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# A Heuristic Approach for Coordination of Plug-In Electric Vehicles Charging in Smart Grid

Amir S. Masoum[a]; Sara Deilami[a]; Mohammad A.S. Masoum[a]; A. Abu-Siada[a], *

[a] The Electrical and Computer Engineering Department, Curtin University, WA, Australia.
* Corresponding author.

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## Abstract

In this paper, a heuristic load management algorithm (H-LMA) is proposed for Plug-in Electric Vehicles (PEVs) charging coordination. The proposed approach is aimed to minimize system losses over a period T (e.g., 24 hours) through re-optimizing the system at time intervals $\Delta t$ (e.g., 15 minutes) while regulating bus voltages through future smart grid communication system by exchanging signals with individual PEV chargers. Scheduling is performed based on the allowable substation transformer loading level and taking into account PEV owner preference/priority within three designated charging time zones. Starting with the highest priority consumers, H-LMA will distribute charging of PEVs within the selected priority time zones to minimize total system losses over a period T while maintaining network operation criteria such as power generation and bus voltages within their permissible limits. Simulation results are presented for different charging scenarios and are compared to demonstrate the performance of H-LMA for the modified IEEE 23 kV distribution system connected to several low voltage residential networks populated with PEVs. The main contribution of this paper lies in the detailed simulations / analyses of the smart grid under study and highlighting the impacts of $\Delta t$ and T values on the performance of the proposed coordination approach in terms of accuracy and coordination execution time.

**Key words:** Heuristic; Load management; PEV; Coordination and smart grid.

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## INTRODUCTION

Power utilities are moving toward smarter solutions for generation, distribution and control of the grid. The consumers are also expressing their concerns about the environment by adjusting their life styles, reducing energy consumption, utilizing renewable energy resources such as roof-top PVs, and promoting pollution free transportations such as plug-in electric vehicles (PEVs). Preliminary studies indicate that PEVs will dominate the market in the near future as pollution-free alternatives to the conventional petroleum based transportation and they will populate residential feeders, especially in the developing countries such as USA and Australia (Amin & Wollenberg, 2005; Amin, 2008; Lightner & Widergren, 2010).

It is well-known that uncoordinated (random) charging of PEVs at high penetration levels during the peak load hours will have detrimental impacts on the operation and performance of the power grid such as unpredictable system peaks, unaccepted voltage deviations, significant increases in losses and poor power quality, as well as overloading of the distribution and substation transformers (Moses, Deilami, Masoum & Masoum, 2010; Moses, Masoum & Hajforoosh, 2012; Masoum, Abu-Siada & Islam, 2011).

To overcome some of these problems, a number of PEV coordination approaches have been suggested in the literature (Clement-Nyns, Haese & Driesen, 2010; Masoum, Deilami, Moses, Masoum & Abu-Siada, 2011; Deilami, Masoum, Moses & Masoum, 2011; Ashtari, Shahidinejad & Molinski, 2012; Wu, Aliprantis & Ying, 2012; Bashash & Fathy, 2012; Han, Han & Sezaki, 2012; Sortomme & El-Sharkawi, 2011). In general, PEV chargers can be controlled to operate in charge or discharge modes with the energy being transferred from grid to vehicle (V2G) (Clement-Nyns, Haese & Driesen, 2010; Masoum, Deilami, Moses, Masoum & Abu-Siada, 2011; Deilami, Masoum, Moses & Masoum, 2011; Ashtari, Shahidinejad & Molinski, 2012; Wu, Aliprantis & Ying, 2012) or from vehicle to grid (G2V) (Bashash & Fathy, 2012; Han, Han & Sezaki, 2012; Sortomme & El-Sharkawi, 2011), respectively. One of the first approaches for PEV coordination based deterministic and stochastic dynamic programing was presented in (Clement-Nyns, Haese & Driesen, 2010). Reference (Deilami, Masoum, Moses, Masoum, 2011) performs peak load saving with PEV coordination without considering the random nature of PEV arrivals and departures. A relatively fast PEV coordination algorithm suitable for online applications is proposed in (Deilami, Masoum, Moses & Masoum, 2011). Reference (Ashtari, Shahidinejad & Molinski, 2012) predicts PEV charging profiles and electrical range reliability based on recorded vehicle usage data. Reference (Wu, Aliprantis & Ying, 2012) designs a minimum-cost load scheduling algorithm based on the forecasted electricity price and PEV power demands. Operation of PEVs in V2G mode to support the grid by performing frequency regulation and/or energy storage is investigated in (Bashash & Fathy, 2012; Han, Han & Sezaki, 2012; Sortomme & El-Sharkawi, 2011).

This paper proposes a heuristic load management algorithm (H-LMA) to coordinate PEV charging activities while reducing system stresses that can impact grid reliability, security and performance. H-LMA coordinates PEV charging to perform total system loss minimization over period $T$ using optimization time interval $\Delta t$ while improving node voltage profiles and considering designated charging time zone priorities specified by PEV owners. To demonstrate the improvements in smart grid performance, H-LMA is simulated with a detailed system topology consisting of a high voltage feeder with several integrated low voltage residential networks populated with PEVs. Simulation results are presented for uncoordinated and coordinated charging with different values of $T$, $\Delta t$ and different levels of PEV penetration considering three designated time zones namely; red: 1800h-2200h, blue: 1800h-0100h, and green: 1800h-0800h. The impacts of $\Delta t$ and $T$ on the performance of H-LMA are investigated.

## 1. PROBLEM FORMULATION

PEV charge coordination is a constrained optimization problem that could be solved using online algorithms (i.e., PEV coordination is performed as soon as vehicles are randomly plugged-in (Masoum, Abu-Siada & Islam, 2011; Deilami, Masoum, Moses & Masoum, 2011) or offline schemes (i.e., all vehicles are assumed to be plugged-in according to their pre-known/forecasted charging patterns (Clement-Nyns, Haese & Driesen, 2010; Masoum, Deilami, Moses, Masoum & Abu-Siada, 2011; Ashtari, Shahidinejad & Molinski, 2012; Wu, Aliprantis & Ying, 2012). This paper assumes the charging patterns of all PEVs are known or forecasted and utilizes a heuristic approach to solve the optimization problem.

The optimization problem objective function is formulated based on the minimization of total system power losses:

$$min\ W_{loss} = \sum_t P_t^{loss}, \quad t = \Delta t, 2\Delta t, 3\Delta t, ....T \tag{1}$$

$$P_t^{loss} = \sum_{k=0}^{n-1} R_{k,k+1}\left(\left|V_{k+1} - V_k\right|\left|y_{k,k+1}\right|\right)^2 \tag{2}$$

where $\Delta t$ is the optimization time interval and $T$ is the optimization period used for loss minimization. $P_t^{loss}$ is the system power loss at time $t$ (computed using the Newton-based power flow), $V_k$ is voltage of node $k$ at time $t$, and $n$ is total number of nodes while $R_{k,k+1}$ and $y_{k,k+1}$ are resistance and admittance of line section between nodes $k$ and $k+1$.

PEV coordination constraints are node voltage limits and system demand level at time $t$:

$$V^{min} \leq V_k \leq V^{max} \quad for\ \ k = 1,..,n. \tag{3}$$

$$P_{max\,demand,t} = \sum_k P_{k,t}^{load} \leq D_{max,t} \tag{4}$$

where $V^{\min}$=0.9$pu$, $V^{\max}$=1.1pu, and $P_{max\ demand,t}$ is the total power consumption at time $t$, while $P_{k,t}^{load}$ is the power consumption of node $k$ at time $t$ and $D_{m,t}$ is maximum demand level at time $t$ that would normally occur without any PEVs.

For example, if $T$=24 hours and $\Delta t$ =15 minutes, system modeling, updating vehicle status (plugged in/out), loss calculation (Eq. 2) and PEV coordination (Fig. 2) will be performed every 15 minutes such that total system losses over the 24 hour period are minimized while all node voltage are regulated and generation limits are not violated (Eqs. 1-4).

## 2. PROPOSED HEURISTIC LOAD MANAGEMENT ALGORITHM

As an alternative to immediately charging PEVs when first plugged in, or after some fixed time delay, H-LMA of Fig. 2 is proposed that will decide which PEVs will be charged at what time. H-LMA will perform loss minimization over the designated time $T$ using the selected time interval $\Delta t$ based on Eqs. 1-2 while considering the system constraints (Eqs. 3-4).

### 2.1 Charging Time Zone and Priority Scheme

The developed H-LMA allows PEV owners to select one of the following three charging time zones (Fig. 1):

- Red charging zone (1800h-2200h)- coinciding with most of the on-peak period and is designated for high-priority PEV owners willing to pay higher tariff rates in order to charge their vehicles as soon as possible.
- Blue charging zone (1800h-0100h)- is intended for medium-priority consumers that prefer to charge their vehicles at partially off-peak periods and pay lower tariff rates.
- Green charging zone (1800h-0800h)- is the period that most PEV charging will probably take place due to the cheapest tariff rates as most low-priority consumers will require their vehicles fully charged for the following day.

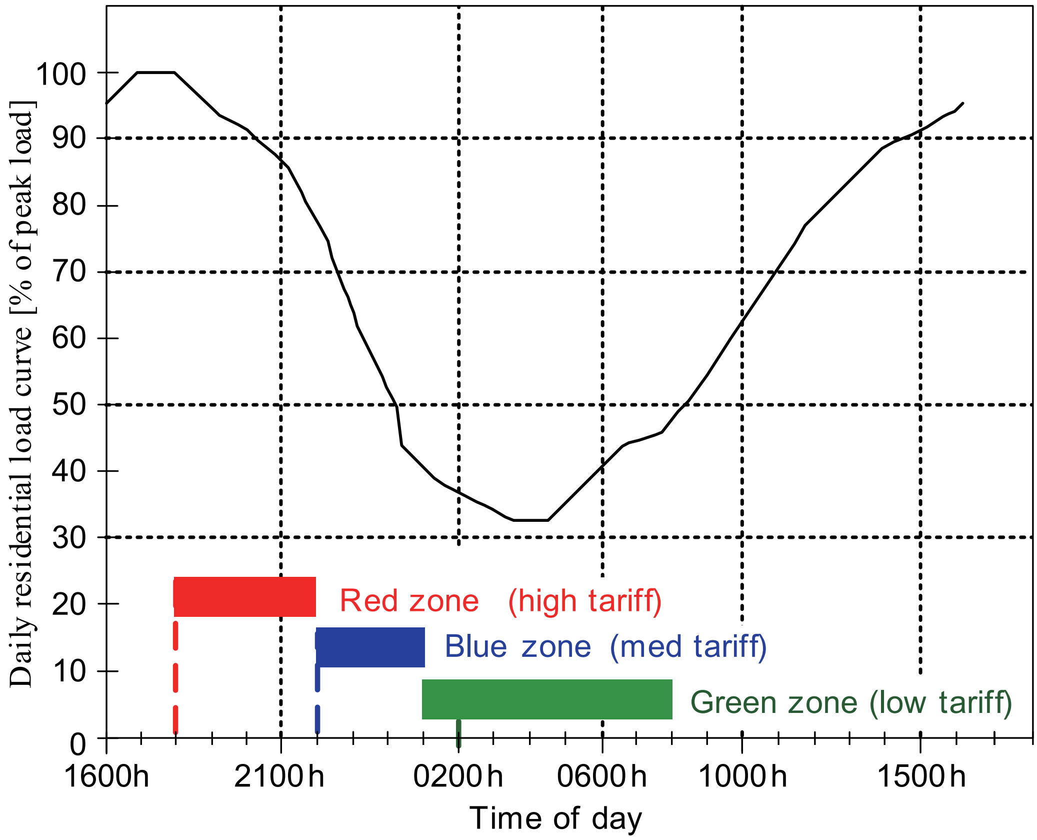



**Figure 1**
**Daily Residential Load Curve and Subscription Options of Charging Time Zones for PEV Owners.**

### 2.2 Implementation of H-LMA

A MATLAB source has been developed and coded to perform PEV scheduling based on H-LMA of Fig. 2 with user options for $\Delta t$ and $T$ values.

The main program loop progresses from high-priority (red) to low-priority (green) PEV groups. Within the selected priority group, individual PEVs are temporarily activated to determine system performance at all possible PEV nodes and charging time combinations within that priority charging time zone. H-LMA selects the PEV and the charging start time resulting in the minimum system losses (Eq. 1) over designated $T$ taking into consideration the charging duration and current demand level of the smart grid.If the load flow indicates a constraint violation at any node (Eqs. 3-4), H-LMA will try the next possible charging start time such that the constraints are satisfied. Therefore, it may not be possible for all PEV owners to be accommodated in their preferred charging zones. Once it has been determined which PEV node in that priority group can begin charging and at what time resulting in minimum system losses (over period $T$), the selected PEV is permanently placed and the system load curve is updated (Fig. 1). This process is repeated for all nodes in that priority group before advancing to the next priority charging zone.

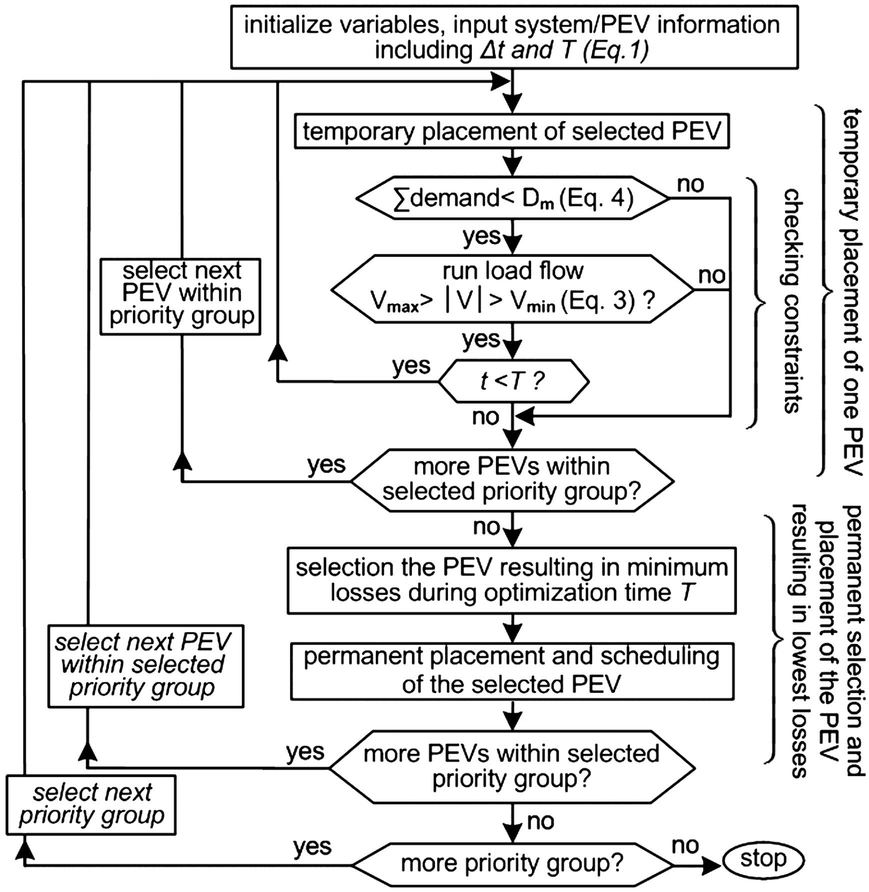



**Figure 2**
**Proposed H-LMA for Coordination of PEVs to Minimize Total System Losses Over Period T Using Optimization Time Interval $\Delta t$ Considering Node Voltage Profiles and Maximum Demand Level.**

## 3. SMART GRID TEST SYSTEM

The selected test system is a modification of the IEEE 31 bus 23 kV distribution system (S. Civanlar & J.J. Grainger, 1985) combined with 22 residential 19 node LV 415 V networks populated with PEVs. The resulting 449 node system is supplied from the HV main bus via a 23kV/415V 100 kVA distribution transformer as shown in Fig. 3. System data are listed in the Appendix.

A typical residential Western Australian daily load curve is used to model the domestic load variations (without PEV charging) at each house over a 24 hour period (Fig. 1). The peak power consumption of a house is assumed to be on average 2 kW with a power factor of 0.9. Three priority levels and charging time zones are considered as shown in Fig. 1. Four PEV penetration levels are selected including 16% (with nodes "o", "b" and "q" randomly designated with red, blue and green priorities, respectively), 32% (with nodes "o", "b, r" and "f, h, q" randomly designated with red, blue and green priorities, respectively), 47% (with nodes "o", "b, j, r" and "f, g, h, m, q" randomly designated with red, blue and green priorities, respectively) and 63% (with nodes "o, s", "b, d, j, r" and "f, g, h, k, m, q" randomly designated with red, blue and green priorities, respectively).

For this study, a 10 kWh battery capacity per PEV with a depth of discharge (DOD) of 70% and battery charger efficiency of 88% is assumed (Duvall, Knipping & Alexander, 2007) which will require a total of 8 kWh of energy from the grid to charge a single PEV. A standard single-phase 240V outlet (Australia) can typically supply a maximum of 2.4 kW. There are also 15A and 20A outlets (single-phase and three-phase) which can supply approximately 4 kW and 14.4 kW, respectively. In this paper, a fixed charging power of 4 kW is used.

## 4. SIMULATION RESULTS AND DICUSSION

Simulation results for uncoordinated and coordinated (using H-LMA of Fig. 2) PEV charging for the smart grid system of Fig. 3 are presented and compared in Figs. 4-6 and Tables I and II.

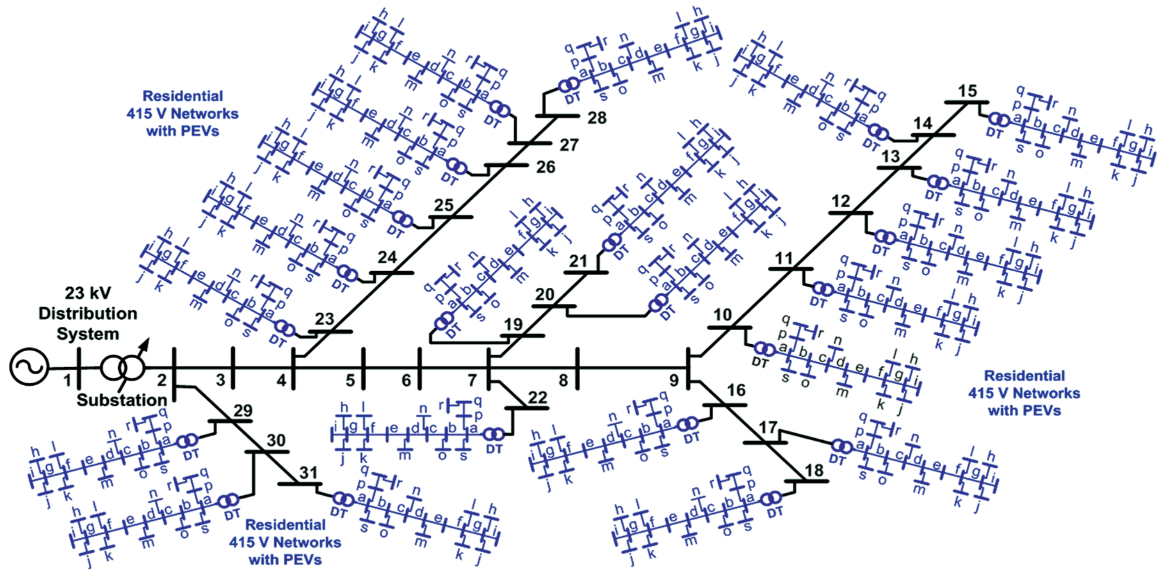
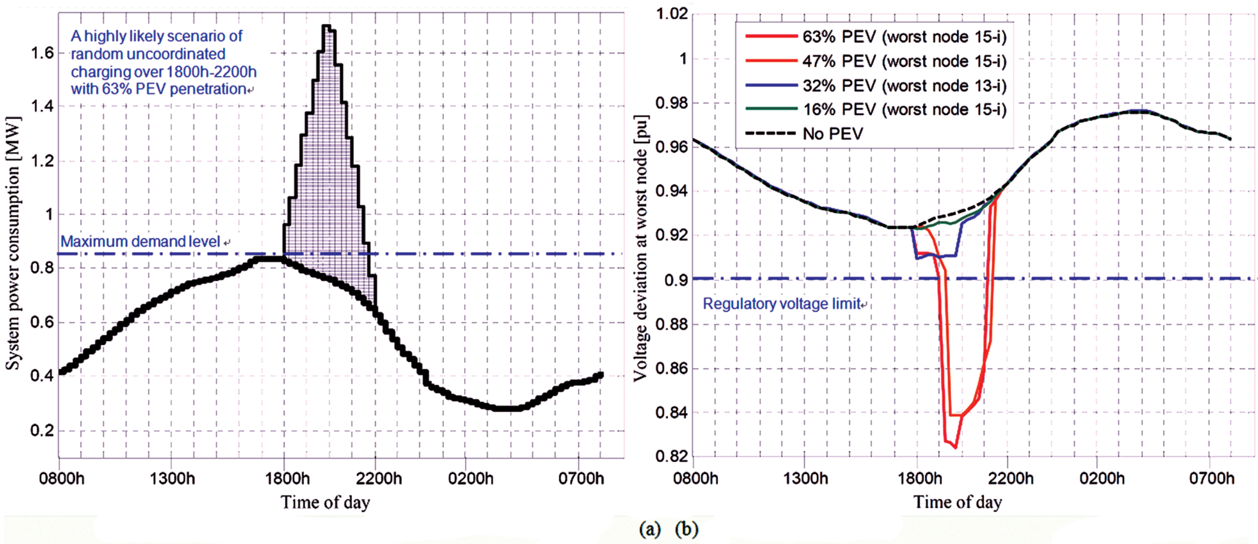



**Figure 3**
**The 449 Node Smart Grid Test System Consisting of the IEEE 31 Node 23 kV System with Several 415 V Residential Feeders.** Each low voltage residential network has 19 nodes representing customer households populated with PEVs randomly arriving within 24 hours.



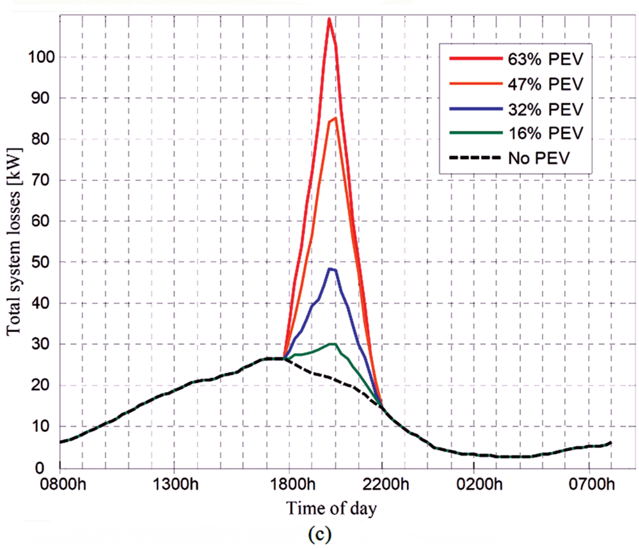




**Figure 4**
**Simulation Results ($\Delta t$=15 min, T=24 Hours) for Random Uncoordinated PEV Charging Across the Red Zone (Case A1: 1800h-2200h); (a) System Power Consumption for 63% PEV Penetration, (b) Voltage Profile (For the Worst Affected Nodes), (c) Total System Power Losses.**

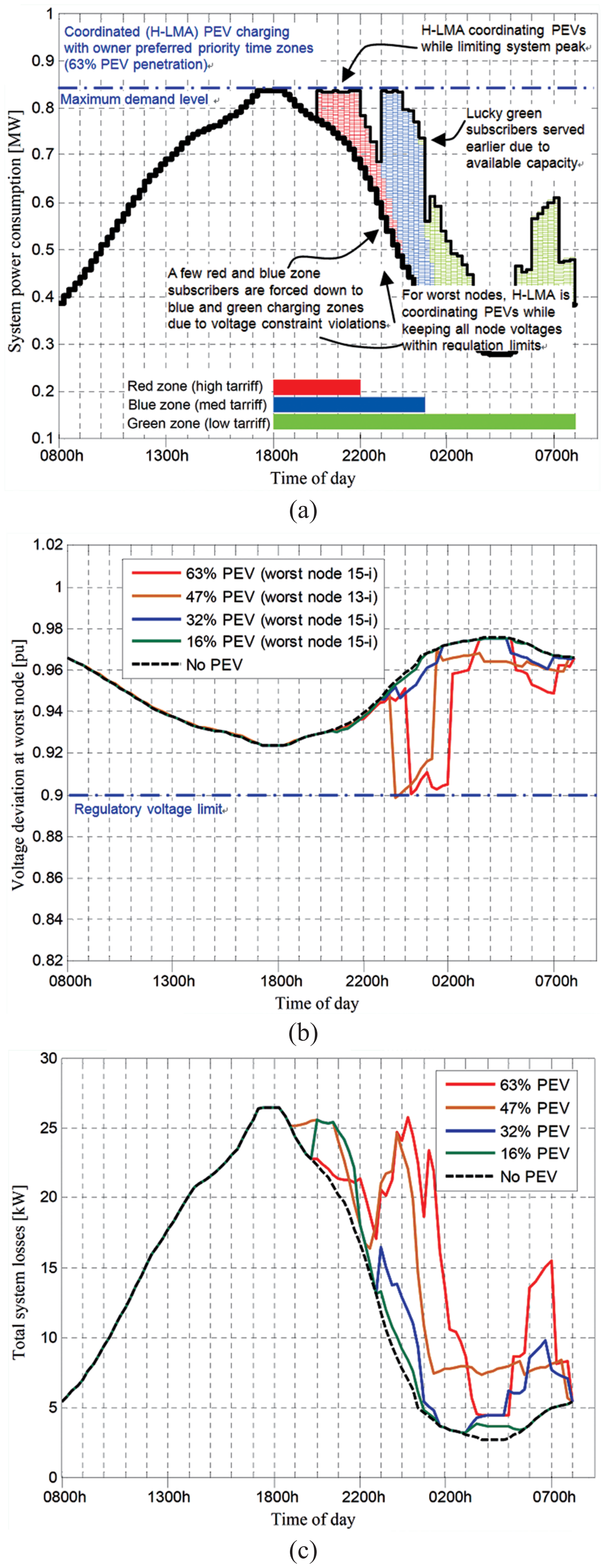



**Figure 5**
**Simulation Results ($\Delta t$ =15 min, T=24 Hours) for Coordinated PEV Charging Using the Proposed H-LMA of Figure 2; (a) System Power Consumption for 63% PEV Penetration, (b) Voltage Profile (For the Worst Affected Nodes), (c) Total System Power Losses.**

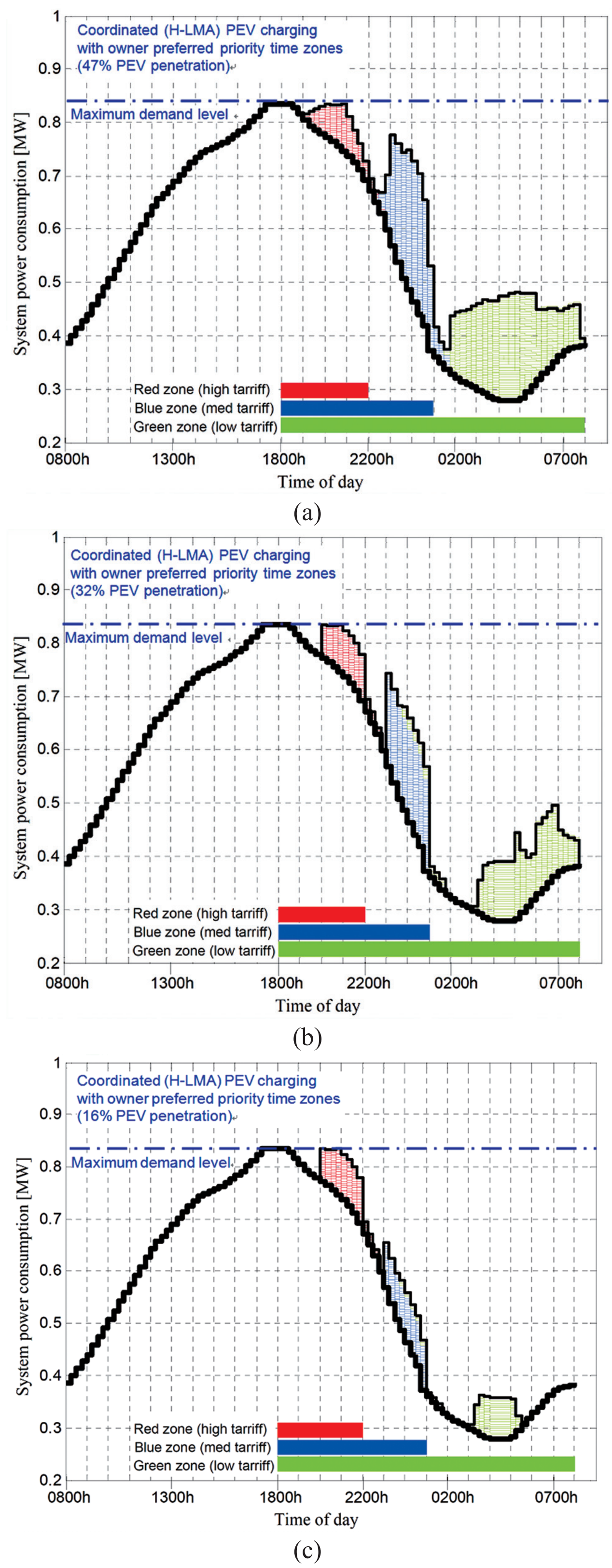



**Figure 6**
**System Power Consumption with Coordinated PEV Charging Using the Proposed H-LMA ($\Delta t$ =15 min, T=24 Hours) for PEV Penetration Levels of; (a) 47%, (b) 32%, (c) 16%.**

### 4.1 Case A: Random PEV Charging

Simulation results of Fig. 4 and Table 1 highlight the detrimental impacts of uncoordinated PEV charging at four penetration levels. As expected and well documented (Clement-Nyns, Haesen, & Driesen, 2010; Masoum, Deilami, Moses, Masoum & Abu-Siada, 2011; Ashtari, Bibeau, Shahidinejad & Molinski, 2012; Bashash & Fathy, 2012; Han, Han & K. Sezaki, 2012; Sortomme & El-Sharkawi, 2011), random charging, especially during the peak residential load hours (18:00-22:00), results in unpredictable power consumption peaks (Fig. 4(a), at 19:45 for 63% PEV penetration), unaccepted voltage deviations (Fig. 4(b), at node 15-i for 63% and 47% PEV penetrations at 19:45) and significant increase in losses (Fig. 4(c), 110kW, 85kW, 47kW and 30kW for PEV penetration levels of 63%, 47%, 32% and 16%, respectively, at 19:45). Detailed simulation results for this case study are presented in Table 1 (columns 3-5).

### 4.2 Case B: H-LMA Coordinated PEV Charging

To overcome the detrimental impacts of random PEV charging, coordinated PEV charging based on the proposed H-LMA is performed and demonstrated. Coordinated PEV charging is performed with (Fig. 5-6) and without (Table 1) PEV owner preferred time zone priorities. Compared to Case A, a significant improvement in smart grid performance is achieved. Most notably, the system demand peak has been reduced (Figs. 4(a) and 5(a)) which is more favorable from a standpoint of generation dispatch and preventing overloads.

Comparison of results also indicates the significant impacts of coordinated (H-LMA) PEV charging on voltage profile where the unacceptable voltage deviations of about 17% (Fig. 4(b)) at the worst bus for uncoordinated PEV charging is compensated to less than 10% (Fig. 5(b)) which is within the regulation limits. However, there is a trade off in that a few PEV subscribers who designated a preferred priority charging time zone were not accommodated in their requested charging zone (Fig. 5(a)) because the system reached a point where PEV loading caused voltage regulation to be violated. H-LMA handled these cases by attempting to schedule the PEV owners causing the violations to a charging time where the system is not under strain, thereby satisfying constraints. Conversely, after placement of higher priority PEV subscribers, in some cases (Fig. 5(a)) H-LMA permitted "lucky" lower priority PEVs to charge earlier and sometimes ahead of their requested charging time zone because there was available system capacity to do so without violating system constraints.

The improvements in system efficiency with H-LMA coordination strategy are also evident in Table 1. Energy losses for the high penetration (63%) with H-LMA are limited to 2.59% of system consumption versus the worst uncoordinated charging scenario with losses of 3.09%.

Furthermore, peak power losses are limited to less than a third of the worst case random uncoordinated charging (Fig. 5(c)). The H-LMA charging also has positive impacts on peak transformer load currents. For many of the uncoordinated random charging scenarios (Table 1), distribution transformers are experiencing load currents of up to 0.88 pu, while with H-LMA coordination, transformer currents are reduced to levels of approximately 0.54 pu (Table 1).

**Table 1**
**Comparison of Simulation Results for Uncoordinated and Coordinated (H-LMA, $\Delta t$=15 min, T=24 Hours) PEV Charging for the Smart Grid Test System of figure 3.** PEVs are assumed to be randomly arriving at each time interval Δt. For comparison, consumer priorities are not considered and the same Gaussian random distributions are used in the simulations.

| Case Study | PEV Penetration level | Case A: Uncoordinated PEV Charging (random charging) | | | Case B: Coordinated PEV Charging (using H-LMA of Fig. 2) | | |
|---|---|---|---|---|---|---|---|
| | | Dloss* [%] | DV** [%] | $I_{MAX}$*** [%] | Dloss [%] | DV [%] | $I_{MAX}$ [%] |
| No Priority, Charging Period: 6pm-10pm | 16% | 2.3553 | 7.8499 | 0.5546 | 2.3332 | 7.646 | 0.47243 |
| | 32% | 2.5312 | 9.2298 | 0.64324 | 2.4048 | 7.646 | 0.47243 |
| | 47% | 2.9263 | 15.8182 | 0.77095 | 2.5849 | 10 | 0.51682 |
| | 63% | 3.089 | 17.1467 | 0.88626 | 2.5963 | 9.9996 | 0.54002 |
| No Priority, Charging Period: 6pm-1am | 16% | 2.3401 | 7.6984 | 0.52591 | 2.3149 | 7.646 | 0.44071 |
| | 32% | 2.4712 | 8.5243 | 0.57259 | 2.4172 | 7.7832 | 0.45499 |
| | 47% | 2.7659 | 13.9102 | 0.64256 | 2.5737 | 9.7039 | 0.45872 |
| | 63% | 2.8706 | 14.7455 | 0.68842 | 2.6217 | 9.7946 | 0.49038 |
| No Priority, Charging Period: 6pm-8am | 16% | 2.3141 | 7.7242 | 0.47831 | 2.2939 | 7.646 | 0.44071 |
| | 32% | 2.3818 | 8.3553 | 0.52900 | 2.3411 | 7.646 | 0.44071 |
| | 47% | 2.6188 | 13.6146 | 0.60348 | 2.4936 | 8.7893 | 0.44071 |
| | 63% | 2.6184 | 14.3304 | 0.58385 | 2.4921 | 9.1211 | 0.44071 |

Note: Ratio of system losses over 24 hours compared to total power consumption over 24 hours.
Voltage devataion at the worst bus.
Maximum of all distribution transformer load current.

### 4.3 Case C: Impacts of $\Delta t$ and T on PEV Coordination

Detailed simulations are presented and compared in Table 2 to highlight impacts of $\Delta t$ and *T* (Eq. 1) on the performance of H-LMA. In general, the speed and accuracy of the PEV coordination algorithms will depend on the selection of optimization time interval ( $\Delta t$ ) and period (*T*).

**Table 2**
**Impact of Coordinated (H-LMA) PEV Charging with Diffident Optimization Time Interval Δt and Period T (Eq. 1) Values on the Power Quality and Performance of Smart Grids Test System of Figure 3.**

| PEV [%] | Coordinated PEV Charging (H-LMA) Based on Loss Minimization (eqs. 1-3) | | | | |
|---|---|---|---|---|---|
| | Dloss [%] | DV [%] | $I_{MAX}$ [%] | $E_{loss}$* [kWh] | Computing time** |
| **Case B: $\Delta t$ =15 min, loss minimization over $T$= 24 hours** | | | | | |
| 16 | 2.336 | 7.646 | 0.443 | 326.4 | 15.7 mins |
| 32 | 2.373 | 7.646 | 0.444 | 344.1 | 2.02 hrs |
| 47 | 2.530 | 9.999 | 0.444 | 380.2 | 5.53 hrs |
| 63 | 2.551 | 9.999 | 0.4801 | 396.9 | 6.29 hrs |
| **Case C: $\Delta t$ = 60 min, loss minimization over $T$= 24 hours** | | | | | |
| 16 | 2.319 | 7.646 | 0.440 | 321.2 | 5.2 mins |
| 32 | 2.372 | 7.646 | 0.455 | 340.9 | 26.9 mins |
| 47 | 2.520 | 9.996 | 0.441 | 375.6 | 1.14 hrs |
| 63 | 2.530 | 9.562 | 0.450 | 390.4 | 1.55 hrs |
| **Case D: $\Delta t$ = 15 min, loss minimization over $T$= $\Delta t$ = 15 min** | | | | | |
| 16 | 2.338 | 7.646 | 0.442 | 326.7 | 2.33 mins |
| 32 | 2.375 | 7.646 | 0.462 | 344.4 | 17.67 mins |
| 47 | 2.517 | 9.999 | 0.462 | 378.3 | 48.4 mins |
| 63 | 2.529 | 9.999 | 0.458 | 399.4 | 56.9 mins |

Note: Total energy consumption over *T*.
Intel Core 2 Quad 3.0 GHz processor, 8 GB RAM, using MatLab ver. 7.

The accuracy can be improved using shorter time intervals (e.g., checking the status of PEVs and network as quickly as possible based on online information and measurements available through smart meters) and performing loss minimization over a long period (e.g., 24 hours). However, the drawback is the computing time will dramatically increase, especially in realistic large smart grids with many nodes and high penetration levels of PEVs. Therefore, a compromise should be made between the solution accuracy and computation time considering system size and the anticipated PEV penetration level.

Based on the results of Table 2, the practical options may be to use moderate time intervals with large optimization periods for offline PEV coordination (e.g., $\Delta t$ =60 min and *T*=24 hours for applications where all vehicles are plugged-in or their charging patterns are known/forecasted before the start of optimization) and select small values for online PEV coordination (e.g., $\Delta t$ =*T*=15 min to start charging batteries as soon as vehicles are randomly plugged-in).

## CONCLUSION

This paper studies the impacts of uncoordinated and coordinated (based on a heuristic approach) charging of electric vehicles on smart grid power consumption, losses and node voltage profiles. The focus of the research is not on improving the optimization algorithm but on the impacts of its parameters such as optimization time interval and period on the performance, accuracy and speed of PEV coordination. Based on detailed simulations, the main conclusions are:

- The proposed H-LMA is shown to be beneficial in limiting overall system overloads and voltage fluctuations as well as reducing the burden on local distribution circuits (e.g., cables and transformers). Therefore, the risk and cost of premature failure of transformers and associated outages can be minimized.
- The speed and accuracy of H-LMA depend on the selected values for optimization time interval and period. The accuracy can be improved using shorter time intervals and performing loss minimization over 24 hours. This will however, require long computing times. Therefore, a compromise should be made between the solution accuracy and the associated computation time considering system size and the anticipated PEV penetration levels.
- For online PEV coordination, small time interval and optimization period should be selected to start charging vehicles as quickly as possible; otherwise moderate time intervals with a large optimization period should be selected for offline coordination where all vehicles are plugged-in or their charging patterns are known/forecasted ahead of time.

H-LMA could be adapted to function with smart meters as inputs in lieu of load flow to determine vehicle statues and system performances necessary for the PEV coordination.

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## APPENDIX

Parameters of the 19 bus low voltage and 31 bus distribution system are provided in Tables 3-4 and (S. Civanlar & J. J. Grainger, 1985), respectively.

**Table 3**
**Linear and Nonlinear (PEV) Loads of The Typical Low Voltage residential System (Figure 3)**

| Linear and PEV Load | | Power | |
|---|---|---|---|
| Bus | Name | kW | kVAR |
| 1 to 19 | Linear loads | 2.0 | 1.7 |
| Selected buses | PEV charger | 4.0 | 0 |

**Table 4**
**Line Parameters of The Low Voltage residential System (Figure 3)**

| Line | | Line Resistance R [Ω] | Line Reactance X [Ω] | Line | | Line Resistance R [Ω] | Line Reactance X [Ω] |
|---|---|---|---|---|---|---|---|
| From bus | To bus | | | From Bus | To Bus | | |
| a | b | 0.0415 | 0.0145 | f | l | 1.3605 | 0.1357 |
| b | c | 0.0424 | 0.0189 | d | m | 0.140 | 0.0140 |
| c | d | 0.0444 | 0.0198 | c | n | 0.7763 | 0.0774 |
| d | e | 0.0369 | 0.0165 | b | o | 0.5977 | 0.0596 |
| e | f | 0.0520 | 0.0232 | a | p | 0.1423 | 0.0496 |
| f | g | 0.0524 | 0.0234 | p | q | 0.0837 | 0.0292 |
| g | h | 0.0005 | 0.0002 | q | r | 0.3123 | 0.0311 |
| g | i | 0.2002 | 0.0199 | a | s | 0.0163 | 0.0062 |
| g | j | 1.7340 | 0.1729 | Distribution transformer reactance | | | 0.0654 |
| f | k | 0.2607 | 0.0260 | | | | |