Smart Charging – A Strategy for Charging EVs in Big Cities with Load Shifting and Control

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***Abstract*—The threat of climate change has made Sweden to start replacing conventional vehicles with electro-mobility on a large scale. A significant proportion of the vehicles in Swedish major cities can be expected to be electrified in the coming years. However, the electricity supply of Swedish major cities is strained for a number of hours during a year. With the trend towards higher penetration of electric vehicles (EVs), the charging pattern of EVs will pose a number of challenges to the cities' power supply system. The paper addresses this aspect and looks at strategies of how to deal with the challenges brought by increasing EV penetration rates in urban environments. The paper describes the possible charging scenarios studied and presents the strategies resulting from a vision project within the E-Mobility programme performed at Vattenfall R&D. Based on load demand analysis the paper concludes that uncontrolled charging of large numbers of EVs in big cities would stress the electricity network, and that the need of controlled charging is a key aspect in the strategy for smart charging of EVs in big cities. The details of the analysis and charging strategies are given in the paper.**

Keywords - charging strategy; e-mobility; load shifting; controlled charging; smart charging

I. Introduction

The overall goal of the Swedish transport sector is to lower the use of fossil fuels by 70% by 2030 compared to 2010. Climate change has motivated Sweden to start replacing conventional vehicles with electro-mobility on a large scale towards the goal. A significant proportion of the vehicles in Swedish major cities can be expected to be electrified in the coming years. Near 100% electrification of passenger cars by 2030 is a feasible option.

However, the electricity supply of Swedish major cities is strained for a number of hours during a year. For example, in the Stockholm region network constraint can arise during high loads of about total 100 hours distributed during a year. The network constraint issues may still persist, even after today's ongoing power boost and network enhancement. With significant penetration of electric vehicles (EVs), the charging pattern of the EVs will pose a number of challenges to the city's power supply system.

In order to deal with the challenges brought by increasing EV penetration rates in urban environments, a vision project was carried out within the E-Mobility programme at Vattenfall R&D, Stockholm. The project examined typical load profiles of residential consumers in Stockholm city, studied possible charging scenarios in the case of a fully electric transport system in the city by the year 2030, assessed the effect on grid power loading by simultaneous charging activities of large number of EVs without steered charging, and analyzed typical demand of city residential power consumers.

Based on the load demand analysis, the project designed a strategic controlled charging solution by shifting EV load from high load hours to nighttime and low load hours. It is seen that the need of controlled charging is a key aspect in the strategy for smart charging of EVs in big cities. In the following sections the load profile study is first presented, the analysis and charging strategies are then described, and at the last the conclusion and discussions are given.

II. Typical Load Profiles

It is not easy to achieve smart charging. Restrictions from power system and EV characteristics must be addressed. The former may involve limitations from transformers and power feeders, power supply, etc. The latter includes limits of batteries, driving habits, demands of charging by EV users, etc. When EVs are connected to the power system, the load profiles will be affected by the pattern of EV charging which include time of charging, energy need, charging rate and the travel behavior of the EV users.

In order to understand how load profiles would be affected by the charging pattern, the project started with study of real power consumption and load profiles of a typical Swedish residential apartment area consisting of about 90 households with 90 parking places. The hourly measurement of electrical energy consumption in a full year was examined.

Table I gives the overall aggregated power consumption in the residential area for each month. It is seen from the table that the power demands are different in different months and different seasons. The high power consumption occurred during winter season in Jan.–Feb., and Nov.–Dec. The electricity usage during 06:00–22:00 in weekdays is about 50% of the total consumption in yearly average. According to the statistics the maximal power load in the Swedish system 2017 occurred on a Monday morning in February.

Figure 1 shows the consumption of active power on the first Monday in Feb. and Figure 2 load curves for the whole first week in Feb. It can be observed that these load profiles are very similar. The load pattern over a day has similar shape representing the pattern of electricity usage of typical Swedish households.

TABLE I. OVERALL POWER CONSUMPTION

	Total Load (kWh)	**Percentage of Total Load, Weekdays 06:00-22:00**	**Percentage of Total Load, Other Times**	**Max. Load (kW)**	**Min. Load (kW)**
Jan.	36434.4	44.6%	55.4%	92.0	22.8
Feb.	31715.4	52.4%	47.6%	90.0	27.0
March	31914.0	46.7%	53.3%	81.6	0.0
April	29536.8	49.6%	50.4%	74.4	2.8
May	26962.8	47.7%	52.3%	71.4	19.8
June	23340.0	49.6%	50.4%	67.8	16.2
July	20277.0	47.8%	52.2%	52.8	15.0
Aug.	23208.6	53.2%	46.8%	70.2	15.6
Sep.	24803.4	52.5%	47.5%	70.2	18.0
Oct.	30916.8	48.7%	51.3%	83.4	21.0
Nov.	33075.6	53.2%	46.8%	94.8	26.4
Dec.	34960.2	50.0%	50.0%	85.8	26.4

The daily load profile in Figure 1 clearly shows two peak loads, one in the early morning around 7:00-8:00 and one during the evening at 18:00. There is less power consumption during the day and night.

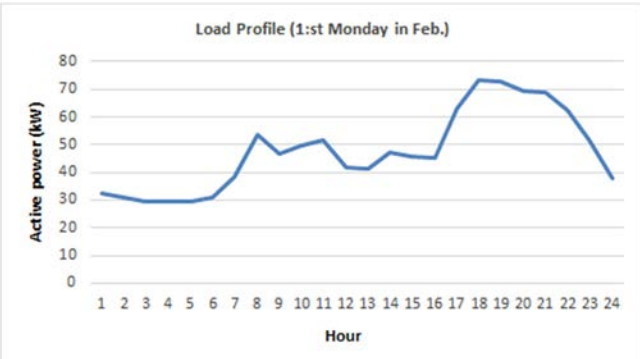

Figure 1. Daily load profile

III. SENARIO WITHOUT CHARGING CONTROLL

EVs belong to individuals who would not be willingly submitted to control or restriction when charging without good reasons or compensation. It is reasonable to assume that EV users would charge their vehicles in their own convenient way if there is no charging control.

This situation was explored in a scenario without charging control in order to see the impact on the load profile. The EV users were assumed to be completely free to connect and charge their vehicles when parking at home without any kind of charging control or restrictions.

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In order to estimate expected change of load profiles the driver behavior and charging needs were first analyzed. The scenario assumes that the EV charging is unidirectional and the power flows in the grid-to-vehicle direction only, and the EV charging starts directly when the EV is parked and connected to an charging outlet.

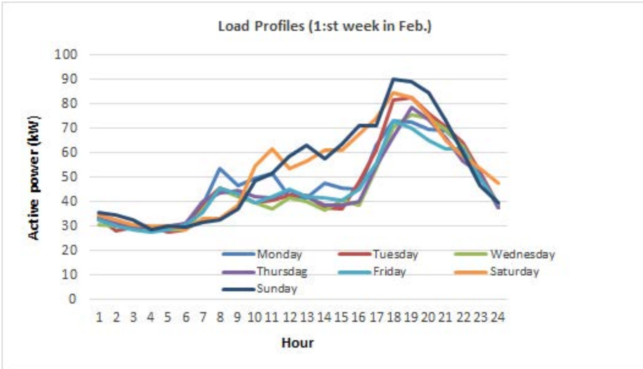

Figure 2. Load profiles during the first week in Feb.

Plug-in time refers to the time when an EV is plugged into an outlet and starts charging. It is a data input to the analysis. In reality the plug-in time has stochastic nature and is difficult to determine accurately. The scenario assumes that EVs are charged once a day, directly after their last trip. The arrival time at home of the last trip is defined as the start charging time. Considering that most people in Stockholm return to their homes around 17:30-18:30 during weekdays, the scenario assumes that the EV owners plug in their vehicles at 18:00 in the evening to obtain a fully charged battery for the next morning.

The charging rate of each EV and the number of EVs are two other parameters in determining the required power for charging the EVs. The charging power varies, but the most common power is 3-3.3 kW for home-charging and 6.6-22 kW for public station-charging. The number of EVs depends on the EV penetration level. This scenario assumes a charging rate for each EV to be 3 kW, and that each household uses one electric vehicle, and 50-90 EVs could be charged simultaneously.

Figure 3 illustrates the load situation in the scenario without charging control. As shown in the figure the uncontrolled charging can affect the existent load negatively with significant increase of peak load at 18:00-19:00.

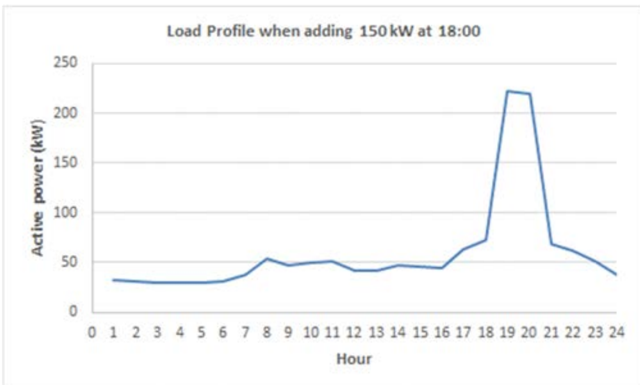

Figure 3. Influence of uncontrolled charging on the load profile

Without control the charging pattern with 50-90 EVs charging at 3 kW would add 150-270 kW to the peak load at 18:00. Figure 3 shows the case of simultaneous charging of 50 EVs, the absorbed peak power reaches 223 kW, an increase by 147% compared with the maximum subscribed power of 90 kW.

IV. CONTROL STRATEGY AND ASSUMPTION

Uncontrolled charging can lead to unacceptable peak load. To overcome this problem, we can increase the subscribed power or the power delivery capacity to meet the new peak demands for EV charging. However this would result in significantly increased cost.

On the other hand, we can use a smart charging solution, which coordinates the EV charging to avoid increase of maximum power subscription, and prevents grid overload.

Based on the analysis of the real load demand in a residential city area, the project looked at alternative approaches for EV charging and presented a simple and feasible charging strategy. The core of the strategy is shifting the charging events from high-load time to off-peak time, typically night hours, avoiding additional load peaks caused by the peak of EV charging load, e.g. avoiding overlap with the peak of evening non-EV base load. This approach is referred to as valley filling method [4].

This strategy offers the possibility to take advantage of low load level during nighttime and have no or minimal impact on the subscribed maximum power. The principles of the control strategy are:

- Manage the EV charging power as an off-peak load to the electrical system, and control the majority of charging to be moved to night hours during the off-peak period.
- Not increase the peak of non-EV base load, and retain the total power demand without exceeding the subscribed maximum power.
- EVs are charged on a daily basis at controlled rate between maximum and minimum charging power. The charging energy of each EV is controlled to a reasonable amount which meets the daily need for EV energy consumption.

The strategy is designed on the following assumptions:

- An EV battery can be charged at a rate between its maximum and minimum charging rate.
- The EV charging points are situated at residential city area where the arrivals and departures of EVs are relatively stable.
- Bidirectional power flow is not considered between grid and vehicles. Plug-in electric vehicle charging from grid (G2V) is considered only.

Based on the proposed control strategy and the assumptions made, two control scenarios are simulated to explore the impact of controlled EV charging on load demand.

V. CONTROLL SENARIO 1

The control scenario 1 simulates shifting EV charging load away from the evening load peak around 18:00 into low load hours from 22:00 to 06:00 when the network capacity is high. Figure 4 indicates the assuming energy for EV charging and valley hours.

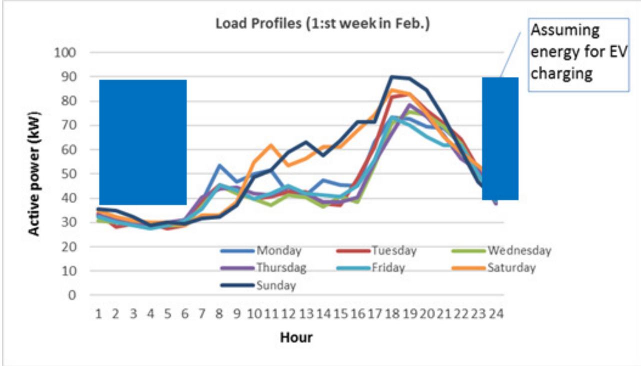

Figure 4. Assuming energy for EV charging of the control scenario 1

The driving distance on a daily basis directly reflects an EV's energy amount of daily electricity consumption. According to statistics the average daily driving distance by a resident in Stockholm is around 30-40 km. The scenario assumes that all the EVs (50 vehicles) have a daily driving distance equal to 40 km.

In order to determine an average required energy per day, an energy consumption of 0.15 kWh per kilometer is considered [2]. Table II shows the required average energy values of EV's used in the simulation.

TABLE II. AVERAGE DISTANCE AND REQUIRED ENERGY

Required energy (kWh/km)	Average driving distance (km/day)	Average daily required energy (kWh/day)
0.15	40	6.0

The charging rate is controlled at 0.75 kW, and during 8 valley hours each EV is provided with 6 kWh energy for the daily energy usage. Figure 5 shows the charging load curve together with the non-EV daily load profile.

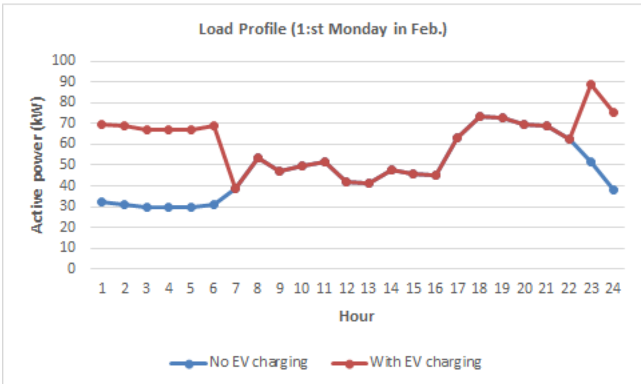

Figure 5. Charging load profile of the Control Scenario 1

Compared with the scenario without charging control it is clearly seen that while the charging is performed at night during valley hours, the total energy delivered to 50 vehicles for daily driving results in no increase of the maximum subscribed power (90 kW).

As expected the additional charging demand for 50 vehicles is now not coincidental with the evening base peak load around 18:00.

VI. CONTROL SCENRIO 2

The control scenario 2 simulates a coordinated charging situation considering higher charging demand, variable charging rate and different EV parking times. The idea is to also use low load hours during daytimes to deliver more charging energy and charge power during 06:00-15:00 for those vehicles that park a long time over a whole day. Figure 6 shows the assuming charging energy and charging durations.

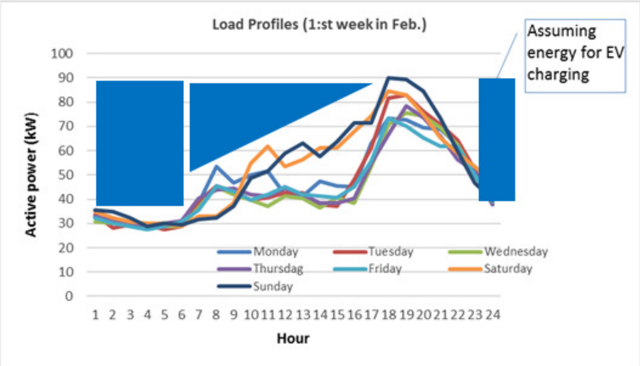

Figure 6. Assuming energy for EV charging of the control scenario 2

The scenario further assumes that:

- The charging demand increases to 540 kWh in order to fully charge 90 vehicles for daily energy usage.
- The vehicles are divided into two groups, one group for night charging and the other for daytime charging. 50 vehicles will depart in the morning and are included in group one, and 40 vehicles are connected and park over a day and will be charged during daytimes.
- When there is a high load capacity during 0:00-05:00, the charging rate is controlled to utilize this opportunity. The charging power is set to 1.0 kW during 0:00-05:00, and 0.75 kW after 05:00, and 0.75 kW during 22:00-24:00.

The result of the simulation is shown in Figure 7. The result indicates that it is possible to deliver more energy to EV charging without increase in the facility electricity subscription. As shown in Figure 7 the peak power of the charging load profile is maintained below 90 kW, and the daily charging demand for all 90 EVs are satisfied, thanks to a coordinated charging plan.

VII. CONCLUSIONS

This paper addresses an EV charging study based on load measurement in a residential area in Stockholm city. The study simulates both uncontrolled and controlled charging scenarios and demonstrates that with a high level of EV penetration it is possible to deliver charging energy to meet the daily driving need with no or minimal impact on the subscribed power.

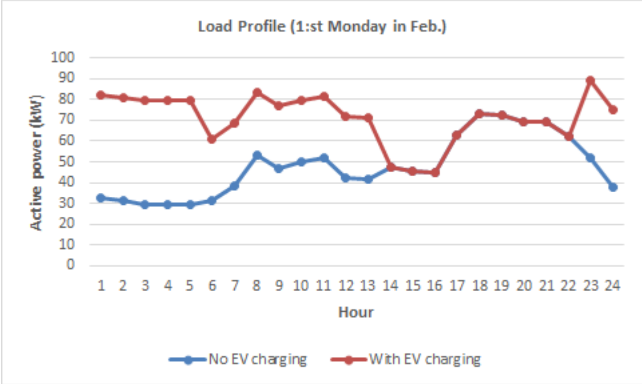

Figure 7. Charging load profile of the Control Scenario 2

The paper concludes that smart charging control is a key solution to the challenges brought by increasing numbers of electric vehicles in big cities. If no charging control is provided the charging load may coincide with the non-EV system peak load, thus being very likely to cause system overloads and having a negative impact on the electric network and customers. Managing the charging process can alleviate or avoid such negative effect. Moving EV charging load to low load hours, typically night valley hours, is a simple and feasible approach.

An aspect stressed by the paper is that the residential load profile has fundamental importance for the analysis of the control strategy. A schedule-controlling EV charging should be based on real-time load profiles and residential practical load variations.

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