On the Optimization of the Load of Electric Vehicles

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Abstract: E-Mobility provides a wide potential for diversification of traffic sectors primary energy source. Until now petrol could be seen as the dominating one. The rollout of battery electric vehicles - plug-in-hybrids included - can be supplied by wind, solar, water, and coal and nuclear as the primary energy source. Mobility of tomorrow could be fully made in Germany. Obviously the rollout is strictly connected to the issue of grid capability to the additional electric load. First investigations show a concentration of charging in the noon and evening hours, which is coincident with common grid load. As a matter of fact there will be an overload on distribution grid devices, especially on low voltages cables, transformers and mid voltage cables. The rate of overload is hardly connected to the amount of supplied electric vehicles as well as to grid topology and galvanic distance between charge points. The following work deals in modelling and optimization of the expected electric load “EV”.

Keywords: Electric Vehicles, Centralised Control, Load Regulation, Load Modelling, Optimization

1. INTRODUCTION

Due to political and ecologic demands, technological improvements and the need for diversification of traffic sector’s primary energy source, there is an increasing interest in electric vehicles (EV) to replace vehicles with combustion engine. According to projections of Germany’s National Development Plan E-Mobility or the International Energy Agencys Technology Roadmap, the number of EV’s and plug-in hybrids will increase rapidly, and until 2020, there will be up to 1.5 million EV’s and 1 million PHEV’s in Germany. It is expected that worldwide 2020 the sales of PHEV’s reaches 4.7 million and of EV’s 2.5 million (Diefenbach 2010; FDR 2009; IEA 2009). Due to the same charging technology and expected same electric energy needs of EV’s and PHEV’s in this paper, both concepts are similar from the power systems point of view, so in this paper, PHEV’s will be also referred to as EV’s.

1.1 State of Art - Charging of Electric Vehicles

The impact of dumb charging depends on charging infrastructures and/or fundamental concepts. Actually two main concepts are in discussion:
- Change batteries in a specific infrastructure (Better Place 2009),
- Charge the battery at dedicated public or private charge points (Rehtanz, 2009; Bauer 2010; Greenlots 2009; Coulomb 2009).

Both concepts are in development and used for several field tests of electric vehicles. The evolving standards SAEJ1772-2009 and IEC62196-2010 divide these charging methods into three categories, listed in Table I. (Bauer 2010; IEC62196 2009; SAEJ1772 2009). Both standards allow dumb and intelligent charging utilizing Power Line Communication between EV and charge point. Table 1 shows three different type of charging modes which are defined ISO 61851 (Rehtanz 2009), see also Bauer 2010.

<table>
<thead>
<tr>
<th>Type</th>
<th>kVA</th>
<th>Charging Time</th>
<th>Charging Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow/Normal</td>
<td>up to 3.6</td>
<td>6h</td>
<td>AC 1ph, 230V up to 16 A</td>
</tr>
<tr>
<td>Medium/Fast</td>
<td>11-20</td>
<td>1 – 3h</td>
<td>AC 3ph, 230V up to 32 A</td>
</tr>
<tr>
<td>Fast</td>
<td>&gt;=20</td>
<td>&lt; 1h</td>
<td>DC off-board charging</td>
</tr>
</tbody>
</table>

1.2 Dumb Charging versus Smart Charging

Dumb charging of EV’s means an immediate start of charging the battery after the plug-in event. This can result in additional peak loads with impact to distribution grids and the energy demand (Agsten 2010; Bauer 2010; Diefenbach 2010).

Future EV’s will be able to communicate with the charge spot to optimize their charging process. For this purposes the state of the art technique is utilizing Power Line Communication (PLC) and exchange information based on smart charging protocols (Daimler 2010, Diefenbach 2010), see Fig. 1. As long as PLC is available on both sides, the charging process can be managed utilizing the smart charging approach, see Fig. 2 as basic example. The term smart charge is a process in which information is exchanged between cars and the charging point.

Fig. 1. Smart charging technology (Daimler 2010)

First of all a technical authorization based on the approach in SAEJ1772 and IEC62196 determines the maximum of power, which is exchangeable between the charging point and EV. Second, the charging infrastructure provides a cost
function and a maximum power function over the optimization horizon between the plug-in and the expected plug-off time, which has to be defined by the customer for every charging event just-in-time.

![Fig. 2. Simplified smart charging approach](image)

The car optimizes its charging shape with respect to the costs function and returns the shape to the charge point. This information is used for cost recalculation and maximum power functions with respect to the power grid’s special needs for further charging events.

### 2. EV FLEET LOAD MODELLING

#### 2.1 Data basis of charging events

In July 2009 fifty electric vehicles were deployed to end customers in Berlin (Mini-E 2009; Agsten 2009). The author’s contribution is the charging process management at home for maximizing regenerative energy consumption of the fleet. The scientific focus lies on the customer’s behaviour and how it influences load shapes for a group of cars to answer four basic questions:

1. Plug-in and plug-off time?
2. How many cars are plugged in every day?
3. How much energy is consumed at every charging event?
4. Is it possible to modify the load?

The system architecture is depicted in Fig. 3. It has been designed for managing the charging process and features enhanced communication capabilities for observation. All cars charge one-phase with 7.3 kW, which leads to a (load?) current of 32 A. The charging point at the end customer’s home has a GPRS based communication functionality via TCP/IP, IEC60870-5-104 protocol. The current flow is activated only when the Demand Side Management System sends a control signal. The user can choose a defined plug-off time by utilizing a web portal.

![Fig. 3. Test bed E-Mobility (Schlegel 2009, Agsten 2010)](image)

Due to a lack of forecast ability of the amount of energy usage of individual charging events as well as the fleet’s daily energy amount, the only way to optimize the charging process was to shift it to load valleys at night or avoid charging between 11 and 13 o’clock in order to reduce additionally noon peak load. On average every vehicle is charged every three days and has a demand of approximately 5.6 kWh.

The field test originated a profound database with more than 7000 charging events, based on which a load model for EV’s can be derived. The model can be utilized to investigate the impact of EV’s on power networks assuming a broad rollout with domestic charging.

#### 2.2 EV calculation model

For calculating time series of EV’s fleet load every individual charging process needs to be recalculated due to the original measured time series of the test bed which are influenced by the demand side management system. Every charging event is characterized by a dataset of four elements: plug-in, plug-off time, energy consumption and maximum charging power, see the equations (2.1) and (2.2). The charging power \( p(kT) \) over time is \( p(kT) \) inside the interval \([T_{\text{plugin}}, T_{\text{plugoff}}]\). The fleet load \( \hat{p}_{\text{flees}}(kT) \) is the sum over all charging events.

\[
\hat{p}(kT) = \begin{cases} 
  p(kT) & T_{\text{plugin}} \leq kT \leq T_{\text{plugoff}} \\
  0 & \text{else}
\end{cases} 
\]  

(2.1)

\[
\hat{p}_{\text{flees}}(kT) = \sum_{i=1}^{N} \hat{p}_i(kT) 
\]  

(2.2)

If no dumb charging is used \( \hat{p}(kT) \) equals \( p(kT) \).

To find out the optimization potential the smart charging process has to be modelled. The goal of smart charging is to minimize charging costs with respect to the maximum
available power at a charging point. This problem can be described as follows ($\vec{\phi}$ - vector of charging power, $\vec{c}$ - vector of costs, $\vec{mp}$ - vector of maximum power of the charging point and EV, each vector element represents one time step, $e$ represents the energy demand):

$$\min \{ f(\vec{c}, \vec{mp}, e) \}$$

(2.3)

The problem can be solved by applying a short sorting algorithm. The cost function, which is sorted in ascending order, indicates a priority list of time steps to charge. The energy demand will be spread up regarding the priority list by charging with the maximum available power at every time step, see algorithm in Fig. 4.

An example (result) of an individual charging process is shown in Fig. 5. The EV is plugged in at time step 1 and available until time step 26. To fill up the vehicle completely, 15 kWh have to be delivered in this time at a maximum of 7.2 kW charging power. The technical handshake limits the maximum power over the whole time to 7.2 kW (dotted line). That is the power one EV can charge due to its own technical limits. The dark grey curve in the first plot represents the maximum near to time step 5 until 8 and between time steps 15 and 16. The light grey curve represents the costs development over time. In this special case it is better to charge at the end near to the plug-off event at time step 26.

![Fig. 5. Example of an optimization result](image)

As long as future EV’s are consequently charged with respect to the physical limits of the infrastructure and cost function this model is valid since it determines the global minimum of the objective function.

3. POTENTIAL OF SMART CHARGING

Most of the EV’s charge in a very short duration of time compared to the time span between plug-in and plug-off, see Fig. 6 as an example day from the test bed. Inside the dark grey bars the light grey bars mean that a single EV is charging. There are not many charging events which have a short duration between plug-in and plug-off. Which means - if a smart charging infrastructure for home charging exists - the most events can be shifted or optimized towards the above described approach?

![Fig. 6. Sample day of the field test](image)

3.1 Fleet load shape with dumb charging

For a numerical analysis, a comprehensive view on a distribution grid is chosen. This investigation focuses on the accumulated time series of the load at the step-up transformer and how it can be modified. The grid supplies about 25,000 private households which have a yearly consumption of 3000
kWh. The chosen network size is typical for small size cities as well as suburban areas of large cities. It is assumed that 30% of all households use an EV with home charging which has the same characteristics like the EV in the field test which was described above. The power grid itself has been modelled as a single busbar.

This model is acceptable to show how a large amount of EV’s affect the systems load which is supplied by the High Voltage (HV)/Mid Voltage (MV) transformer from the HV power grid.

Fig. 7. Simple distribution grid model for global analysis

In the numerical analysis, 15,000 charging events are used (1 week simulation), which equals twice the times series that was extracted from the field test. All EVs are being charged immediately, if they are plugged in. As shown in Fig. 8 and Fig. 9 three charging modes are applied. Three load curves are shown – each one stands for 3.6 kW (slow), 11 kW (medium) and 20 kW (fast) EV charging.

Fig. 8. Fleet load shape for 30% market penetration

The calculation shows, the faster the charging process or higher the charging power is, the higher the peak load will be. This happens because many charging events start at the same time. The systems load without EV’s has a maximum of ~18 MW, but with EVs it increases up to ~22 MW if a fast charging infrastructure is used. If the additional peak load would be damped by utilizing smart charging, then a load management system has to be installed at the HV/MV transformer which communicates with each home charge point, see Fig. 10. The results are similar to the numerical forecasts of Schlegel (2009) and Rehtanz (2010).

Fig. 9. Global load shape for 30% market participation

3.2 Example 1 - Application of Smart Charging at home to avoid peak load

For avoiding or minimizing the effective peak loads, the management system needs a forecast of the uncontrolled load. This load corresponds to the H0 shape - a standard load shape for private households (see Fig. 9.). The cost function for avoiding the peak loads is very simple (it uses the forecasted uncontrolled load (H0) and the EVs load) as follows:

\[ \text{cost}(kT) = H0(kT) + EV(kT) \]  

(3.1)

The basic sequence for each charging event is shown in Fig. 11. Between the load management system and the charge points, the EV’s cost function and load curve is exchanged after local optimization. The information about the EV’s load curve is used to update the cost function for the next charging event, which is similar to eq. 3.1.

The smart charging process does not seem to be predictable, since all individual charging events are user driven. Without additional ex-ante information directly from the user, no significant values can be derived to calculate a forecast function. On the other hand, the daily amount of energy for all cars could be predicted if the fleet size is large, but it is not useful to predict daily load curves or charging events. Due to the forecast problem of the smart charging process, the closed loop control design has to fix the special needs of managed charging.
Charging Spot
Load Management System
Plug-In
Plug-In Event
Optimisation
Calculation of cost function
send load shape
send cost function
Fig. 11. Smart charging communication principle

All charging points are connected with the load management system, so that the EV fleet load curve can be calculated by considering the power measurement at the Step-up transformer. Also the uncontrolled system load could be derived, see Fig. 12 for the architecture of management system.

Fig. 12. Smart charging closed loop control

For a numerical analysis, it is assumed that the load’s forecast function is exactly like the H0 shape. The cost function is updated after each charging event for the best performance analysis. The optimization technique results are shown in Fig. 13 and Fig. 14. It is possible to shift the afternoon and evening peak loads into the load valley of the global system loads. There are no significant differences between the slow, normal and fast charging approaches.

Fig. 13. Fleet load shape for 30% market penetration with Smart Charging

Smart charging behaviour at home of end users under consideration, shifts the main load into the night time. In this scenario the market participation of EVs is 30%, which means that 12 million electric cars are being used in Germany, which fits the forecast of the amount of PHEV’s and pure EV’s and IEA (Diefenbach 2010; IEA 2009) at the year 2020.

The optimization result shows that the slow charging of all cars (~3.6 kW) after 6:00 pm can reduce peak loads of fast charging by 43%. The benefit of smart charging is not included in this scenario, especially if all cars would charge after 6:00 pm in slow mode (3.6 kW) which reduces the peak load significantly. Next steps are the detailed power flow analysis on reference power grids to determine the exact impact of EV charging to the distribution grid infrastructure.

3.3 Example 2 - Application of Smart Charging at concentrated points to avoid overload situations

This scenario describes the future challenges of managing the commercial fleets with EV in urban areas. A parking garage is equipped with fifty charging points for a fleet of electric vehicles; as shown in Fig. 15. A local load management function ensures that no overload situation occurs. Overload situations will occur if the transformer is used with more than 500 kVA. Each charging point supports slow/normal/fast charging as long as the transformer is not overloaded. It is assumed that the fleet is available from 6:00 pm until 6:00 am of the next day – which should be the off-time period. Each vehicle requires an energy consumption between 60 and 80 kWh and has the ability of fast charging with 20 kW charging power.

Fig. 14. Global load shape for 30% market participation with smart charging

If all vehicles would charge simultaneously a peak load of 1000 kW emerges and the transformer would be used with 200% nominal load, see Fig. 16. In this example the cost function in Fig. 16 indicates two periods for cost effective
charging from time step 0 to 15 and 25 to 40, assuming the costs function represents a time variable tariff. By applying dumb charging, all the vehicles would charge in the first period but without any knowledge about the coincidental cost effective time to charge. Also the charging process would exceed the physical limits of the step down transformer (up to 500 kVA).

If all vehicles and the charging points are equipped with Smart charging technology, all charging events can be optimized regarding energy costs and physical limits of the charging infrastructure without loss of any comfort or safety of full charged vehicles on the next day morning, see Fig. 17.

Both applications which damp peak load and avoid local overload situations can be combined. In this case both load management technologies have to communicate in the same way as described in Fig. 12. It is also imaginable to change the global control strategy or enhance it with respect to the integration of regenerative or local generation or by increasing the power system’s base load.

REFERENCES


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