Coordinated Charging of Plug-in Hybrid Electric Vehicles to Minimize Distribution System Losses

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1

Main Reference

- Sortomme, E.; Hindi, M.M.; MacPherson, S.D.J.; Venkata, S.S., "Coordinated Charging of Plug-In Hybrid Electric Vehicles to Minimize Distribution System Losses," *Smart Grid, IEEE Transactions on* , vol.2, no.1, pp.198,205, March 2011

Outline

- Introduction
- Relationship: losses, Load factor, and load variance
- Problem Formulation
- Simulation Model
- Result and Discussion
- Conclusion

Introduction

Electric Drive Vehicles (EDV): reduce dependence on fossil fuel, Environmental incentives(low emission), low operating cost.

Plug-in Hybrid Electric Vehicles (PHEV): Type of EDV, run by both fuel and stored electric energy. (10 – 40 miles), ~10 kWh

Introduction

For Example:

Ref: http://wot.motortrend.com/

Introduction

- Impacts of PHEV on distribution grid: increases system peak load, losses, decrease in voltage and system load factor

- Solution is Coordinated charging of PHEV

- Relationship between feeder losses, load factor, and load variance

- Three optimal charging algorithm to minimize impacts (system losses) and improve voltage regulation

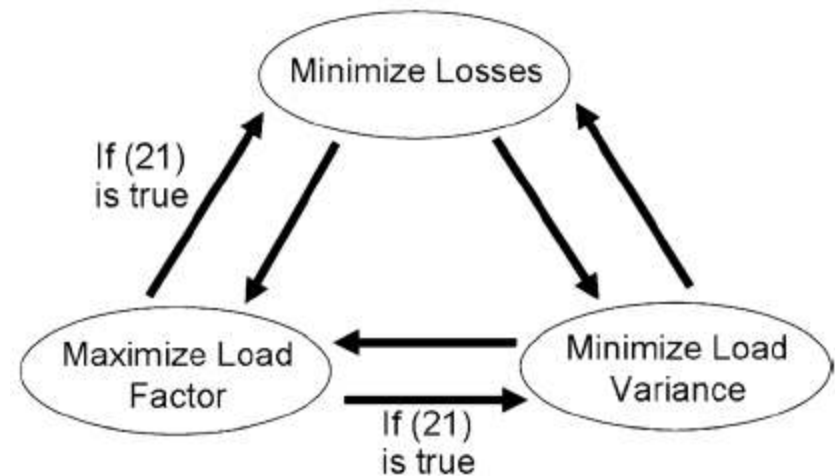# Relationship: losses, Load factor, and load variance

- Losses = total loss due to current flow in feeder in form of heat (I^2R).

- Load Factor (LF) [0,1] = ratio of average demand to maximum demand over the time of observation

- Load Variance

$$\text{LF} = \frac{\left(\sum_t D_t / T\right)}{D_{\max}} = \frac{I_{\text{avg}}}{I_{\max}}$$

$$\sigma_I^2 \equiv \frac{1}{T} \sum_t (I_t - \mu_I)^2.$$

(21)

$$E_{\text{tot,PHEV}} + E_{\text{tot,base}} \geq I_{\max,\text{base}} V T$$

Minimize Losses

If (21) is true

Maximize Load Factor

Minimize Load Variance

If (21) is true

Problem Formulation

- Assumption
  - Load profile at each node is know (with some degree of certainty)
  - Only PHEVs are controllable load
  - PHEVs are unidirectional
- Three Formulations
  - Minimizing Losses
  - Maxmizing Load Factor
  - Minimizing Load Variance

Problem Formulation

A. Minimizing Losses Formulation

$$\underset{I}{\text{minimize}} \sum_{t=1}^{T} \sum_{l=1}^{lines} R_l I_{l,t}^2$$

subject to :

Not Convex
$$S_{m,t} = V_{m,t}(I_{m,t})^*$$
$$I_{m,t} = I_{l,t} - I_{l+1,t}$$

$$S_{m,t} \geq S_{\min,m,t}$$

$$S_{m,t} \leq S_{\max,m,t}$$

$$\sum_t S_{m,t} = E_{\text{tot},m}$$

where

R_l	is the resistance of line l;
$I_{l,t}$	is the current of line l at time t;
$S_{m,t}$	is the load at node m at time t;
$S_{\min,m,t}$	is minimum allowable load at node m at time t;
$S_{\max,m,t}$	is maximum allowable load at node m at time t;
$V_{m,t}$	is the voltage at node m at time t;
$E_{\text{tot},m}$	is the total energy delivered to node m over the period.

$$S_{\max,m,t} = S_{\min,m,t} + (\text{EVnode}_{m,t}) M P_{m,t}$$

EVnode	is 1 if there is a PHEV at the node and 0 otherwise;
MP	is the maximum power draw of the PHEV at the node.

Problem Formulation

B. Maximizing Load Factor Formulation (linear)

$$\underset{S}{\text{maximize}} \; \frac{\mu_D}{\max \left(\sum_{m=1}^{\text{nodes}} S_{m,t} \right)}$$

Equivalently

$$\underset{S}{\text{minimize}} \; \frac{\max \left(\sum_{m=1}^{\text{nodes}} S_{m,t} \right)}{\mu_D}$$

Subject to:

μ_D = Avg. Dist System load during T (usually one day)

$$S_{m,t} \geq S_{\min,m,t}$$
$$S_{m,t} \leq S_{\max,m,t}$$
$$\sum_t S_{m,t} = E_{\text{tot},m}$$

C. Minimizing Load Variance Formulation (quadratic)

Subject to:

$$\underset{S}{\text{minimize}} \sum_{t=1}^{T} \left(\frac{1}{T} \left(\sum_{m=1}^{\text{nodes}} (S_{m,t} - \mu_D) \right)^2 \right)$$

$$S_{m,t} \geq S_{\min,m,t}$$
$$S_{m,t} \leq S_{\max,m,t}$$
$$\sum_t S_{m,t} = E_{\text{tot},m}$$

Problem Formulation

- Formulations give optimal charging profile of PHEVS during the time period T
- Linear and quadratic has advantages over minimal losses formulation that can be
Solved without having to compute a power flow or for solved in less number
f iteration.

Simulation Model

- Optimization function solved by Matlab using optimization package CVX
- Two test residential distribution systems:
  - Nine bus, radial, three-phase unbalanced primary distribution system (138kV-12.47kV); 6 load bus: 36 houses
  - Adjusted version, 18 bus system, 102 houses
  - Randomly assigned load profiles
- Monte Carlo Simulation with PHEVs randomly placed at different nodes at penetration level of 10%, 20%, 50%, and 100%
- PHEV load modeled as a constant real power; 10 kWh; 33 miles; charging infrastructure - 120 V/ 15 A wall outlet
- PHEVs plug fully discharged at 18:00h to 6:00h next day

Results and Discussion

Performance : For different penetration levels

Compare: three algorithms

Based on: Average losses, PHEV load profile and Run time of Monte Carlo simulation
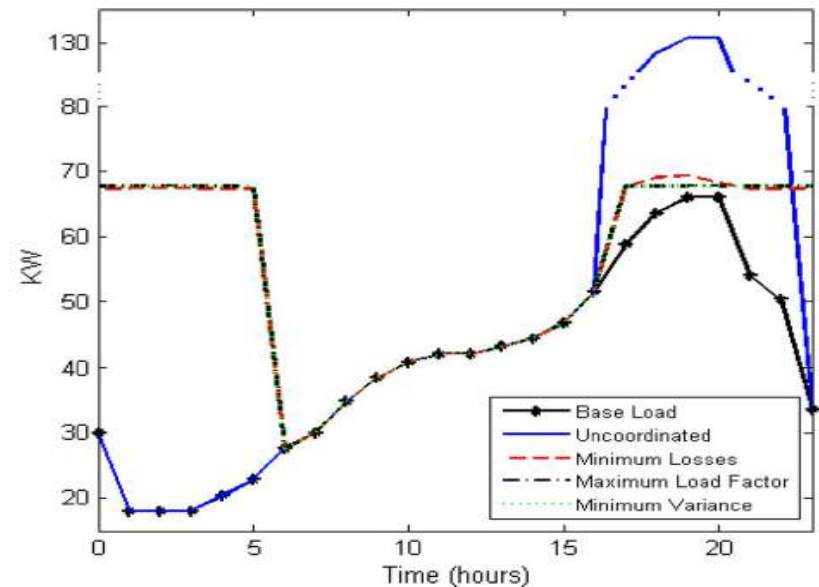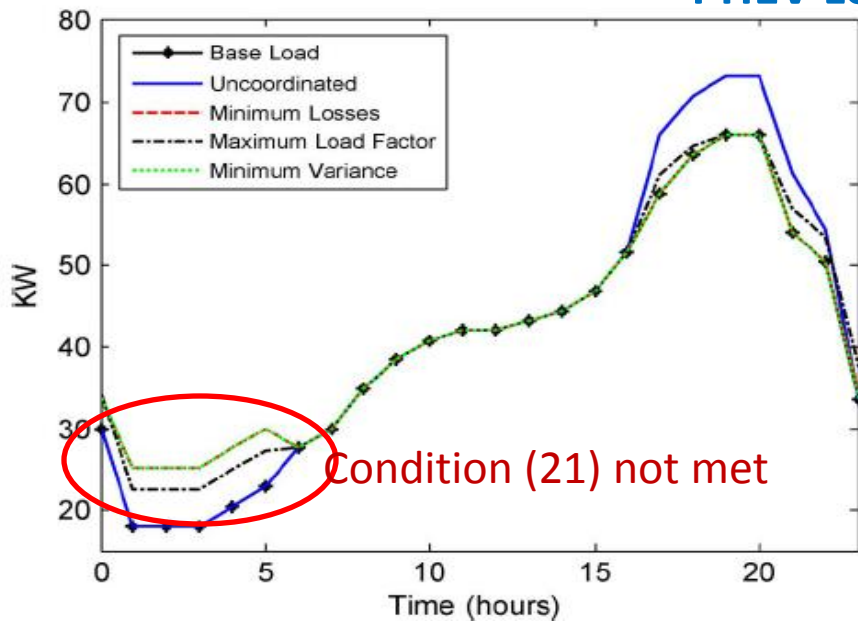
PHEV Load profile

Fig: Load profiles for the different charging algorithms at 10% (left) and 100% (right) PHEV penetration for the nine-bus system

- Un coordinated charging significantly adds peak loads
- Min. losses and Min. loss charging has almost same profile,
- Max. LF charing has diff. Load profile only when condition 21 is not met
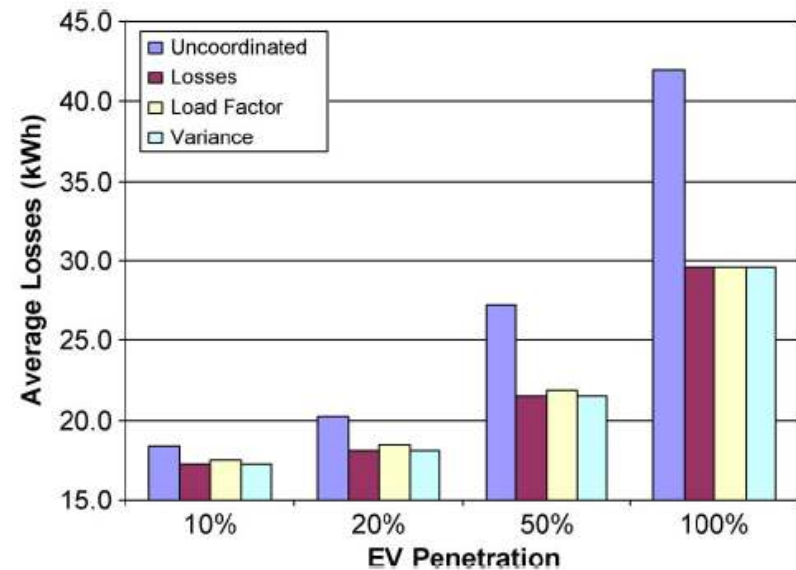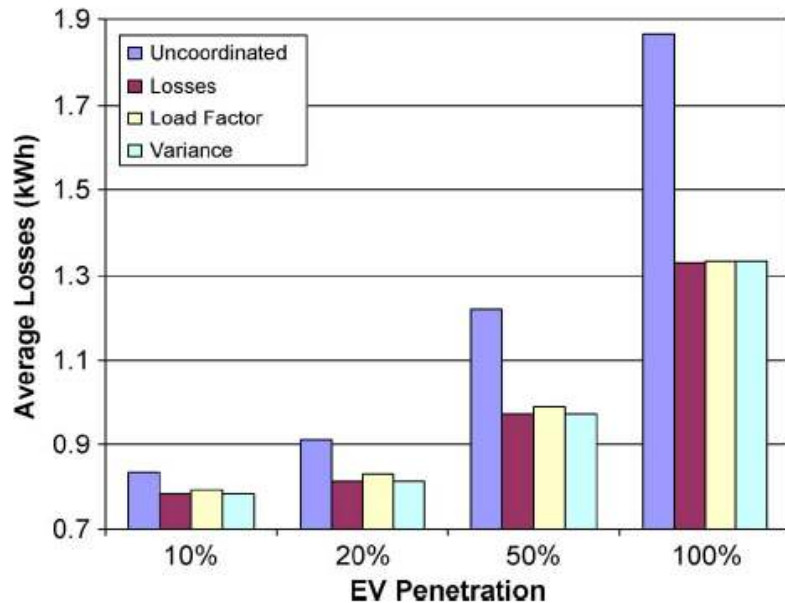
Result and Discussion
Losses

Fig: Total losses for each charging profile over a 24h period for the 9-bus(left) and 18-bus (right)system

- Uncoordinated charging is worst
- Min. Losses and Min. Load variance difference is less than 0.1%
- Max. Load Factor with other two charging difference is less than 2% (reduces with increase in PHEV penetration)
- System size and topology independent results

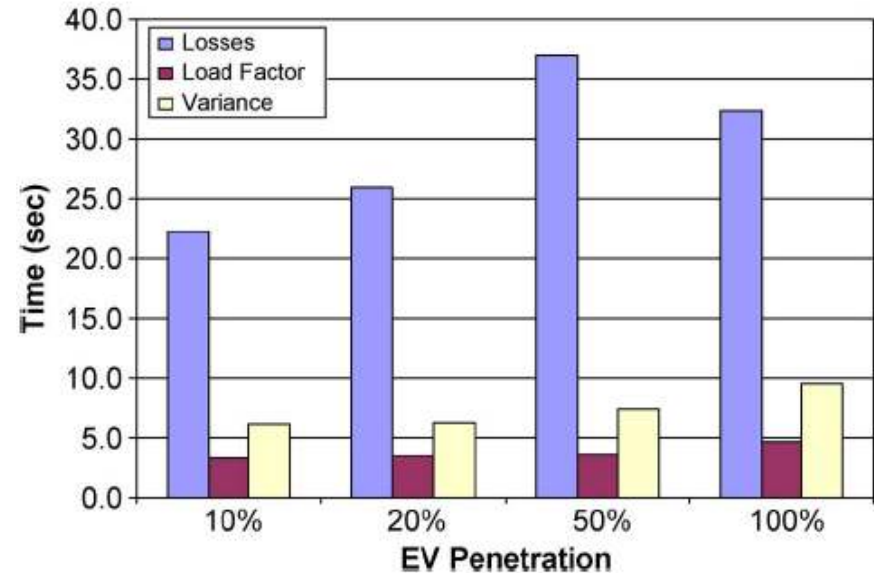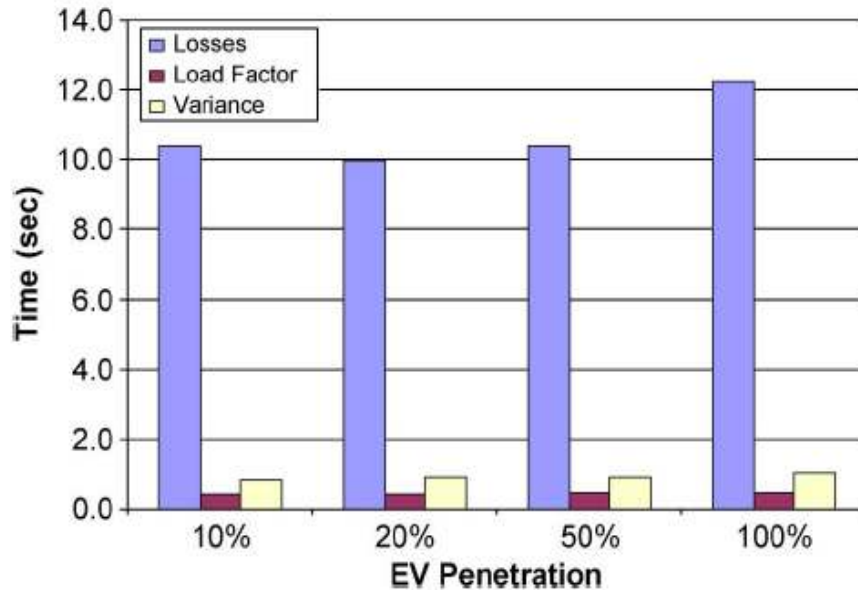# Results and Discussion
Run Time

Fig. Time required for each Monte Carlo run for 9 bus (left) and 18 bus (right) system

For a stable solution around 400 runs required.

For 9 (18) bus: Min Losses 20 (6) times and 10 (3) times slower than Max. LF and

Min. Load Variance resp.

Min. Losses uses line current as a decision variable while other two use demand at nodes only.

The difference function of ratio of no. of lines to no. of load points

•Faster : Max. LF and Slowest : Min. Losses

•Time required to minimize loss increases non-linearly with size and topology of system.

Conclusion

- Coordinated (controlled) charging plays vital role in reducing impact of PHEV charging

- Primary goal is to minimize loss but with less computation time (important for real time dispatch of PHEVs)

- Minimizing loss, Minimizing Load variation and Maximizing Load factor charging are fairly equivalent to each other.

- For a given daily load profile forecast both Minimizing losses and Minimizing load variance produces same results

- Maximizing Load factor produces same results but with at least half of computational time during the condition of unavoidable peak

- The formulated objective functions can be used as either linear or quadratic constraints to other optimization functions involving PHEVs that focuses on charging cost minimization or V2G profit maximization

Thank You !