INTELLIGENT CHARGING OF PLUG-IN VEHICLES

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ABSTRACT

Abstract: This paper discusses many fundamental and practical issues related to charging of plug-in vehicles. Aspects related to the electricity market and management of power systems are covered. When considering intelligent charging, it is important to do so from the user's point of view, take other new loads in the network and other novel strategic design and operation related paradigms carefully into account.

1 INTRODUCTION

Transportation has a very important function in today's society. Globally, the energy production of transportation systems is highly dependent on oil, and there are strong expectations that the price as well as the volatility of the price of oil will increase in the future. The transportation sector is also a significant consumer of energy and a significant source of greenhouse gases and other emissions (Davis et al. 2008). Today's climate and energy policies imply strongly towards diversification of transportation fuels improving energy efficiency and reducing emissions. The use of electrical energy in a broader manner by means of plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) offers a potential to partly fulfill these challenging requirements. Emission reductions and the amount of primary energy conservation due to plug-in vehicles are, however, highly dependent on the energy system.

There are some barriers related to high penetration of plug-in vehicles (PHEV and EV). The most important barrier is the battery technology. Batteries suitable for transportation appliances are very expensive at the moment, but the technology is continuously evolving and prices are expected to go down (Lache et al. 2010). Secondly, a lack of adequate charging infrastructure is a major barrier. This paper concentrates on this issue, and the investigations are often made from the perspectives of the Finnish power system and the Nordic electricity market.

The operation of charging infrastructure can be divided into three parts: charging point functions, electricity network operation and electricity markets operation. Charging points are needed to connect battery chargers of the vehicles to the electricity network. Charging points also form a part of the user interface between chargers and vehicle users and between vehicle users and the electricity system. Electricity network transfers the electrical energy to the battery pack. Vehicle chargers affect the power system. Small penetration level of plug-in vehicles does not necessarily have a great impact on the electricity network (except on the low voltage residential networks when high charging powers are used). However, great penetration level of the vehicles can have a remarkable impact on the distribution network at all voltage levels. Some results regarding medium voltage (MV) networks are presented in (Lassila et al. 2009) and (Peças Lopes et al. 2009), and results concerning distribution transformers are presented in (Roe et al. 2009). The functions of the electricity market specify the transactions between different parties of the power system and the electricity market.

To minimize charging infrastructure costs, to make electricity market operation more effective, and, to mitigate harmful impacts on the network (i.e. to avoid high cost grid investments), different kinds of "intelligent" or "smart" charging methods have been developed. In this paper, some charging concepts are presented and discussed. These concepts do not include vehicle-to-grid (V2G), vehicle-to-home (V2H) or reactive power related functions, but are restricted only to control of unidirectional flow of active power drawn by the chargers. The paper is organized as follows. In chapter 2, some general aspects of charging are discussed. Models regarding relations between charging infrastructure and electricity market are presented and discussed in chapter 3. In the fourth chapter, intelligent charging methods whose aim is to avoid harmful electricity network effects or even improve the operation of the network are presented and discussed. Some issues of chapters 3 and 4 are somewhat overlapping, but are however discussed separately. Finally, some conclusions are made.

2 GENERIC ASPECTS OF CHARGING

Vehicles with internal combustion engines (ICE) have a long history, and they represent very mature and developed technology. These conventional vehicles are also very user- friendly, because it takes only a few minutes to refuel them, and their range can be a thousand kilometers. In developed countries people are used to this high convenience, and this creates a user point of view challenge for the penetration of plug-in vehicles, because at the moment the charging of a large battery pack usually takes fairly long time in the case of low state of charge (SOC). However, average daily driving distances of a vehicle are typically a few dozens of kilometers (in Finland ca. 50 km/day/car (Ministry of Transport and Communications et al. 2006). Charging events satisfying the energy needed for the daily driving does not necessarily take a very long time, especially if charging can be carried out in several locations.

The charging time problem in the case of low SOC can be tackled in many ways. Fast charging concepts (maximum charging power of some dozens of kilowatts and above) could be used to charge the batteries rapidly, but this requires an expensive high power electricity network connection, and it sets high requirements for batteries (materials and design) and their heat management systems (Zaghib et al. 2009, Ceder&Kang 2009). Challenges of heat management systems can be illustrated with a simple example. If the internal resistance, which depends on the battery design and is partly a tradeoff between specific energy and specific power of the battery pack, of a 15 kWh $LiFePO_4$ battery pack is of the order of 0.05...0.25 Ω (Vuorilehto 2009), and if the operating voltage of the battery is 200 V, 50 kW charging power leads to a current of 250 A which leads to heat loss of 3...16 kW. Battery replacement systems are also possible, but they require a very high level of battery system standardization. When using PHEVs, this charging time problem is not as critical due to the existence of an ICE. However, the aim of the vehicle users would probably be that the portion of driven kilometers using electrical energy should be as large as possible.

3 OPERATION IN THE ELECTRICITY MARKETS

Electrical energy used by plug-in vehicles is bought from electricity markets. Liberalization of the Nordic electricity market has also brought liberalization of the electricity retail market. In this context, the domestic consumer can make a comparison between the products of different electricity retailers, and choose the best “electricity product” from the product selection. Consumers can make a decision based on different criteria, for example electricity price or the way of electricity production. New technology and new load (vehicle chargers) also bring possibilities for retailers and service providers to apply demand response to operate more efficiently in the electricity market.

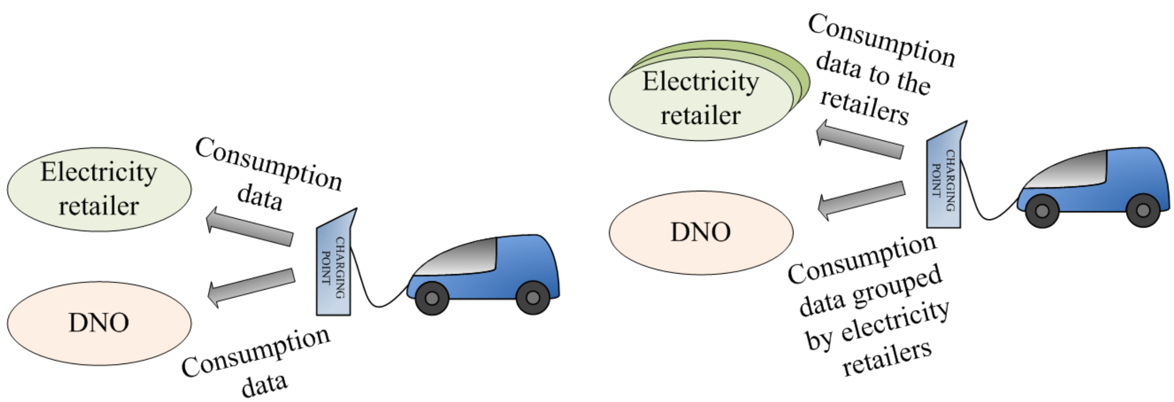
3.1 Market mechanisms

Plug-in vehicles are mobile electric loads and can be charged in many physical locations. If the goal is to maintain the freedom of choice of the electricity retailer and the electricity product simultaneously also out of domestic charging points, some intelligence is needed for the charging infrastructure. Next, a few market mechanisms are presented and discussed. Mechanisms are applied in such situations where the charging is carried out outside of the home (at home the vehicle acts as a normal domestic load) in public charging points. The differences between different mechanisms are found in the way that balance settlement is carried out and the way in which transactions (for example billing) between different parties are realized. These mechanisms can be applied to slow, “semi fast”, and fast charging concepts.

The simplest mechanism is a constant payment mechanism. In this option, when a vehicle is using a public charging point, the vehicle user pays a constant payment regardless of the amount of electrical energy taken from the grid. This energy payment can be included for example in a normal parking payment. In this approach, energy measurement equipment is not mandatory for the charging point, which lowers the infrastructure cost. In normal situations the amount of energy taken from the grid is fairly small. If the vehicle absorbs energy at average rate of 3 kW, the cost of the energy is today in Finnish electricity retail market of the order of 0.30 €/h. This market mechanism is very simple, and can be realized with low costs.

In fig. 1 a), a second market mechanism called the “fueling principle” is presented. This mechanism is also simple. When compared to the previous one, this mechanism includes payment in accordance to the amount of energy taken from the grid. The charging point acts as a regular network load, and payment for energy is made (by the owner of the charging point) to the electricity retailer (chosen by the owner of the charging point) and transfer fee is paid (by the owner of the charging point) to the distribution network operator (DNO). In this mechanism, the energy meter can be located in the charging point or in the vehicle. In the latter case, a meter reading can be carried out (for example wirelessly) by charging point using for example centralized “data server” located near the physical charging points. This kind of concept is discussed in (Rolink&Rehtanz 2009). The “fueling principle” model leads to greater infrastructure investments (compared to constant payment market mechanism) because of the need for vehicle-specific energy measurement.

In fig. 1 b) the "Multi retailer" mechanism is presented. The difference to the previous one is that now the vehicle user can choose the electricity retailer or a single product from a certain retailer's product selection. In this case, the user can have great freedom to choose for example the cheapest or a renewable energy based electrical energy. In this mechanism, it is also possible that the user could use the same retailer as in domestic consumption, and the price of the electricity used by the vehicle could be added to the customer's normal electricity bill. This kind of an operation requires an identification of the customer. However, the fee for energy transfer has to be paid to the local DNO for example by the owner of the charging point. Also, the consumption data grouped by retailers has to be given (by the owner of the charging point) to the DNO for the needs of balance settlement.



a) b)

Figure 1 a) "Fueling principle" market mechanism, b) "Multi retailer" market mechanism

In fig. 2, the "vehicle electricity" market mechanism is presented. In this concept, the vehicle has its own AMR (Automatic Meter Reading) energy meter. Wherever the vehicle is charging, the energy which is absorbed from the grid is measured in the vehicle and the billing is carried out by reading the meter remotely. In this model the energy transfer fee is again paid to the local DNO. This market model offers a great freedom for the vehicle user to use any electricity product available always when charging. However, this mechanism brings the problem of two meters. Vehicles have their own energy meters, and when they connect to a regular domestic or other similar charging spot the energy is measured also in the domestic meter. To avoid paying twice for the same energy, some kind of communication between meters would be needed. Also, in this mechanism, the fee for energy transfer should somehow be paid to the local DNOs, and the realization of this depends on the type of charging point. Also, for the needs of balance settlement, consumption data grouped by electricity retailers should be delivered to the DNO. These issues make "vehicle electricity" mechanism very complicated, and infrastructure needed for this is expensive and complex.

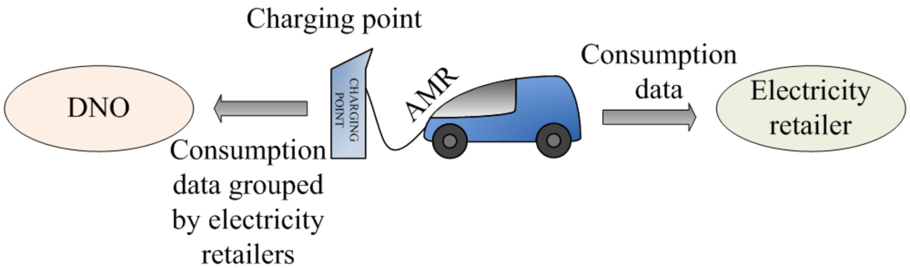


Figure 2 "Vehicle electricity" market mechanism

In addition to previous mechanisms, charging can also have some other forms. Different kinds of open communities are widely spread especially in the area of information and communication technology (ICT). "Open" charging infrastructure, as presented in (Biomeri 2009), is an interesting option. Private owners (members of the "open charging" community) of domestic charging points could offer their charging points for the use of the other members of the community. In exchange these owners could use charging points of the other members of the community. In this concept, the users of the open charging points may or may not pay (to the owner of the open charging point) for the electricity which they use. This kind of operation has some similarities with some communities, for example the FON (FON 2009), whose members share their wireless internet connections with each other. Open charging is however a concept which includes many practical and social challenges.

Charging opportunities in a row house, an apartment building or a workplace environment incorporate some special aspects. In Finland these types of places often have sockets available for preheating car engines in winter times, and these sockets can be also used for charging purposes. However, it is common that the users of these sockets do not pay for the electricity that they use, but are paying a small yearly or monthly constant payment for the right to use the sockets.

3.2 Plug-in vehicles as demand response resource

Plug-in vehicle fleet is a new load which could be used as a resource of demand response (DR). DR can be defined as "changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time", and different DR concepts can be divided into three types (Albadi & El-Saadany 2008). In the first concept, electricity users reduce their electricity consumption during high prices without changing their consumption habits during other periods. This concept includes a temporary loss of comfort and may include a decrease in total energy consumption. In the second concept, users shift their electricity consumption from a period of high price to a period of lower price. This operation can include a loss of comfort. Third concept is related to such customers who have onsite distributed generation. This case includes a coordination of load and local generation.

These concepts can be applied to charging of plug-in vehicles. In the case of plug-in vehicles the first DR concept implies that batteries are not charged to a full state. Thus, this approach is not perhaps suitable for vehicle charging, because people usually want to charge the battery to a full charge. The second DR concept is, however, suitable for vehicle charging. Charging could be shifted to a time of lower electricity price, if the vehicle user allows this kind of a time shift. One approach related to this is that vehicle users could set boundary conditions for the intelligent charging system, which could operate freely within these limits. The user can set for example a time deadline (for example 7:00 in the morning) by which the charging process is to be finished, and then the charging system could construct a plan for the charging process. The driving needs of people can, however, change suddenly, and in some cases it is necessary to charge the battery immediately or as soon as possible. Different ways to realize time dependent prices are presented in (Albadi & El-Saadany 2008). The third DR concept makes many sophisticated control methods possible when the customer has onsite generation. The use of generation can be used to substitute the lowering of the load level of the customers.

Demand response can have different kinds of goals, and the possibilities of DR are dependent on the structure and policies of the electricity market. However, the energy needs of a vehicle are not very large. If the electricity consumption of a PHEV is of the order of 0.2 kWh/km, if the yearly mileage is 18000 km (average value in Finland) and if 70% of the kilometers are driven using electrical energy, the energy needs of the vehicle is about 2500 kWh/a. In this sense, vehicles do not have very large potential to be used as DR resource. The potential is, however, dependent on the volatility of the price of electricity.

4 MANAGEMENT OF ELECTRIC NETWORKS

As mentioned previously, charging has impacts on the electricity network, and the extent of the impacts depends on the penetration level of plug-in vehicles. To avoid harmful effects or even to improve the operation of a power system, intelligent charging concepts have been developed.
Different methods have different goals, different levels of complexity and different investment costs. One goal of these methods is to avoid overloading network components. Another task can be an increase in the expected life of power system components, especially distribution transformers. Increase of loading can cause remarkable loss-of-life of distribution transformers even without overloading (Roe et al. 2009).

Intelligent charging methods can be divided in two groups: methods which need and methods which do not need a communication system to realize control actions. The latter type can, however, include a communication system to receive (from utility or a service company) setting values and parameters for their local operation. Methods which do not need a communication system for control are simple when it comes to their operation and realization. Methods based on communication systems make more sophisticated control operations possible. However, these methods are more complex and require greater investments on the system. Next, different load control methods are presented and discussed.

4.1 Methods based on local control

Control based on time

Charging control based on time is often presented in literature. In this concept, the charging is shifted to night time or to some other time of low loading level of the network. In addition to time shift of the whole charging process, control of charging power also is an option to realize this type of control. In this case charging process is modified and the power drawn by the charger is controlled as a function of time to achieve a desired load profile. The timing of different chargers can be different so that simultaneous start-up is avoided.

Time control, although based on local information, does not have to be static and rigid. The method can be dynamic and flexible in many ways. One way is to adjust the timing process in accordance with the SOC of the battery pack. In this approach, vehicles are prioritized to for example charge the emptiest batteries first. Setting boundary conditions for the charger (as discussed in chapter 3.2) could also be applied together with time based control.

Coordination of local loads

Customer electricity grid connections have a limited power capacity. If “semi fast” (three-phase) charging is used with a regular domestic connection, the maximum current capacity can be exceeded. The capacity of the network connection can be enhanced by enlarging the rating of the main fuses, but if this is applied broadly, it can lead to extra network enforcement investments and hence to an increase in transfer tariffs.

In Finland, electric space heaters, electric sauna stoves, which are very common in Finland (43 % of households had an electric sauna stove in 2006, (Adato Energia 2008) and boilers are often coordinated with each other to manage the peak power. When for example a sauna stove is switched on, space heaters are automatically switched off. This kind of an alternating system could be extended and applied to the charging of the vehicle. Operation of such a system could be as follows. When semi fast vehicle charging is switched on, heating is switched off, and if a sauna stove is switched on, the charger is also switched off. Some other load prioritization could also be used, and in addition to the load types mentioned here also other types of loads could be applied. Also, it is possible to restrict the charging power at some periods instead of off-switching.

Another way to restrict peak power is to share the capacity of the network connection for different loads in a pulse-like manner. Power could be delivered to each of the three loads in pulses, whose lengths can be adjusted with different criteria. In this approach, energy is delivered to each load one after the other, and the energy needs of every load could be met to some extent.
In these methods, it is important that indoor temperature does not decrease to a level too low when the heaters are switched off. This might happen in some circumstances during cold weather. Coordination of local loads could be further enhanced by incorporating local temperature measurements in the control method to ensure proper temperatures in the sauna and in the rooms.

Dependency on locally measured frequency or voltage level

Charging can be made dependent on locally measured grid frequency. This concept is investigated in more detail in (Rautiainen et al. 2009). Frequency dependent battery charging can be used to enhance a power system’s frequency regulation capacity (which operates in normal grid conditions), to enhance its disturbance reserves (which operate in abnormal grid conditions) or to enhance both of these. Control based on local measurements is an effective way to utilize large number of distributed resources which have to react to frequency disturbances in a very dynamic manner. Also, severe frequency disturbances occur fairly rarely, and the harm caused by a control method like this to the vehicle user can be very small as a whole, but the importance to the power system can be remarkable.

It is also possible to control the active power of the charger in accordance of locally measured voltage. This, however, needs more investigation.

Mitigation of asymmetric loading

Asymmetric loading of different phases in a distribution network is a non-desired phenomenon. It is most common in low voltage (LV) networks, because at higher voltage levels loads of different phases balance well statistically due to a large number of individual network customers. However, if some large one-phase loads are present, asymmetric loading can exist also at networks with higher voltage levels. Using appropriate converter technology in a battery charger, it is possible to adjust the phase specific loading of a three-phase charger to participate in the mitigation of the asymmetry. This could be done based on locally measured voltages of different phases. Chargers would adjust their phase specific loads to mitigate negative sequence component of the voltages. However, the impact of this kind of a function to power system protection equipment should be carefully investigated.

In addition to asymmetric power mitigation, chargers could also be used to improve some other power quality related quantities of a network such as flicker and harmonics. These things are, however, out of the scope of this paper.

4.2 Control methods based on communication

Methods based on communication are often presented in literature. In this concept chargers interact actively with an information system managed by a network company or a service provider. The information system can be for example an extension of a distribution management system (DMS). The system can utilize state estimation of the network using network calculations (data from network information system, NIS) and measurements (brought by SCADA and perhaps by AMR systems). Based on this information, the system can make decisions and give information or operation instructions to the chargers. Control based on communication has not to be applied whole network wide, but can also be applied to a part of the system such as a LV network and the corresponding distribution transformer.

In principle, the possibilities of these kinds of systems are very wide. Monitoring the state of the power system and the loading level of different parts and components of the network is possible. Using this information it is possible to operate a power system efficiently and apply different kinds of optimization algorithms.

Control actions and an optimization can have different goals. Goals can be minimizing of losses, minimizing peak powers in a network or in a part of it, maximizing plug-in vehicle penetration without new grid investments etc. Charging can be shifted from a time period of high or peak load to a time period of lower loading level of network (or part of a network) (Schneider et al. 2008; Lassila et al. 2009). In (Lassila et al. 2009) a peak power increase of 45% in a 20 kV feeder located in densely populated area and a 150 % peak power increase in a 20 kV rural area feeder could be avoided, if optimized charging method was applied. In (Peças Lopes et al. 2009) the maximum amount of vehicles to be charged is determined using an optimization algorithm. In (Roe et al. 2009) coordination between distribution transformers and chargers is proposed. (Østergaard et al. 2009) present starting and stopping of charging according to the availability of wind energy in the grid. It is also possible to use a vehicle fleet with large number of vehicles as a manually activated disturbance reserve which could be used to adjust balance between power production and consumption of a power system.

5 CONCLUSIONS AND DISCUSSION

Cost effective but still flexible and dynamic charging infrastructure is often a target of the plug-in vehicle infrastructure development. In this paper opportunities and challenges of plug-in vehicle fleet operation in the electricity market and power system environments were discussed from this point of view.

In addition to cost effectiveness, user-friendliness is an indispensible feature of the plug-in vehicle system. Many of the intelligent charging methods presented in this article set some kind of restrictions for the user of the vehicle. It can be said that many of these methods can be intelligent from a network company's or an electricity retailer's perspective, but not necessarily from a vehicle user's perspective.

It is therefore very important that vehicle users have a reasonable economic incentive to apply different intelligent charging methods. Creating services with such incentives is not necessarily easy in practice. Concepts of dynamic pricing (including dual tariff policy) of electrical energy (as discussed in chapter 3.2) and electricity transfer are presented often as incentives. The energy needs of a vehicle are not, however, very large. When considering today's electricity price volatility in Nordic markets the benefits provided by dynamic pricing of energy to the customers may be too small. Markets are changing and the Nordic system is integrating with the other European systems, and this will probably reduce the volatility of the prices. Different kinds of dynamic transfer tariffs could also be developed. One option is to apply power based transfer tariff covering all electricity consumption of domestic consumers. Technically this could be realized by intelligent energy meters. Another way to realize a dynamic transfer tariff is to change the tariff via communication in accordance of the free capacity of the network.

An alternative approach for avoiding harmful impacts to an electricity network is to reinforce the network so that charging becomes freer. The cost of this kind of an approach can, however, be large.

Although plug-in vehicles are discussed in this paper, it is very important to remember that plug-in vehicles are only one of the new issues affecting the loading of the networks in the future. In Finnish environment other new loads are for example heat pumps as their amount increases all the time. Also, an increase in local and domestic energy production is expected in the future. This can have a major impact of the load levels supplied by the distribution grid. Thus one should always consider the development of the load in the network as a whole.

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