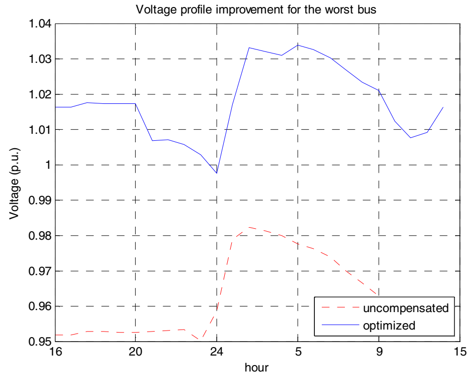
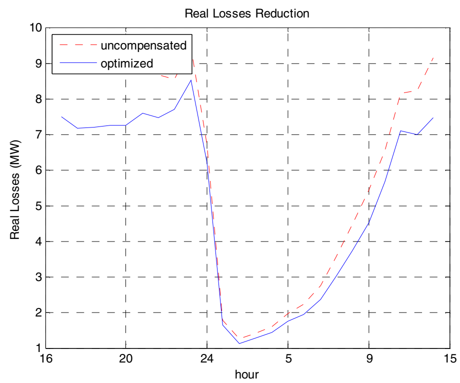


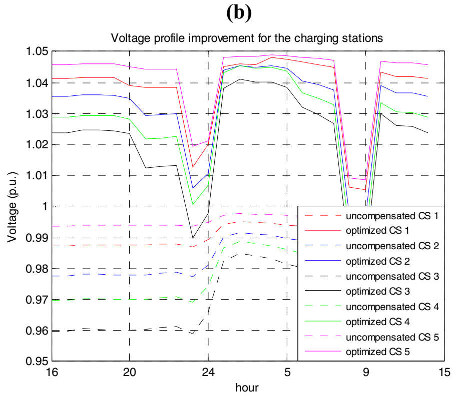
Fig. 5. Optimal scheduling of LTC and SSCs using GA for the 449 node smart grid of Fig. 2 with random PEV charging in the blue time zone (Fig. 1, 22:00h to 01:00h); (a) voltage profile of the worst node (bus 15), (b) total system losses, (c) voltage profiles of the five PEV-CSs, (d) substation transformer loading.



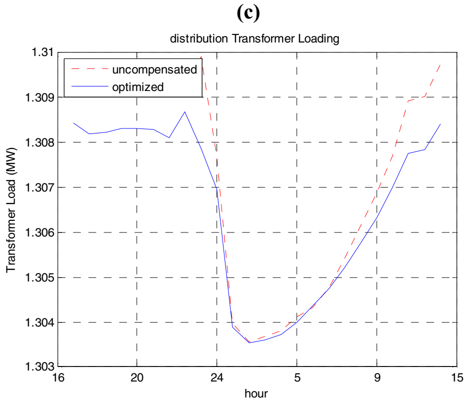
(a)



(b)



(c)



(d)

Fig. 6. Optimal scheduling of LTC and SSCs using GA for the 449 node smart grid of Fig. 2 with MSS coordinated PEV charging [3]; (a) voltage profile of the worst node (bus 15), (b) total system losses, (c) voltage profiles of the five PEV-CSs, (d) substation transformer loading.

V. Conclusion

This paper presents a relatively simple and practical approach to improve the performance of smart grids with PEV charging activities at consumer premises (within residential feeders) and PEV-CSs (within distributions networks) by performing optimal dispatch of LTC and SSCs using GAs. First, residential feeders with (un)coordinated PEV charging activities are simulated to calculate their expected (forecasted) daily load curves while the forecasted daily load curves of PEV-CSs are assumed to be available. These daily load curves are then included in GAs performing the optimal dispatch problem to generate the new updated 24 hour schedules of LTC and SSCs that considers impacts of PEVs. Simulation results before and after optimal dispatched are presented for (un)coordinated charging of PEVs considering five charging stations located in the medium voltage distribution network. Based on the simulation results, main conclusions are:

- Uncoordinated charging of PEV batteries can deteriorate the performance of smart grid particularly in the presence of PEV-CSs resulting in poor voltage profiles and high system losses.
- Vehicle charging at PEV-CSs will affect supply quality and grid capacity even at small PEV penetrations.
- Inclusion of PEV charging and PEV-CSs in the optimal dispatch solution can significantly improve system performance, enhance node voltage profiles and reduce system losses over the 24 hour period.

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