SCHEDULING CHARGING OF ELECTRIC VEHICLES FOR OPTIMAL DISTRIBUTION SYSTEMS PLANNING AND OPERATION

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ABSTRACT

In the not so distant future, it is expected a large-scale integration of fleets of plug-in electric vehicles (PEVs) in the transport sector. Such large number of PEVs will increase the demand of electrical energy and as a consequence the losses in the electric distribution grid will increase. Equally there might be a need to reinforce the grid to be able to adequately supply the increased load. This paper presents a model to schedule the charging of PEVs while minimizing the grid losses. The model can also determine the maximum number of vehicles that can be handled by the grid without any need for reinforcement. The result shows that the losses can be reduced with up to 6% as compared to those of the uncontrolled charging and the number of vehicle that can be handled by the grid increases substantially.

NOMENCLATURE

PEV	Number (No.) of PEVs.
i	Bus index.
h	Hour index.
$P_{PEV\,i,h}$	Power determined by PEVs at bus *i* at hour *h*.
$\mathrm{P_{max}}_{i,h}$	Maximum possible power drawn from substation *i* at hour *h*.
CP	Charge power.
$\mathrm{PEV_{stop}}_h$	No. of vehicles finished their trip at hour *h*.
$P_{i,h}$	Power injected at bus *i* at hour *h*.
$\mathrm{P_{min}}_{i,h}$	Minimum power drawn from bus *i* at hour *h*, i.e. no vehicles connected.
$V_{i,h}$	Voltage magnitude at substation *i* at hour *h*.
$\mathrm{Y}_{i,j}$	Element of the network admittance matrix.
$\theta_{i,j}$	Angle associated with $\mathrm{Y}_{i,j}$.
$\delta_{i,h}$	Voltage angle at bus *i*, at hour *h*.
$\mathrm{G}_{i,j}$	Conductance of cable *(i,j)*.
$PEV_{charge\,i,h}$	No. of vehicle charging at bus *i* at hour *h*.
$\mathrm{PEV_{parked}}_{i,h}$	No. of vehicle, with SOC<100%, parked at bus *i* at hour *h*.
$\mathrm{P_{max}}_{cap}$	Maximum grid capacity.
$\mathrm{P_{max}}_{cap\,N-1}$	Maximum grid capacity considering reliability.
$\mathrm{P_{max}}_{load}$	Peak load in 2008.

INTRODUCTION

The impact on the electric grid due to charging Plug-in Electric Vehicles (PEVs) is highly dependent on when and at which power rating the charging takes place, as well as the capacity of the grid. With a massive penetration of PEVs the power consumption can increase to critical levels resulting in needs to reinforce the electric grid, [1]-[7],

One way to minimize the peak power consumption is to shift the charging to times when the consumption is low. Studies on countries such as Belgium [1], Canada [2], U.S.A. [4]-[5] and Portugal [6] show that by scheduling the PEVs' charging while enforcing grid constrains: the actual number of vehicles that can be integrated to the grid is larger compared to that when uncontrolled charging is allowed. Furthermore a coordinated PEVs charging schedule also reduces the system losses, resulting into a further incentive to the grid operator for managing the charging timings.

In Sweden there are currently only minor incentives for the customer to optimize the power consumption, [8]. However since most meters in Sweden have been replaced by newer models with added functionalities (e.g. remote reading capability and hourly measurements sampling among others); it is possible for the distribution system operator (DSO) to develop and implement incentives to reduce the customer's power consumption during the peak hours, [8]. Similarly the vehicles usage patterns (which varies from country to country) must be taken into account when proposing and implementing such incentives, [9].

This paper presents a scheduling model for PEVs in distribution systems from the DSO's perspective. Two different areas are investigated; one residential and one commercial. The number of road vehicles for each of the areas is obtained from the national travel survey, [10], and regional statistics [11-12]. The increased losses due to charging according to the optimal schedule are compared to the losses incurred if uncontrolled charging is permitted. The maximum number of PEVs that the network can integrate is also compared for both scenarios.

The outline of this paper is as follow; in the next section the input data and assumptions such as load profiles and maximum capacity and number of vehicles are presented. Section 3 describes the charging scenarios. Section 4 presents the optimization algorithm. Section 5 presents the results and discussions from the simulations and finally a section presenting the concluding remarks.

INPUT DATA AND ASSUMPTIONS

Two different areas in Gothenburg, one residential and one commercial, based on real data are selected. The residential area consists of three 10 kV feeders and 26 10/0.4 kV substations. This sector consists mostly of small houses with various heating alternatives. The commercial area consists of four 10 kV feeders, nine 10/0.4 kV substations and three 10 kV custom stations. In this area there are mainly office buildings and apartments. The grid is designed as a meshed grid but is under normal operation operated as a radial system.

Load Profiles without PEVs

The load profiles for a weekday with high demand in 2008 for both areas are presented in Figure 1. The residential area has one peak in the morning and one in the evening, (i.e. when families wake up and when they return home from work). In the commercial area the peak occurs in the middle of the day, i.e. when most people are at work. The peak load is also presented in Table I.

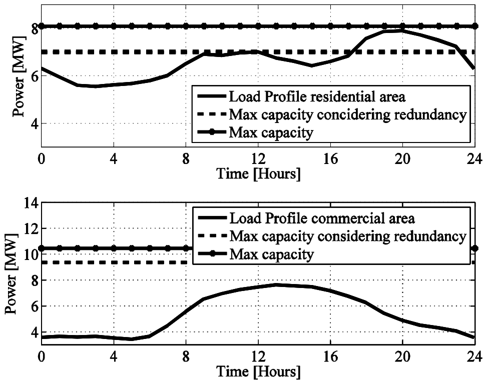

Figure 1 Load profile peak day

To assure the reliability of the electric grid, the grid operator in Gothenburg aims to maintain high level of supply (which tends to the N-1 reliability criterion). This means that the loss of any feeder would result into an acceptable minimum load curtailment which should be restored by topology changes in a short time. The capacity is limited either by the cables or by the transformers in the substation.

The maximum capacity in the system depends on the grid architecture e.g. the number of feeders and substations, the placement of the circuit breaker etc. The maximum power that can be drawn from the grid considering the reliability criterion is presented in Figure 1 and Table I.

Table I Maximum capacity and load

	Residential	*Commercial*
$P_{\text{max cap}}$ (MW)	8.10	10.45
$P_{\text{max cap N-1}}$ (MW)	7.04	9.37
$P_{\text{max, load}}$ (MW)	7.91	7.63

Vehicle assumptions

The number of vehicles in both areas is derived from the load, the number of customers and regional statistics for each area [11]-[12]. However, one must bear in mind that the PEVs are effectively a roaming electric load. That is, it must be considered that the vehicles are used for transportation and may be charged at different locations. To consider this feature, additional data, such as number of workplaces, employees, vehicle commuting share among others is modeled. In this paper only the work related journeys are considered; during the weekdays the majority of all journeys are work related. Similarly it is assumed that the vehicles are charged twice per day. The geographical distribution of workplaces in the different areas is also taken into account. In Table II the estimated number of vehicles commuting to/from respectively area is presented, the estimated numbers are including the differences in vehicle density and number of workplaces between the areas.

Table II Total number of commuting vehicles

		Residential		*Commercial*	
		Morning	*Afternoon*	*Morning*	*Afternoon*
People commuting:	to	471	2 766	2 146	528
	from	2 766	471	528	2 146
Share of journeys by vehicle:	to	29.1%*	39.4%**	29.1%*	22.7%**
	from	39.4%**	29.1%*	22.7%**	29.1%*
Vehicle commuting:	to	137	1 091	624	120
	from	1 091	137	120	624

*Only average statistical values are available for the city of Gothenburg.
**These values include the vehicle distribution by districts in the city of Gothenburg.

To determine when and for how long the vehicles will be charging, results from a national travel survey were used, [10]. From the travel survey it was derived that in average 29.1% of the work related journeys where conducted by cars, however, due to difference in vehicle density this varies between the districts. The start time for the journeys is presented in Figure 2.

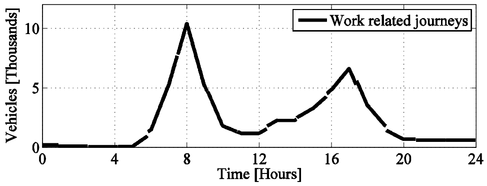

Figure 2 Start time for work related journeys

CHARGING SCENARIOS

The vehicles' charging is assumed to be performed from standard single- phase outlet of 230 V, 16 A. The charger is assumed to charge with a 0.95 power factor.

The average distance/day was 30 km and the average travel time was 39 minutes.

It is assumed a daily average driving distance of 30 km which is conducted in 39 minutes [10], an energy consumption of 0.2 kWh per km and a charging efficiency of 88% are considered [13]. The charging is performed in two charging periods of 1 hour, one at work and one at home.

The vehicle and work places are distributed according to the peak load for the substations, i.e. a highly loaded substation will take a larger number of vehicles than a substation with less power consumption, since it is assumed that the number of customers is proportional to the power consumption level at the substation.

In this study, two models for PEV charging are considered, one referred to as uncontrolled charging, which assumes that the charging starts immediately after that the vehicle is used, and the other one referred to as optimal schedule which minimize the total losses in the system by scheduling the charging in an optimal way.

Figure 3 shows the flow diagram of the process.

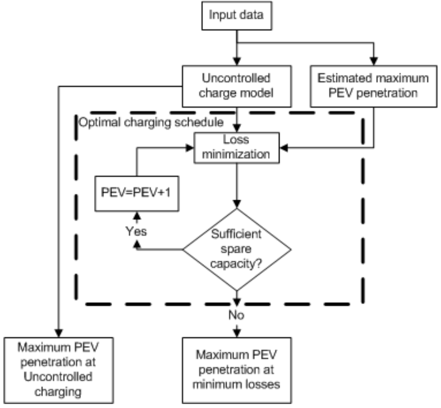

Figure 3 Flow chart illustrating the simulation process

Uncontrolled charging

The objective is to maximize the total number of vehicles:

$$PEV = \sum_{h=1}^{24}\left(\sum_{i=1}^{n}\frac{P_{PEV\,i,h}}{CP}\right) \quad (1)$$

Subject to the following constraints:

- PEV distribution between substations and hours:

$$P_{PEV\,i,h} = \mathrm{PEV_{stop}}_h \frac{\mathrm{P_{min}}_{i,h}}{\sum_{i=1}^{n}\mathrm{P_{min}}_{i,h}}\mathrm{CP} \quad (2)$$

- Power flow equations:

$$P_{i,h} - (\mathrm{P_{min}}_{i,h} + P_{PEV\,i,h}) =$$
$$\sum_{j=1}^{n}|Y_{i,j}||V_{i,h}||V_{j,h}|\cos(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}) \quad (3)$$

$$Q_{i,h} - \left(Q_{\min\,i,h} + Q_{PEV\,i,h}\right) =$$
$$-\sum_{j=1}^{n}|\mathrm{Y}_{i,j}||V_{i,h}||V_{j,h}|\sin(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}) \quad (4)$$

- Voltage limit at load buses:

$$0.90 \le |V_{i,h}| \le 1.10 \text{ p.u.} \quad (5)$$

- Power limit at load buses

$$\mathrm{P_{min}}_{i,h} \le P_{i,h} \le \mathrm{P_{max}}_{i,h} \quad (6)$$

$$\mathrm{Q_{min}}_{i,h} \le Q_{i,h} \le \mathrm{Q_{max}}_{i,h} \quad (7)$$

The losses are then calculated by Eq. 8 for the maximum penetration [14].

$$P_{Loss} =$$
$$\frac{1}{2}\sum_{h=1}^{24}\left(\sum_{j=1}^{n}\sum_{i=1}^{n}G_{i,j}\left(|V_{i,h}^2| + |V_{j,h}^2| - 2|V_{i,h}||V_{j,h}|\,cos(\delta_{j,h} - \delta_{i,h})\right)\right) \quad (8)$$

Optimal charging schedule

The objective of the optimal charging schedule is to minimize the losses in the grid for a given penetration level based on the ac- optimal power flow framework and to find the maximum penetration possible. The objective function in the model is given by Eq. 8, subject to Eq. 1, 3-7 and 9-11:

- PEV distribution between substations and hours:

$$\sum_{i=1}^{n}PEV_{charge\,i,h} \le \sum_{i=1}^{n}PEV_{parked\,i,h} \quad (9)$$

$$\sum_{(h=1)}^{24}PEV_{charge\,i,h} = \sum_{(h=1)}^{24}PEV_{stop\,h}\frac{\mathrm{P_{min}}_{i,h}}{\sum_{i=1}^{n}\mathrm{P_{min}}_{i,h}} \quad (10)$$

- PEV power balance:

$$P_{PEV\,i,h} = PEV_{charge\,i,h}\mathrm{CP} \quad (11)$$

The model is also taken into account that the PEVs must be charged before departure. The maximum penetration level can be found by iteratively increase the number of PEVs until a binding constrain occurs, according to Figure 3. To optimize the process, a starting point close to the maximum can be found by maximizing Eq. 1 subject to Eq. 3-7 and 9-11.

The two models are implemented using General Algebraic Modeling System (GAMS) and solved using MINOS solver [15].

RESULTS

Uncontrolled charging

As explained above the uncontrolled charging allows the charging to take place directly after the vehicle is connected to the power outlet (which in this cases is assumed to be as soon as the vehicle finishes a journey).

Based on the charging time, the drive pattern and the number of vehicles the charge profile can be obtained for both areas. The charge profile for 100% penetration of PEVs is presented in Figure 4 for the residential and commercial areas.

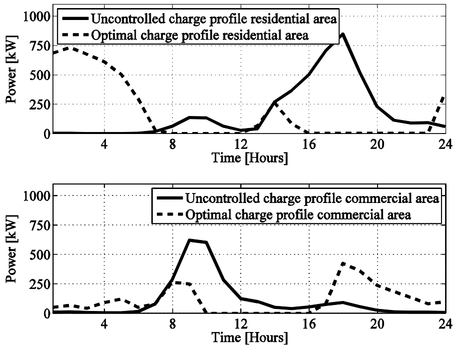

Figure 4 Uncontrolled and optimal charge profile

From the model the maximum the PEV penetration is found and is presented in Table III and Table IV. As expected, the maximum penetration level for the residential area, considering the N-1 criteria, is 0%, due to the high peak load in this area. The total loss for the residential 10 kV grid and for a 24 h period was found to be 2.67 MWh which equals 1.67% of the total energy consumed in the area during the peak day.

For the commercial area the maximum penetration level is 400%, i.e. there is a large spare capacity in the commercial area to accommodate four times the already existing number of vehicles assuming that these are PEVs. The total loss for the commercial 10 kV grid and for a 24h period was found to be 690 kWh which is equal to 0.53% of the total energy consumed in the area during the peak day. By introducing 100% PEVs the losses increase by 4.7% to 723 kWh which equal 0.55% of the total energy consumption in the area.

Table III Losses in the residential 10 kV grid

PEV penetration	*0%*	*100%*	*288%*
Uncontrolled charging [kWh]	2673	---	---
Optimal charging [kWh]	2673	2806	3089

Table IV Losses in the commercial 10 kV grid

PEV penetration	*0%*	*100%*	*400%*
Uncontrolled charging [kWh]	690.7	723.1	831.5
Optimal charging [kWh]	690.7	711.9	784.1

Optimal charging

By optimizing the charging according to the optimization model described above; the losses will decrease for a given penetration level and the grid will be able withstand a larger penetration level. The charge profile for a 100% penetration is presented in Figure 4. As seen the total peak charging power is reduced and/or shifted in time as compared to the uncontrolled scenario.

The maximum penetration level was increased for both the residential and commercial area. For the residential the maximum penetration was 288% compared to 0% by the uncontrolled charging. Since only unidirectional power flows have been considered, the reliability constrain is still violated during the peak hours, however the charging does not violate the system further. The losses for different penetration levels are presented in Table III. The grid in the commercial area can accommodate more than 5 times PEVs if the charging was controlled according to optimization model compared to the uncontrolled charging. The increase in losses was also lower than for the uncontrolled charging and is presented in Table IV.

CONCLUSIONS AND FUTHER WORK

This paper proposes an approach to estimate the maximum number of PEVs that can be integrated in a distribution network in a secure way, while maintaining security standards and network losses at its minimum.

The proposed methodology was tested into two 10 kV networks in Gothenburg, Sweden; one residential and one commercial area. The driving patterns are taken from surveys and the demand is in these areas are for typical week days. The results show that, on the one hand, by means of allowing uncontrolled PEVs charging, the number of PEVs that can be accommodated in the existing networks might be marginal; furthermore, this strategy might result into early grid reinforcement requirements. On the other hand, by employing coordinated scheduling algorithms, the number or PEVs that can be accommodated in a secure way is significant. Similarly, by using these algorithms network reinforcement requirements would also be deferred in time. Both Chalmers and Vattenfall are partners in the EU FP7 project G4V and an important share of the future work will be conducted within this project.

ACKNOLEGEMENTS

The authors would like to express their gratefulness to Göteborg Energi and E.ON for their support. They are also grateful to Göteborg Energi for facilitating data to perform this study.

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