INTEGRATION OF ELECTROMOBILITY IN A DISTRIBUTION GRID: RESULTS OF THE BEACON PROJECT "WELL2WHEEL"

Peter FRANZ
TU Darmstadt – Germany
peter.franz@e5.tu-darmstadt.de

Arnaud HOFFMANN
TU Darmstadt – Germany
arnaud.hoffmann@re.tu-darmstadt.de

Jutta HANSON
TU Darmstadt – Germany
jutta.hanson@e5.tu-darmstadt.de

Bernhard FENN
HSE AG – Germany
bernhard.fenn@hse.ag

ABSTRACT

The increased penetration of electric vehicles (EVs) leads to fundamental changes in the electric demand profiles of private households. Today's standard load profiles will not be valid anymore. Therefore additional requirements for grid stability besides the rising share of dispersed generation occur. The research project "Well2Wheel", funded by the German federal ministry for the environment (BMU), analyses in practice the prospective effects of EVs in distribution networks and develops automatised solutions for the shift of charging processes to avoid peak loads or behave in accordance to new business cases of utilities.

In addition to hardware solutions for a direct charge control and the functionality of information and communication technology (ICT) also the effects of various business cases on load flow and grid elements are tested in this beacon project.

INTRODUCTION

Presently the mobility sector in Germany is responsible for around one fifth of the country´s CO_2-emission. To achieve the target of reducing greenhouse gas emission by at least 40 % until 2020 (compared to the year 1990) the German government pursues the goal to have a minimum of at least one million EVs in Germany by 2020 [1]. In case of being charged by electrical energy of renewable generation units EVs can be a promising solution to reduce greenhouse gas emission. However these new types of consuming units will completely change the present load profile of private households because of their high power demand (3,7 kW – 22 kW) during charging cycles. Especially low-voltage networks are not designed for these additional power demands. Already small accumulations of simultaneous charging processes can cause bottlenecks (thermal overloading or voltage band violation) in the distribution networks.

On the one hand Distribution System Operators (DSOs) have to be prepared for these new challenges caused by an electrification of the mobility sector, on the other hand EVs offer huge potentials for load management because of their mobile storage capacities and numerous time intervals being located at parking areas. These parking times can be easily utilised for a demand side management without having any influence on the user`s behaviour if controlled by a smart charging system.

RESEARCH PROJECT "WELL2WHEEL"

The research project "Well2Wheel", which is funded by the German federal ministry for the environment, tries to analyse these challenges and potentials occurring by a large-scale introduction of EVs. The consortium of the project includes seven partners of research and industry (tab. 1) which have expertise in the different fields of integrating EVs into electrical power systems.

Table I: Project consortium of "Well2Wheel"

Project partner	Project tasks
HSE DAS GANZE SEHEN	- Local utility - Provision of grid infrastructure - Integration of EVs and VPP
TECHNISCHE UNIVERSITÄT DARMSTADT	- Power system simulations - Integration of smart charging stations in building automation systems
EUS KISTERS GROUP	- Database of VPP - Development of business cases - Modelling of energy tariffs
FH FFM Fachhochschule Frankfurt am Main	- Accompanying scientific research - Evaluation of charging behaviour and user acceptance
Fraunhofer LBF	- Operational stability of charging plugs - System reliability
NTB	- Project coordinator - Technical consult
Continental	- Integration of communication systems in the EVs and data transmission

The whole project is executed in the Rhine-Main region around Darmstadt (fig. 2). By participation of the local utility HSE AG the complete energy supply chain from the dispersed generation units via electrical networks to the consumers with their charging points and EVs can be represented in practice. "Well2Wheel" bases on an existing Smart Grid and a Virtual Power Plant (VPP) established within the European research project "Web2Energy", which was completed in 2012 [2]. The VPP already includes several dispersed generation units (photovoltaic, wind, biogas, hydropower, cogeneration), flexible loads (heat pumps, swimming pools, cooling systems) and stationary energy storages (lithium-ion, redox-flow batteries). In addition in the "Well2Wheel"-project around 50 EVs and a couple of charging points are integrated into the VPP via ICT. For that reason EVs are equipped with communication units which transmit vehicle data (charging intervals, driving profiles, etc.) to the VPP.

Virtual Power Plant

The coordination centre for grid control and collecting relevant data is the VPP. By analysis of incoming data like grid conditions, load profiles, procurement prices or generation forecasts, the VPP calculates traffic light tariffs based on different algorithms developed within "Well2Wheel". These traffic light tariffs either control all integrated generation units and flexible loads or are just transmitted to the consumers as an electricity tariff. For the utilities or DSOs various business cases for the management of a VPP are conceivable (fig. 1) [3].

Utilisation of differences in purchase prices (Spot-, Intraday-Market)	Provision of reserve power (secondary and tertiary control)	Voltage control by active or reactive power support
Minimisation of unbalancing costs in a balancing zone	Reduction of costs for grid reinforcement (peak shaving)	Local consumption of renewable generation („green electricity“)

Figure 1: Business cases for the management of a VPP

The first algorithm model in the VPP of this project is a combination of peak shaving and charging of EVs by the use of locally generated renewable energy [4]. Therefore incoming data of network conditions, load profiles and weather forecasts for predicting local energy generation is used. The mathematical algorithm in the VPP calculates traffic light tariffs which indicate the consumers in 5 regional grid zones (fig. 2) whether it is recommended to consume energy in certain time intervals or not. The partition of the HSE supply area in subbalance-areas is done with respect to locally varying types of generation units or consumption profiles.

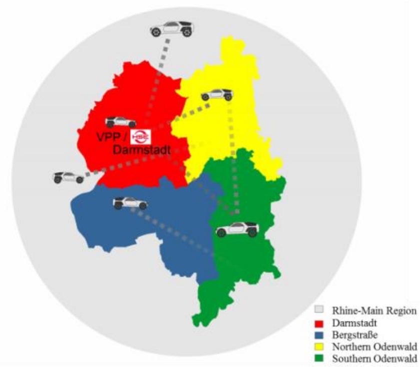

Figure 2: Regional grid zones in "Well2Wheel"

Traffic light tariffs

The traffic light tariffs in "Well2Wheel" consist of red and green time intervals. Green time intervals signal an excess of renewable energies and free grid capacities in a local network area. Red slots represent times in which the residual load is high or renewable generation is low. The traffic light tariffs are representative for variable electricity tariffs in future power system management. An example is shown in figure 3.

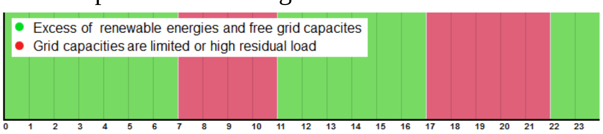

Figure 3: Exemplary profile of a traffic light tariff for one day in "Well2Wheel"

Besides the target of giving recommendations to the owners of EVs when charging of vehicles is preferential also automation approaches for smart charge control via bidirectional communication, which are explained later, are realised in the project. At the first step the variable tariffs are modelled in 1-hour-time-intervals for one day. To get a better acceptance and adaption of the charging behaviour a prediction for the next 48 hours is also available. Depending on the occurring acceptability of users during test operation, shorter time intervals or faster tariff updates coming close to a real-time tariff are also conceivable.

Load profile of electric vehicles

The current algorithm of the VPP for tariff modelling already implements the future residual load profiles in distribution networks with a high share of electrically driven vehicles. A large-scale penetration of EVs will totally change the so far used standard load profiles of the DSOs for power system dimensioning, because of the high power demand for fast charging processes, especially in residential areas. For the development of standard load profiles for EVs (in the following called E0) three categories for the weekdays are grouped: working day, Saturday, Sunday. The basis of creating a standardised load profile for households having an EV is the frequency distribution of arrival times (fig. 4). It can be assumed that vehicle owners will only switch to an EV if their driving behaviour is not restricted by the new technology. Therefore the present distribution will still be valid.

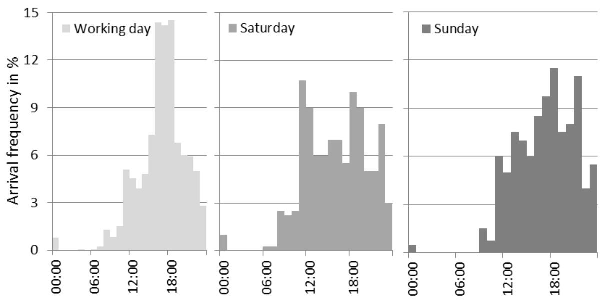

Figure 4: Arrival frequency in Germany [5]

For generating the E0-profiles of EVs, besides arrival frequencies for different weekdays also the average travel distances by car, the vehicle consumption and the charging power have to be considered. Present available electric cars have an energy consumption of 15-25 kWh per 100 kilometres. The average driving distance of cars in Germany is determined to 42 km for a working day, 50 km for Saturday and 56 km for Sunday corresponding to [6]. For the vehicle consumption an average of a mid-sized car like the Nissan Leaf (20 kWh/100 km [7]) is assumed, which results in durations for charging cycles between 1 and 3 hours (see tab. II).

Table II: Average charging time on working days

Charging power	Energy consumption per 100 km		
	15 kWh	20 kWh	25 kWh
3,7 kW	2,3 h	3,1 h	3,9 h
11 kW	0,7 h	1,0 h	1,3 h

Due to practical reasons the E0-profiles have been rolled out for charging powers of 3,7 kW and 11 kW. These are typical ratings for a 1-phase or 3-phase charging if the charging current is limited to 16 A. Additionally, the installed types of smart charging stations for charging control in the project operate with a maximum power of 11 kW. High charging powers reduce the simultaneity of charging processes, because of faster charging cycles. This is the reason why the peak demand for a charging at 11 kW is not much higher than at 3,7 kW (fig. 5). Like for all standard load profiles the assumption for E0 is only valid for a high number of consumers. By comparing the established standard load profile for private households H0 with the E0-profile, it can be seen that the load profile of a private household owning an EV will completely change and maximum power demand will be more than doubled. These changes in energy consumption have to be considered for network planning by the DSOs in the future.

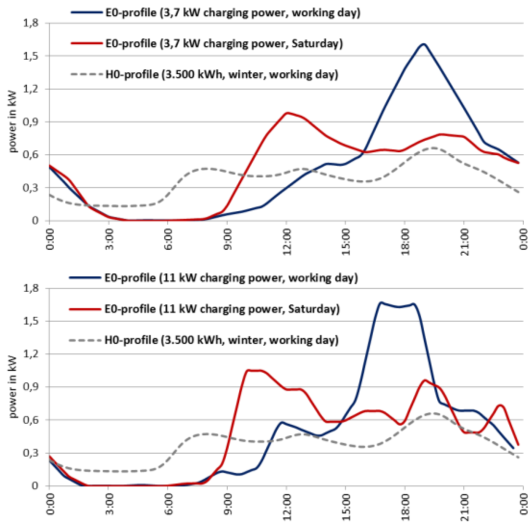

Figure 5: E0-profiles for different weekdays

Figure 4 shows that on working days most of the cars arrive at their destination points after work in a time slot around 18:00. This peak can also be seen in the standard E0-load-profile for EVs where depending on charging power and vehicle consumption the peak occurs more or less pronounced in this time (fig. 5). Unfortunately this is the time slot where peak load occurs in the networks. At present the annual peak load commonly occurs in Germany on a cold winter working day around 19:00 in December or January [8]. On the weekend the demand of charging power of EVs is more distributed to the midday. The power demand of EVs during the night is very low because the level of the battery is at 100 % if immediately charged after plugging into the station.

Power System Simulation

Investigating the E0-profile and the increase of energy demand of households having an EV, voltage problems and thermal overloading of grid equipment can be expected. These assumptions have been determined by power system simulations in a low-voltage network in a residential area near Darmstadt. The simulations have been performed for a period of one year.

Topology of the low-voltage network

The residential area has a suburban characteristic with almost exclusively single family houses. In figure 6 a simplified model of the 0,4-kV-grid with concentrated loads is shown.

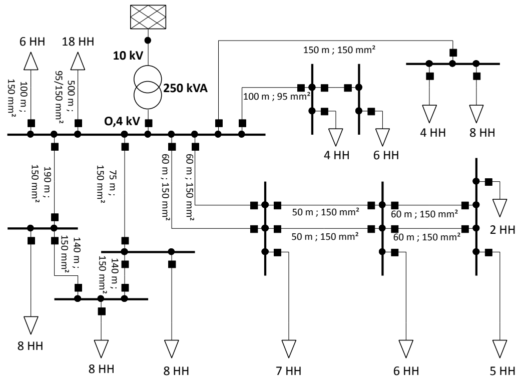

Figure 6: Simplified model of a real 0,4-kV-network in a residential area

The MV/LV-transformer has a rated power of 250 kVA. Seven network feeders are connected to the secondary substation. In the feeders, the cables have cross-sections of 95 mm² and 150 mm². Average distances from the secondary substation to the connection points of the houses can be assumed to be around 200 m. The longest line lengths are around 600 m.

For the load profiles of the 90 households in the low-voltage network real smart meter data is used. The distribution of the load profiles is done randomly. The mean size of all family houses in the grid amounts 2,4 persons per household. Furthermore it is assumed that only households with an EV have a PV-system on the roof of their house. For grid simulations the PV-systems are uniformly set to 7 kWp. The generation profiles of the PV-systems are derived from real measurement data.

Potential for the integration of EVs

The maximum annual peak load in the basic scenario without EVs is 105 kVA. It occurs shortly after 18:00 on a cold working day in the winter. This corresponds to an utilisation of 42 % of the transformer. Therefore, even at peak load a maximum potential for an additional charging of 39 (3,7 kW charging power) respectively 13 EVs (11 kW) is possible (fig. 7).

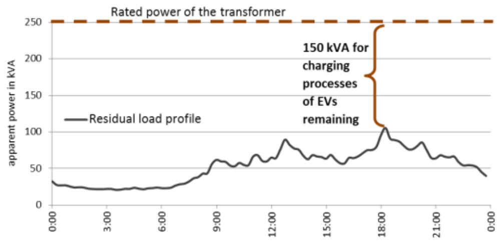

Figure 7: Residual load profile on day of annual peak load

Since by an increasing number of EVs the simultaneity declines, in the analysed grid around 60 EVs (11 kW charging power) can be integrated without any charge control. The results of a random distribution of charging cycles according to the arrival frequency are shown in figure 8. The rated power of the transformer (250 kVA) is never exceeded, however only few reserves remain.

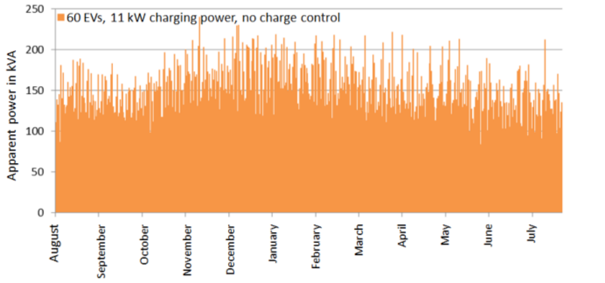

Figure 8: Residual load profile at the transformer (60 EVs)

The profile of residual load is derived from the average arrival frequency. Of course in reality there can be some days with a much higher accumulation of charging processes at certain times. The power system simulation showed that already at a random distribution of ten EVs voltage problems ($U < 0{,}9 \cdot U_n$; DIN EN 50160) occur in a few quarters of an hour in a year. These voltage drops occur basically in times of a high demand of the households at the furthest points from the secondary substation (>500 m) in lines with small cross-sections of the cables, well before thermal overloading of the transformer. Therefore for an improved utilisation of existing grid capacities intelligent charging strategies are advantageous to avoid grid expansion.

Charging strategies

Because a private vehicle is normally driven less than two hours a day, at least 22 hours per day are potentially remaining for shifting the charging processes in times according to the business cases of the operator of a VPP or distribution grid [5]. The first charging strategy to avoid high peak loads is a collective control of charging intervals for the whole low-voltage network. Time slots, e.g. between 17:00 – 19:00 when the maximum demand of households is expected, are blocked by a red interval of the traffic light tariff. When the blocked time period is over, charging processes are enabled again by a remote signal. But this strategy does not achieve the desired results. The simulation results show that a homogeneous control of charging processes in a grid zone does not reduce the local peak load at the transformer. In fact even higher peaks can occur if a remote control releases a charging period, because all EVs which were blocked in the time interval before start to charge simultaneously (fig. 9). If it is not possible for the DSO to manage charging stations in a grid area individually, because of technical or economic reasons, other demand side management strategies have to be considered. This could be a "first come – first serve" or a "lowest state of charge" principle, or the limitation of maximum charging power during certain time slots [9].

In the modelled network another charging strategy is simulated. Based on the knowledge of arrival frequency, average recharge demand and load forecasts of the consumers, the charging cycles of the EVs are arranged in series in the times of a green interval. The release of charging processes starts e.g. at 21:00 and all EVs have to be fully charged until 7:00. Simultaneous charging cycles are avoided as much as possible. By the shift of charging cycles into night hours where the households have a low energy demand, voltage problems decrease. Also the residual load at the transformer is distributed more homogeneously by an arrangement in series and grid expansions can possibly be postponed (fig. 9).

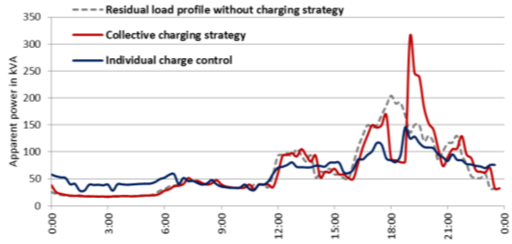

Figure 9: Residual load profiles of different charging strategies on a working day in winter (60 EVs, 11 kW)

Summary of simulation results

In weak distribution grids intelligent charging strategies are necessary even at a low penetration of EVs, because voltage problems can occur at long lines. It can be expected that in future the power of installed charging stations will increase for faster charging processes. Thus problems of voltage drops and thermal overloading in low-voltage networks will occur at smaller numbers of simultaneous charging processes. Problems of thermal overloading can be avoided by the use of remaining parking times in combination with a homogenous distribution of charging cycles. This is only possible by individual control of the charging stations. A collective remote control of charging cycles in grid zones can worsen the problem of peak load as shown before.

Indirect and direct control of charging cycles

For an implementation of charging strategies in practice into a grid management or VPP, two possibilities exist. The starting time of charging cycles can be influenced by an indirect or direct control. An indirect control is based on price incentives. It has a higher customer acceptance in comparison to the direct control due to the fact that flexibility remains at the consumers. By direct control the charging cycles of the EVs are automatically shifted according to the strategy by a remote control signal. In contrast to an indirect charge control, a direct control needs in addition a bidirectional communication infrastructure from the charging point to control centre to transmit the information whether a car is plugged in.

To realise the different charging strategies, within the "Well2Wheel"-project prototypes for tariff visualisation and charge control are developed. The signaling of the valid day-ahead traffic light tariff is done in the project by a visualisation on smart phones or a special tariff box (fig. 10). A forecast for the next 48 hours is available. The users can decide for themselves whether to adapt their charging behaviour according to the red and green time intervals. Since research field tests for demand side management [10] have figured out that the effects of an indirect load shifting by variable electricity tariffs are low, the visualisation boxes for the traffic light tariff are only used at locations where a direct charging control is not possible due to technical or economic reasons, e.g. if the car is charged at a conventional 230-V-socket. For direct control the charging stations in the project are modified with communication interfaces and charging controllers (fig. 10). The traffic light is transmitted via GPRS and the charging processes can be controlled automatically according to the business case of the VPP.

Figure 10: Solutions for an indirect (left) and direct (right) charge control in "Well2Wheel"

For increasing user-acceptance it is possible to pass over the automatically blocked time intervals and charge the EV even in red tariff slots by a control command at the charging station to enable immediate charging. Some of the smart charging stations are also equipped with measurement devices and send back measured data of the local grid to the VPP. This data can be voltage or power factor at the point of common coupling. This information can be used to identify bottlenecks in the grid and serves as input data for calculating the next traffic light tariffs. The data exchange is realised by csv-documents. An ftp-server is used for data management.

Integration of intelligent charging station and energy storage in a home automation system

The next research steps in the "Well2Wheel"-project are long term tests of the described smart charging stations in daily routine and the direct connection of stations into home automation systems of households to increase their flexibility of energy demand. Therefore a modified charging station and a lithium-ion storage are integrated into the existing smart home and low-energy building (SurPLUShome) of the Technical University Darmstadt (fig. 11). SurPLUShome has a building façade covered with PV-panels and a smart home automation system based on a building-control fieldbus for increasing the internal energy consumption by shifting the runtime of flexible loads like white goods automatically according to weather forecasts [11]. The energy storage will help to increase potential times of load shifting and to charge an EV by self-generated energy of the PV-system. The target is to include the smart home with EV and storage into the VPP and optimise its consumption not only corresponding to solar radiation but also to the business cases/traffic light tariff of the VPP.

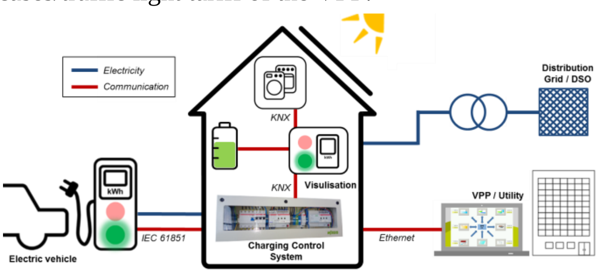

Figure 11: Integration of a charging station into the home automation system of SurPLUShome

OUTLOOK

The next steps in "Well2Wheel"-project are the analysis of impacts of EVs by power system simulation with real network data in networks of other topologies, load and charging profiles (urban areas, commercial zones and industrial parks) to determine possible voltage problems or thermal overloading of grid equipment. The effects of commuter flows and the possibility of charging EVs at work will also be analysed. Assumptions for load-flow calculations will be validated by measurements in the secondary substations. Moreover, it has to be evaluated how real driving and charging behaviour of test users in the project is corresponding to the E0-profiles derived from statistics of arrival frequencies.

REFERENCES

[1] Bundesministerium für Wirtschaft und Technologie (BMWi), 2013, *Energie in Deutschland - Trends und Hintergründe zur Energieversorgung*, Berlin.

[2] Fenn B., et al., 2013, *Advanced technologies of Demand Side Integration by VPPs and through smart metering in households*, CIGRE, Paris.

[3] Bühner, V., Buchholz. B., Probst A., 2012, *New services and business models for Smart Distribution and Smart Markets*, VDE-Kongress, Stuttgart.

[4] Fenn, B., et al., 2014, *Integration of electric-cars into an existing Virtual Power Plant*, CIGRE, Paris.

[5] Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE), 2010, *VDE-Studie Elektrofahrzeuge – Bedeutung, Stand der Technik, Handlungsbedarf*, Frankfurt.

[6] Linssen, J., et. al., 2012, *Netzintegration von Fahrzeugen mit elektrifizierten Antriebssystemen in bestehende und zukünftige Energieversorgungs-strukturen*, Forschungszentrum Jülich, Jülich.

[7] U.S. Department of Energy, 2013, *www.fueleconomy.gov*, EPA fuel economic label.

[8] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, 2012, *Bericht der deutschen Übertragungsnetzbetreiber zur Leistungsbilanz 2012*.

[9] Chatupromwong P., Yokoyama A., 2012, *System Frequency Control using Multi-Step Smart Charging of Electric Vehicles*, IPEC, San Diego.

[10] Klobasa, M., 2007, *Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz auf Landesebene unter regelungstechnischen und Kostengesichtspunkten*, ETH Zürich, Zürich.

[11] Steiner L., Hoffmann A., Hartkopf T., 2010, *Smart metering of SurPLUShome as a base for demand side management*, PV-SEC, Valencia.