Empirical BEV Model for Power Flow Analysis and Demand Side Management Purposes

Dirk Westermann
Power Systems Department
Ilmenau University of Technology
Ilmenau, Germany

Michael Agsten, Steffen Schlegel
Power Systems Department
Ilmenau University of Technology
Ilmenau, Germany

***Abstract*—The discussion about the substitution of fossil driven vehicles by battery electric vehicles (BEV) has raised questions from a power system operation perspective. The focus areas today are distribution networks (medium-to low-voltage level) with respect to the expected impact of a high penetration of the BEV charging action. BEV's will be mainly connected to the lower medium and low voltage power grid. Theoretic research and measurements show that the uncontrolled BEV charging can result in additional peaks at the step down transformers and adjacent cable systems. Assuming that the peak generation can feed in, power must flow over the entire distribution networks to the low voltage level. This results in situations where the operational limits of the power grid could be reached. This paper focuses on the modeling of these phenomena in order to forecast the daily load shape and additionally information as input for the power systems operation and optimization purposes, for example demand side management (DSM) strategies for managed BEV's charging. All models are based on the results of the field test in Berlin, using 50 Mini-E for managed charging.**

Battery electric vehicle, distribution network, power flow, simulation, impact BEV on distribution networks, load modeling, power system operation, demand side management, and optimization

I. Introduction

The substitution of fossil fuels for vehicle by all electric drive concepts opens up a new discussion on power distribution system operation with domestic charging stations [1]. Much research effort is directed towards the question on whether the Battery electric vehicles (BEV) will negatively impact the medium and low voltage power grids [2]. On the positive side BEV's can serve as huge distributed energy storage for the sake of power system operation improvement in particular if it comes to fluctuating renewable infeed [3].

BEV's will mainly be connected to the low voltage and medium voltage grid. Due to the already existing infrastructure it is most likely that the domestic charging stations will be connected on the low voltage level [2-5]. Theoretic studies and field test measurements demonstrate, that uncontrolled resp. uncoordinated BEV charging can result in additional peaks in network loading [6-8].

Due to the end user behavior, these peaks predominantly occur during the evening hours and superimpose the already existing load peak during this time period. If these load peak can be covered by generation it can be assumed, that the decentralized generation units cannot match this demand. The power needs to be transmitted over the medium voltage grid to low voltage loads [9-13].

This results in situations where the limits physical limit of the power grid can be reached. In particular this applies for step down transformers (thermal rating) and low voltage cable (thermal rating and voltage drop). In order to overcome this problem a suitable charging schedule needs to be applied to achieve a managed charging. Furthermore an optimized charging schedule could even leverage the control capabilities of the BEV's in order to minimize the average system loading or harmonize the voltage profile along a distribution network branch [14].

This paper outlines the results of analysis for modeling load shapes of BEV's for power flow analysis and optimization. The data collected in a field test with 50 electro cars are analyzed. A given sample of charging events for one week is presented and the ability of load shifting for demand side management purposes is outlined.

II. Field Test

A. Background

In July 2009 fifty electro vehicles were deployed to end customers in Berlin. This one year field test is scientifically accompanied by the Ilmenau University of Technology to manage the charging process at home for maximizing the participation of regenerative energy consumption of the fleet. The scientific interests are the customer's behavior and how it influences the load shapes for a group of cars to answer four simple questions:

1.) At which time the cars are plugged in and plugged off?
2.) How many cars are plugged-in every day?
3.) How much energy is consumed at every charging event?

4.) Is it possible to shift the load for optimization purposes?

This joint project is supported by the Federal Ministry of Environment, Nature Conservation and Nuclear Safety. The industrial partners are the BMW Group and Vattenfall Europe AG. [20-22].

B. Infrastructure

The system architecture to fulfill managed charging is illustrated in figure 1. It is designed for managing the charging process and has enhanced communication capabilities for observation. All cars charge one-phase with 7.3 kW, which means 32 A current. The home charging point is called "Autostrombox" and has GPRS based communication functionality to transmit information to the central station, the Demand Side Management System via TCP/IP, IEC60870-5-104 protocol. To fulfill optimization of the summarized load shape with respect to wind power feed the forecast and actual wind feed are imported from the TSO's (Transmission System Operator) public web domain.

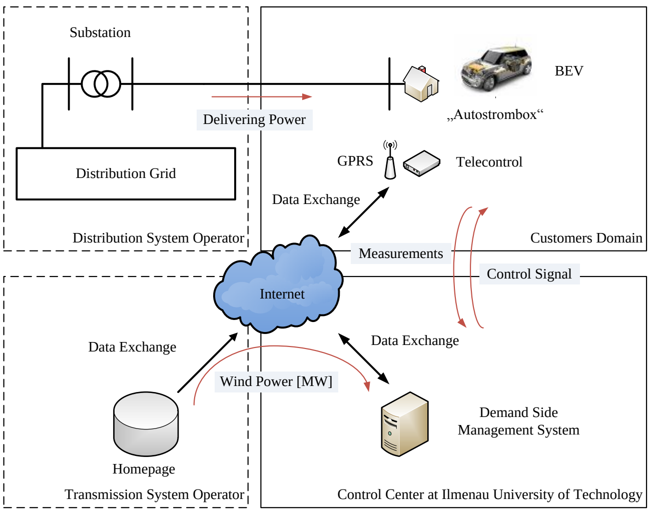

Figure 1. Architecture of the Charging Infrastructure with enhanced Communication Capabilities

This architecture differs in some points from the today's state of art commercial architecture. Commercial solutions aim at authentication of customers and secure billing. To fulfill managed charging the start and stop of every charging event must be shifted in time. This means that the current flow is activated only when the Demand Side Management System sends a control signal to do so. For this functionality the charging spot detect whether a car is plugged in or not - independent of the current flow and sends this information to the backend. The user can choose a defined end point of the charging process by utilizing a web portal. All charging events are stored in a database and used for design the load and optimization models which will be described in this paper.

III. BEV Model for Power Flow Analysis

A. Characterization of the charging process (Charging Events) – BEV Charging Event Model

The charging process can be modeled as a simple state automat. The process starts if the customer plugs the car in. After plug-in the home charging spot detects that a car is available and reports to the demand side management system the charging request. From now until the charging process should start the system goes into idle mode and waits for the start signal to charge. The whole process stops with the plug-off event, independent from the state of charge (if the battery is full, the charging process ends but the car stays connected), see therefore figure 2.

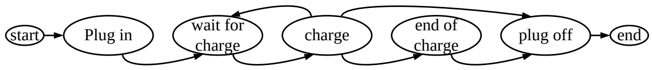

Figure 2. Finite State Machine representing of the whole charging process

B. Analysis of charging events and resulting load shapes

In figure 3 all charging events in week 35, 2009, are illustrated. The behavior illustrated is also typical for all other weeks. The green bar means the time span between plug-in and plug-off event. The blue bar means that the charging process is active. The summarized shapes of availability (green bars) and consumed power (blue bars) is illustrated in figure 4.

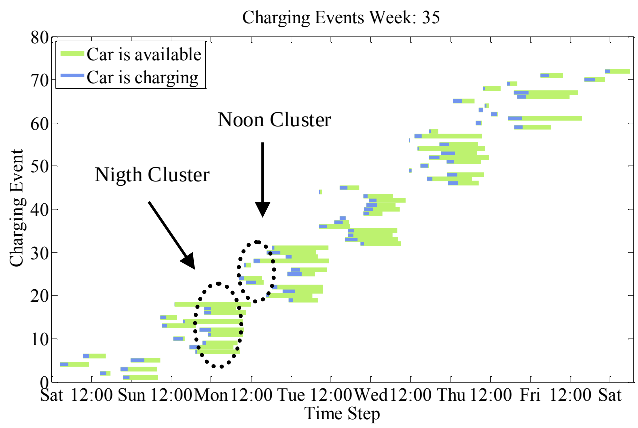

Figure 3. Sample of charging events for week 35 (typical behavior), 2009

In a first analysis the following thesis can be derived:

1.) The most charging events are concentrated around the daily change time span from 10:00 pm until 7:00 am. That's the night cluster. This cluster is very simple to explain. Due to the home charging the most charging events start in the evening and go on until next morning until the costumers use the cars.

2.) There exists a second cluster, which is concentrated around noon from 10:00 am until 1:00 pm. That's the noon cluster. Some (not many) charging spots are installed not only for the private use at home, but by small companies. On the other hand some users charge at home during noon.

3.) Some charging events occur outside both clusters. Those events have mostly a very short time span.

4.) The time a car is available to charge depends on time it is plugged in. If the charging event is belonging to the night or noon cluster the time it is available dominates the time the car is charging.

That's a very important thesis, because if someone likes to manage the charging events, he needs the ability to shift the active charging.

5.) Not all cars were charged every day. In the field test are fifty cars deployed to the costumers, but for one week only 75 charging events occurred.

In figure 4 the sum of all charging events in week 35 is illustrated. Every car charges with a power of 7.3 kW. Due to the concentration of the noon and night clusters some peeks occur. The peaks reach a maximum at 35 kW which means, that for fifty cars (if all charge simultaneously the peak should reach 365 kW) only 10% of the maximum power achieves. The reasons for this low value are:

1.) Not all cars are charged every day.

2.) The cars which charge at one day are not charging at the same time, because the plug-in events are not parallel.

3.) The count of available cars shows, that most of the cars are plugged in during the night. That could be a high potential time span for demand side management and verifies thesis four.

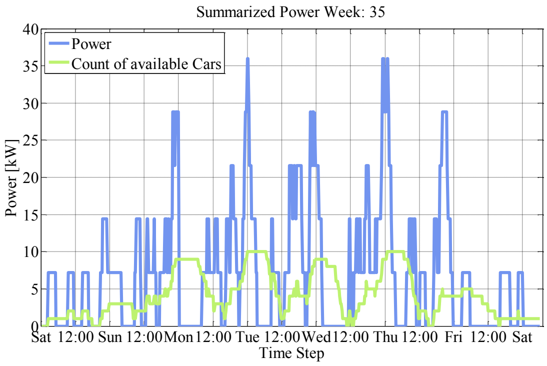

Figure 4. Summarized power and availability for week 35, 2009

The summarized charging shapes of the weeks 30 until 50 are averaged for determining typical load shapes of electric car usage, see therefore figure 5. The load shapes for weekdays are different from those for weekend days. On working days there are distinct peaks around noon and midnight, which does not occur with the same intensity on weekend. At weekend the noon peak is completely missing. This could result from lack of charging events by the small companies or missing return of the customers during lunchtime.

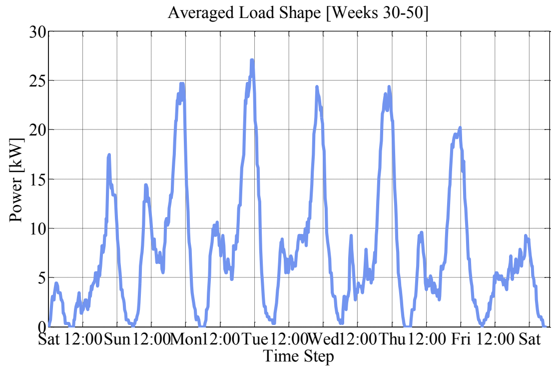

Figure 5. Average Load Shape for weeks 30 until 50, 2009

The field test results confirm that the unmanaged charging can result in additional peaks in network loading, as described in [6-8], but it shows that not all assumptions about electric car usage and home charging are valid. The results give an answer to the expected amplitude based on fifty cars. That differs from the publicized research results in the scaled peak amplitude and the time the peak occurs.

C. Empirical Load Model for Power Flow Analysis

The data collected in the field test should be used to build up models for power flow analysis and optimization. The average load shapes, see before in figure 5, are highly dependent from the customers behavior. If one can model or/and forecast the resulting load shapes, they could be very useful for power flow analysis and planning processes. Therefore two methods are examined to get a forecast model:

1.) Forecast individual charging events. If the charging events could be forecasted this model would help to plan the resulting load, it would also help to optimize the load shape by shifting every single charging event. This paper describes why it is not possible to forecast the individual charging events and what impact this gap has on the optimization purposes.

2.) Reference day analysis. This means, only the resulting load shape is used to model BEV's load. This paper shows, that with the collected data from the field test an exact load shape is not possible to model. This model is also not usable for optimization purposes, because there is no information about the different charging processes included. This information is loss by nature of model design.

To model the charging events three properties are dominant. First is the plug-in time. Second the energy a car needs to be charged. The third property is very important for the optimization purposes and means the time span a car is available for charging. Additionally it is necessary to forecast the count of events which will occur on every day.

As seen before weekdays and weekend have different peak amplitudes. This results from the different frequency the charging events occur. Figure 6 gives an overview of this frequency. All experimental data for half a year are analyzed. The most charging events occur on Tuesday (round about 18.6%). On Monday and Wednesday round about 17% occur, Thursday 15%, Friday 13%, Saturday and Sunday round about 9%.

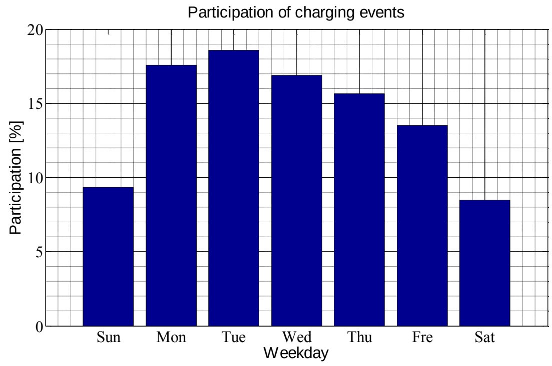

Figure 6. Participation of charging events, depending on the weekday

This information shows that Tuesday could be the day at which most loads are expected; or the most charging events will occur. For forecast purposes it gives an answer on how much charging events at every day will be expected. The figures 7-9 show the distribution of every variable for different all days.

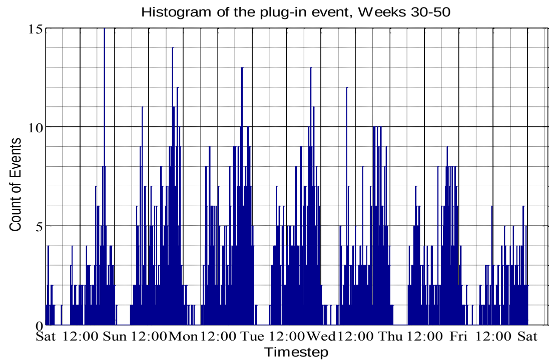

Figure 7. Histogram of the plug-in events

All figures show, that they do not satisfy any standard distribution with an expectation value. In fact they show that there must be more than one for every day. That may be complicated and is not deeper analyzed not yet.

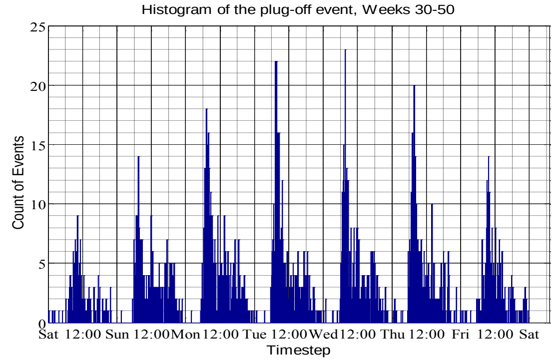

Figure 8. Histogram of the plug-off events

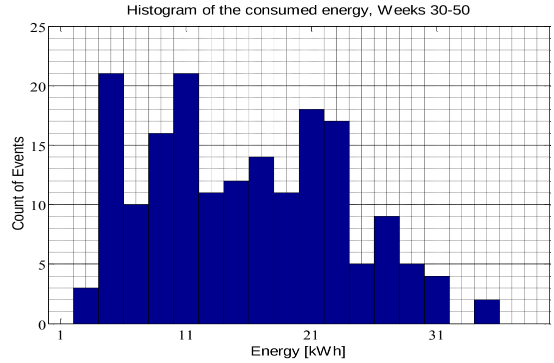

Figure 9. Histogram of the consumed energy

To realize a forecast model it could be useful to determine if there exist some dependencies between the variables or external data, which is done by correlation analysis, see table 1.

TABLE I. CORRELATION MATRIX

	Plug-in Time	***Plug-off Time***	***Consumed Energy***
Plug-In Time	1.0	0.99	0.0656
Plug-Off Time	0.99	1.0	0.0974
Consumed Energy	0.0656	0.0974	1.0

Plug-in time and plug-off time have a high correlation, so it should be possible to forecast the availability of a car on the charging spot depending from the plug-in time. The correlation between the plug-in & plug-off time and consumed energy is very low. It seems that the energy consumption doesn't depend on the time the cars are plugged in or plugged off, which is logical. The customers decide when the cars should be loaded. This behavior is not foreseeable with the collected data. The method to forecast the load shape by forecasting individual charging events failed due to the missing link between the time span the cars are available and energy consumption. A model to estimate the plug-in time is also not available not yet. So at this time it is not possible to forecast individual charging events without additional information.

To fulfill the requirements of modeling a load shape for power flow analysis, the second method of using reference shapes is described. Figure 4 shows a sample of a load shape for week 35. The same method is used for analyzing the standard deviation of the load shape over the time span of the field test, see figure 10.

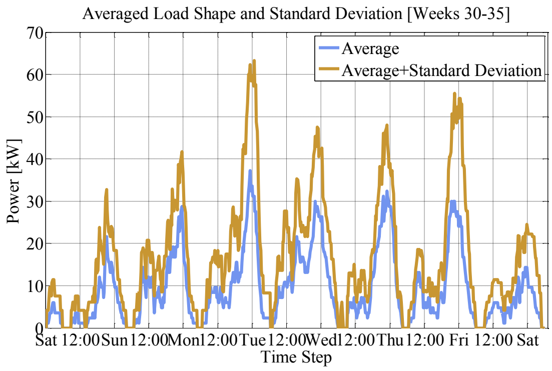

Figure 10. Standard deviation of the five weeks average load shape model

Figure 10 shows that for the five weeks average load shape the standard deviation is very high. This load shape can be used as a time series for modeling BEV's load in the same manner as standard load profiles are used.

IV. Potential for Optimization of BEV's Load Shape Utilizing Shifting the Charging Process

As described above the best time span to optimize the load of electric cars during the night. For example this could span the time between 16:00 and 8:00 o'clock. A subset of 35 samples is modeled with the charging event model, see figure 11. A very simple algorithm is used to illustrate the potential of load shifting with respect to the reference curve, see figure 13.

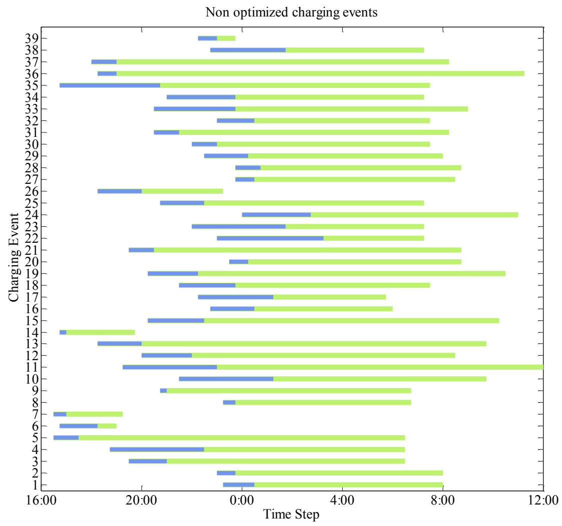

Figure 11. Non optimized charging events

The reference curve could be an indicator of how the load shape should be, if the participation of wind energy for the load shape should be maximized. It could also be a reference to discharge the power system by utilizing demand side management. Figure 12 illustrates the reference curve and the summarized BEV load as a result from unmanaged charging. The load should be transformed to match the reference curve.

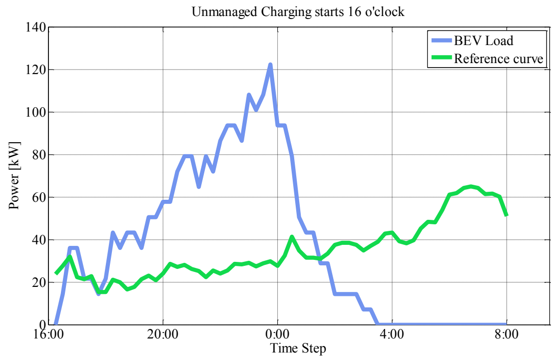

Figure 12. Non optimized Load Shape comparing to the curve to fit

To shift every individual charging a simple algorithm is used, see algorithm diagram in figure 13.

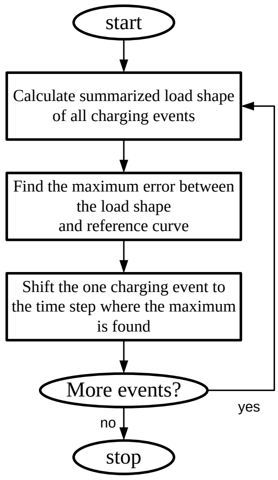

Figure 13. Simple Optimization Algorithm

The first step is to calculate the summarized load shape of all charging events. The maximum positive error between the load shape and the reference curve means that at this time step a charging event is needed to reduce the error. Now the algorithm try to shift one charging event around this time step and so on until no more time charging events are available, see results in figure 14-15. The optimized load shape matches the reference curve is not exactly, but it indicates that it could be possible to transform the unmanaged load. This very simple algorithm fits to get a first estimation which potential for optimization by shifting charging events exist. But it means that every charging event to shift has to be known before the optimization starts. This lack of information could fail the utilization of electro cars for demand side management purposes. On the other, if someone could forecast every charging event or the infrastructure has the ability to estimate the user's behavior (e.g. dedicated for every charging spot), this optimization approach could fit.

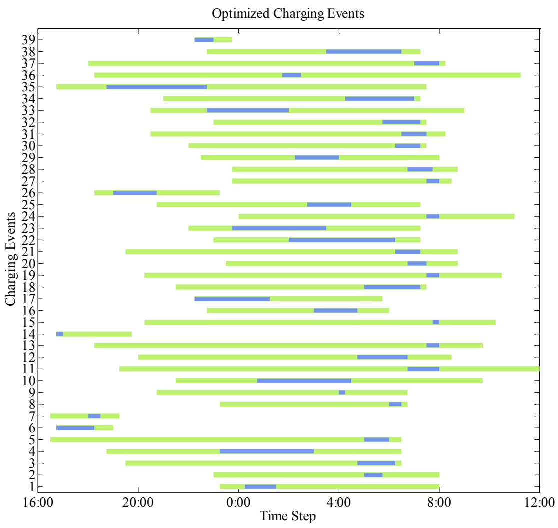

Figure 14. Optimized charging events

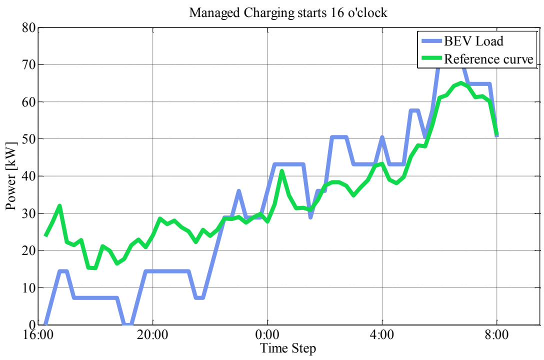

Figure 15. Optimized Load Shape comparing to the curve to fit

V. CONCLUSION

The architecture of the field test for managed charging of fifty electro vehicles is described. With this architecture a data basis is created for analyzing real charging events at home charging spots of electro vehicle. Every charging event has three important properties (plug-in time, plug-off time and energy consumption). The BEV charging event model is presented as a simple finite state machine. The three properties are analyzed for modeling purposes. It is determined that plug-in and plug-off times have a high correlation, but there exist no relation to the energy consumption. That makes it very complicated to generate a forecast model for individual charging events, especially without additionally information. So far an averaged model of measured load shapes is developed which could be used for power flow analysis. To determine the potential of shifting charging events a very simple optimization algorithm is presented. The results for a 39 events sample show that charging events can be shifted to match a reference shape. Further steps will be analyzing what effect the shifting process has on the load shape and which approach could be used to manage charging processes, especially if the information about plug-in time and energy need is uncertain.

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