Requirements on electrical power infrastructure by Electric Vehicles

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***Abstract*— With an increasing number of electric vehicles in operation new requirements on the electrical power networks will occur. Currently these networks are designed to supply on average a typical household load of around 2 kW. If electric vehicles will be connected then this household load might, depending on simultaneity of charging process and charging power, increase to more than 10 kW causing overloading of elements such as lines. On the other hand the storage capacity of the car battery allows providing new services to the networks, like balancing power for increasing shares of stochastically variable generation by renewable energy sources.**

This paper presents the results of an investigation within the medium and low voltage networks operated by Allgäuer Überlandwerk GmbH in the southern part of Germany. The considered network is characterized by a high portion of distributed generation, especially stochastically variable photovoltaic power plants. The region is characterized by a high portion of commuters to a near city.

The investigation shows how many electric cars can be integrated in an existing network depending on different locations and charging strategies. It also demonstrates the interaction between electric vehicles and stochastically varying generation. Basic guidelines for control strategies are derived.

Yearly measured profiles of the loads as well as the generation from wind and solar power plants form the basis for the calculations. Stochastic load flow calculations allow statements regarding the probability of critical scenarios within the network. Based on the results solution strategies are derived and verified.

Keywords-electric vehicles; network planning; decentralized generation; probabilistic load flow

I. INTRODUCTION

Due to increased environmental concerns as well as technological developments such as suitable batteries or information and communication technologies (ICT) at acceptable costs it is expected that in the next years the number of electric vehicles (EV) will increase. According to the national development plan 'Electromobility' of the German government one million electric vehicles are expected in Germany by 2020 [1]. This corresponds to a share of around 2 %, as in 2008 there have been 49.3 million vehicles registered in Germany, with 41.3 million passenger cars as the most dominant subgroup and 3.6 million motorbikes.

One main question currently raised is the impact of increasing shares of EV on electrical infrastructure. Currently, networks are designed to supply an average household load of around 2 kW. Solutions will be necessary to increase the 'hosting capacity' of existing networks for EV. The term hosting capacity is so far used to express the ability of the network to integrate renewable generation units, but can be simultaneously used to judge the share of electric vehicles that can be integrated into existing networks before exceeding limits of network parameters such as loading of equipment or voltage drop.

The goal of a study conducted in close cooperation between Allgäuer Überlandwerke GmbH (AÜW), Hochschule Kempten and Siemens AG was to investigate at the example of a part of the medium and low voltage network operated by AÜW:

- how many electric vehicles can be integrated in the currently existing structures of the electric networks,
- to what extend can this number be increased by intelligent charging control strategies and
- how can the interaction of the high share of generation by distributed photovoltaic power plants and the batteries of electric vehicles being optimized.

The main results of this study are presented in this paper. Further studies are ongoing to refine the results.

II. FUTURE ELECTRIC VEHICLE SCENARIOS

A. Assumptions

In order to judge the impact of EV several assumptions have to be made. Different scenarios need to be developed to simulate the impact of EV depending on their regional distribution. Assumptions need to be done concerning

- future development in number and type of EV,
- regional distribution of EV within the network,
- expected charging profiles and possibilities to control the charging process.

B. *EV Infrastructure*

Charging seems possible at

- home,
- work,
- public charging station,
- large charging infrastructure, such as parking areas in shopping centers.

In the near future it is expected that either private cars that are mainly charged at home or fleets will be the dominant EV. Charging power at home is limited by the fuses. Most likely, it will thus not exceed 3.7 kW (1-phase, max. 16 A) or 11 kW (3-phase, max. 16 A). Also in future 'normal charging' at work or at a corresponding charging infrastructure will be limited to 22 kW (Fig. 1).

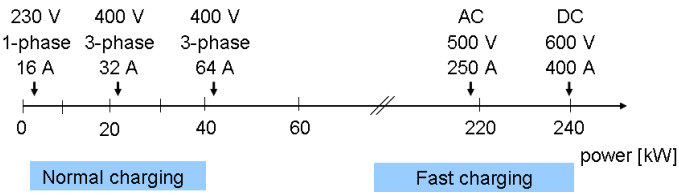

Figure 1. Charging power

Previous simulations have been performed by Siemens PTI with different low voltage (LV) and medium voltage (MV) example networks. It turned out that there seems to be no critical negative impact connecting EV infrastructure to MV networks, even with fast charging stations with capacities up to 240 kW. Thus, results presented in this paper focus on LV networks.

C. *Mobility Behaviour*

In Germany several studies exist on the mobility behavior triggered by German ministries. The study 'Kraftfahrzeugverkehr in Deutschland' (KiD) [2], dated from 2002 provides a closer look to driving profiles. 64 % of all privately owned passenger cars and motorbikes in Germany are mobile per working day (Monday to Friday), respectively 57 % during the whole week (Monday to Sunday). The average distance per mobile private vehicle is 57 km (Mon to Fri), respectively 62 km (Mon to Sun). Time on the road for private vehicles is 75 minutes (Mon to Fri) or 71 minutes (Mon to Sun). Thus, on average only 13 % of all privately owned vehicles are on the street during working day, 11 % during the whole week respectively. That means that on average 89 % of all EV do not move and their battery could be available for the provision of network services.

The number of vehicles per household strongly depends on its available income [3]. For the region in this study it is considered to have one car per household on average.

D. *Charging Profiles*

Full battery electric vehicles (BEV) show highest impact on the network as they require complete charging from electricity networks. In this paper only scenarios with full BEV are considered. The average 'consumption' of full BEV varies between 10 and 30 kWh/100 km depending on the size of the vehicle (compact car, medium-size vehicle, roadster …). Considering losses of around 20 % for charging and discharging of the battery an average consumption of 25 kWh/100 km can be assumed. Depending on the model and its required range the battery capacity varies between 10 and 60 kWh.

Based on the German mobility behavior an average charging demand of 15 kWh per vehicle and day is assumed in this study corresponding to average distance of 60 km and average consumption of 25 kWh/100 km. Although this leads to higher distances than the yearly driving average of 14.000 km [4], this assumption takes higher driving distances in suburban/rural area into account [3].

In general it is possible to charge:

- with highest possible power in shortest time,
- with lowest possible power in longest available time or scenarios in between,
- following the availability of renewable generation.

From a network point of view the second strategy is the best as it reduces most the additional charging peak. Within this study it is assumed that privately owned EV are recharged only at home, dominantly between 6 p.m. and 6 a.m. This leads to an 'ideal' charging profile shown in Fig. 2. Charging with PV generation is – without making use of the EV battery storage capacity – only possible during day and could be used by fleets with EV parking during lunch break (Fig. 3).

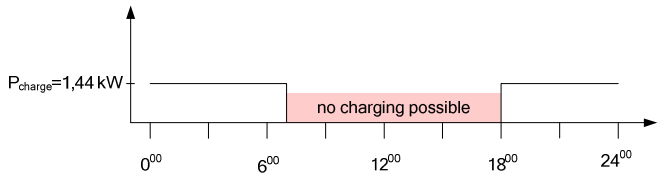

Figure 2. Charging with lowest power during the night, profile "commuter"

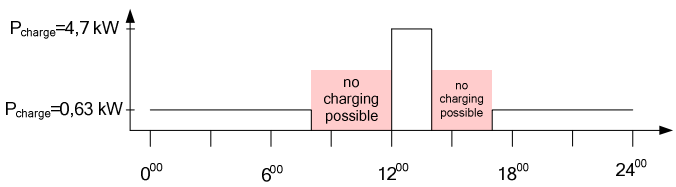

Figure 3. Charging during the day, profile "fleet"

Required charging durations depending on charging demand and its corresponding driving distance are shown in Table 1.

TABLE I. CHARGING DURATION DEPENDING ON DEMAND

Driving distance [km] / Demand [kWh]	**Average charging power [kW]**			
	3.7	11	22	200
30 / 7.5	2.0 h	42 min	34 min	2.3 min
60 / 15	4.1 h	1.4 h	0.7 h	4.5 min
100 / 25	6.8 h	2.3 h	1.1 h	7.5 min
150 / 37.5	10.1 h	3.4 h	1.8 h	11.3 min

E. Network Impact

1) Increased Energy Consumption

The yearly average demand per EV is 3500 kWh (14 000 km * 25 kWh/100 km) and is in the range of a yearly single household consumption. Compared to the yearly electricity generation in Germany in 2008 with 615 TWh and hereof 93 TWh (15.1 %) generated by renewable energy sources (EEG-Strom), the impact of additional energy consumption by EV is marginal with 3.5 TWh in case of 1 million EV as expected for the year 2020. Also in 2030 with expected 5 million EVs in Germany, their demand of 17.5 TWh can be fully covered by expected increase in renewable generation by that time.

Although total EV share is limited in near future the impact on networks depends on their regional distribution. Problems arise especially in LV networks when multiple EV located in the same feeder are loaded at the same time with charging power exceeding the maximum historical load which the network was designed for.

2) Hosting Capacity of the Network

The EV hosting capacity expresses the ability of the network to integrate EV before exceeding limits of network parameters such as loading of equipment with values of 100 % or 120 % or deviations of more than +/- 10 % of the voltage.

Normally, the loading of the lines and transformers in networks is not evenly distributed. Some lines or transformers will be overloaded even by a small load increase. If the number of elements that exceed given limits, especially concerning voltage and loading, is small, this does not mean, that the network has reached its hosting capacity as in reality these elements can be replaced or enforced easily. A more detailed analysis provides the evaluation of the frequency distributions of the loading of the elements and the voltages. For the investigations it was assumed that the hosting capacity of the network is reached when about 2 % of the network elements are overloaded.

F. Methods for Network Impact Analysis

Two different approaches have been applied in this study to judge the impact of EV on target network, namely deterministic calculation and probabilistic simulation.

Both calculation complexity and evaluation accuracy increase significantly from deterministic 'worst-case' calculation to stochastic simulation. Nonetheless, both approaches are essential parts of a successful EV evaluation process as they serve different purposes. Both simulation methods were applied by Siemens PTI to the network to check differences in results.

1) Deterministic Calculation

Deterministic case calculations consider only critical situations in the network. Calculations are performed assuming maximum load and zero renewable and distributed generation (DG) output, corresponding to the fact that PV power is available during day while EV are dominantly charged during night. Such worst case calculations that does not consider simultaneity effects of demand and DG, possibly reducing total network loading, require only one load flow evaluation to reveal the impact of a specific EV charging power level; but, it is incapable of examining the impacts of different EV charging strategies, i.e. time-dependent charging profile, and the interplay with the generation from stochastically varying sources like sun and wind.

As a consequence, the deterministic calculation is ideal for evaluating the minimum hosting capacity of a network in terms of EV type, number, as well as location.

To judge the impact on hosting capacity normally an even distribution of EV in the network at all possible connection points is assumed. This assumption however doesn't reflect the fact that not all components are equally loaded and that there are more critical locations where already a small number of EV could cause significant overload or voltage problems. To overcome this limitation several calculations need to be performed considering different location of EV as long as EV penetration is below 100 %, meaning that all possible consumers are equipped with EV.

Calculations with daily profiles for selected days such as winter, summer, workday, weekend provide the possibility to judge the impact of longer lasting charging processes and to derive results about the daily and the seasonal impact of EV on the network. Typically, each load is simulated with standard German load profiles, typical profiles for renewable and distributed generation are selected based on local measurements. Nevertheless also this approach does not reflect the actual situation in the network with stochastically varying single loads, which especially on low voltage networks with limited simultaneity may significantly differ from average standard profiles, or the full range of possible daily variations in renewable generation.

2) Probabilistic Simulation

Probabilistic evaluations allow consideration of

- stochastically varying load behavior
- stochastically varying dispersed and renewable generation

- EV charging profiles and intelligent strategies for their variation.

Basically, there are two different methods of probabilistic reliability calculations. The analytical method combinatorially generates all possible failure combinations. The results are expected values and variances. The analytical method is not applicable because the time dependency of the charging behavior of the EV is lost. Thus a time-sequential Monte Carlo method has to be used for probabilistic load flow analysis, which generates location-, type-, and time-specific stochastic load and generation profiles based on historical measurement data and simulates system response to different EV charging strategies over the period of one year.

Stochastic simulation methods can provide a very realistic background for evaluation of different EV charging strategies; and in the same time system performance indices can be much more accurately evaluated via statistical analysis.

III. Results of Network Study

A. Description of the Network

To perform the investigations a part of the network operated by AÜW, a regional area comprising low and medium voltage parts close to the city of Kempten, was selected. This network with a peak load of about 7 MW is characterized by a high portion of distributed renewable generation feeding into low voltage network parts:

- 8 power plants using biomass with an installed capacity of 3 to 250 kVA, in total 570 kVA
- 4 small water power plants with an installed capacity of 22 to 30 kVA, in total 107 kVA
- 218 photovoltaic power (PV) plants with an installed capacity of 2 to 140 kWp, in total 3634 kWp

Supported by the public funding schemes there is a high increase in the installed capacities. The data given refers to the year 2009. Currently in June 2010 the installed power of photovoltaic generation sources already exceeds the peak load. In total there is a potential of about 34 000 kWp photovoltaic power in this area which significantly exceeds the hosting capacity of the current network. Soon, it will be necessary to enforce the network to feed back the generated power to the overlaying 110 kV network. As the peak power from photovoltaic power plants is generated only during a short time during the year the usage of storage close to the sources of generation can considerably reduce or at least postpone the network extension required otherwise.

B. Simulation Approach

Different simulations have been performed by Siemens PTI, using Siemens network calculation program PSS®SINCAL. This paper presents results of different methods to evaluate the impact of EV on the network, for both deterministic calculation and probabilistic simulation (see Fig. 4).

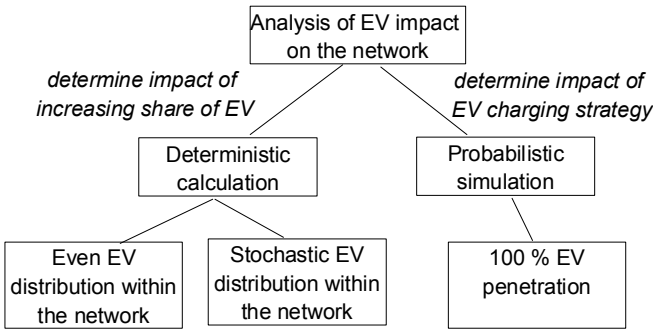

Figure 4. Description of different simulation approaches

1) Load Modelling

The existing loads were classified by customer type:

- household customers
- commercial customers
- agricultural customers
- night-storage heater
- heat pumps

For each of the customers the yearly energy consumption was measured by AÜW. According to BDEW standard load profiles for household, commercial and agricultural load segments the energy data was transformed in a daily load profile for the different week days and seasons. For the night-storage heaters and the heat pumps profiles which had been modified by AÜW to take care of the actual meteorological situation in that area were used.

Based on these standard profiles, for each single customer a separate stochastically varying yearly profile was created for the probabilistic simulation, which in total sum up to the measured consumption profile in the network.

For the deterministic calculation maximum load on each connection point was estimated based on yearly energy measurements considering corresponding simultaneity factors.

2) Generation Modelling

For probabilistic simulation the generation was modeled using the measured generation profiles for wind and photovoltaic power plants in 2008. In deterministic calculations several scenarios have been investigated

3) EV Modelling

As the future distribution of EV within the network is not known, a connection point on each existing household load is assumed. Deterministic calculations determine the impact of increasing shares of EV on the network. 100 % EV penetration is assumed for probabilistic simulations.

C. Deterministic Calculation

1) Even EV distribution

Fig. 5 provides the distribution of the loading of the lines for the scenario without renewable generation depending on the average EV power per load assuming even EV distribution

among all LV customers. While in case without EV 60 % of the lines (app. 2300 out of 3800) are loaded around 10 % of their rated capacity, this loading increases significantly with increasing EV load.

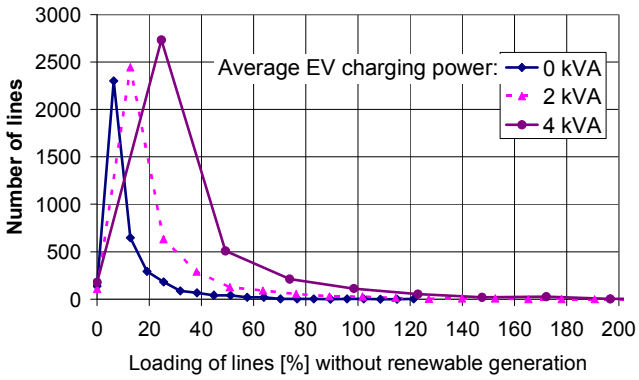

Figure 5. Line loading depending on average EV charging power

Also the number of overloaded lines increases with increasing EV penetration. Table II demonstrates the percentage of overloaded lines depending on the average EV load per existing load. As short term overloading might be possible, it is also evaluated what percentage of the lines is overloaded higher than 120 %. The loading of the lines is shown in Fig. 6 for the case of 4 kVA additionally EV charging power. The 3.5 % of the lines with loading higher than 100 % are marked in red, these with loading between 50 % and 100 % are marked in blue.

TABLE II. PERCENTAGE OF OVERLOADS, SCENARIO WITHOUT DG

Average EV load	1 kVA	2 kVA	3 kVA	4 kVA
Loading > 120 %	0.1 %	0.6 %	2.0 %	3.5 %
Loading > 100 %	0.6 %	1.7 %	3.3 %	3.5 %

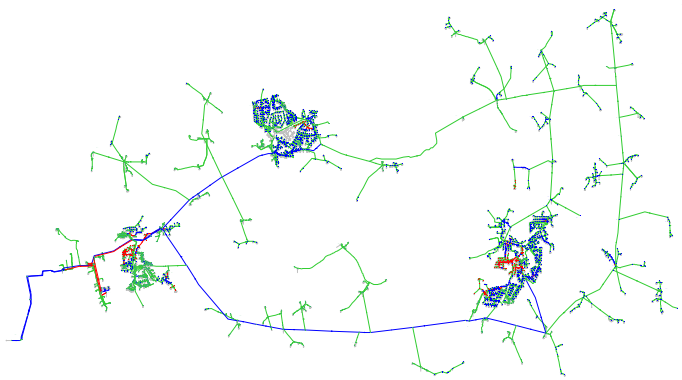

Figure 6. Network loading with EV on average 4 kVA

The hosting capacity of the network strongly depends on the average EV charging power. With the assumption of simultaneous consumption of 11 kW it can be said that for the network under consideration the maximum EV hosting capacity is in the range of 20 % without considering DG. If the charging power is reduced then more electric vehicles can be accommodated. For instance, if the charging power is reduced by an intelligent charging strategy to 2 kW then the network can accommodate an EV at every household with only minor enforcement of 1.7 % overloaded lines needed.

2) Stochastic EV distribution

A high number of repeated simulations each with different EV locations allow identification of highest and lowest impact on the network for a given EV penetration rate. More than 500 simulations have been performed to evaluate the influence of the spatial distribution of the vehicles in the network with simultaneous charging power of 3.7 kW for all vehicles. The results are shown in Fig. 7. There is a high influence on the hosting capacity depending on the location of the EV. If the vehicles are charged at the best locations from a network point of view a penetration level of about 50 % does not lead to considerable overloading of components. If the vehicles are charged at the worst locations the hosting capacity is nearly zero. Depending on actual vehicles positions the effective hosting capacity is somewhere in between.

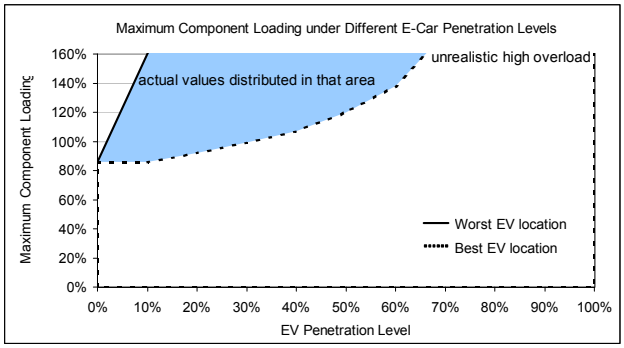

Figure 7. Impact of EV penetration level on loading

Also the maximum voltage drop in the network depends to a large extend on the actual spatial distribution of the EV within the network (Fig. 8). Therefore general statements about EV hosting capacity or the necessary network enforcements on the other hand are not possible without considering the spatial distribution. Detailed analysis of a network with probabilistic methods can define areas in which the connection of EV can be encouraged and others where it has to be discouraged. For the latter areas higher investments have to be made by the utility to integrate the EV.

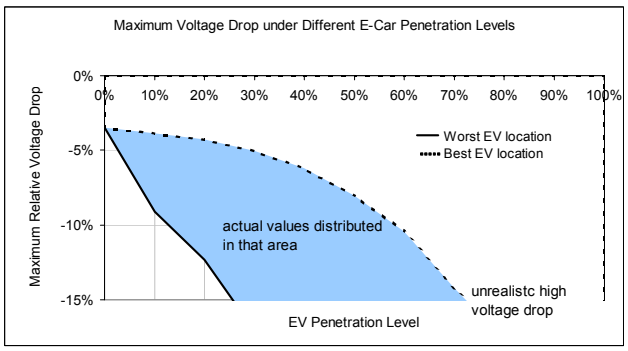

Figure 8. Impact of EV penetration level on voltage drop

Total network losses significantly increase with increasing EV penetration level, almost independent from EV location (Fig. 9).

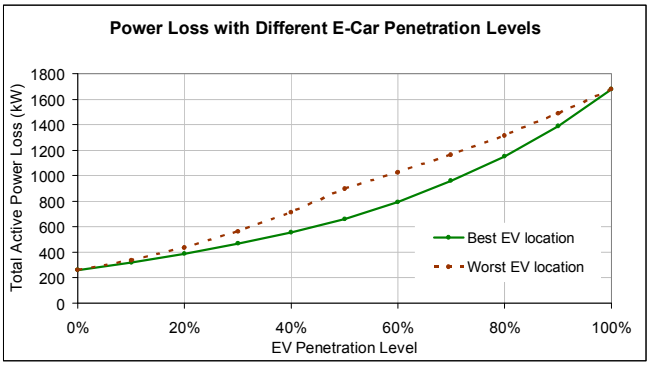

Figure 9. Impact of EV penetration level on losses

IV. SUMMARY

Based on the investigation of an example network it could be found that in the near future with expected low penetration rates of electric vehicles the networks are able to accommodate the additional loads. Minor enforcements might be necessary depending on the actual load distribution and existing weak points in the network.

To allow for a higher penetration the control of the charging power depending on the number of connected vehicles, their location and the current network state is essential. This service has to be provided by the network operator as he is the only player that has access to the current network situation with data like loading of lines, voltages.

While deterministic calculations are sufficient to determine the hosting capacity of the network in case of uncontrolled, simultaneous charging, probabilistic load flow calculations become necessary to determine the impact of intelligent charging strategies of the EV, also in combination with intermittent renewable generation.

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