Modeling and Simulation of Electric Car Penetration in the Distribution Power System – Case Study

Martin Geske
Otto-von-Guericke University Magdeburg
Magdeburg, Germany
martin.geske@ovgu.de

Martin Stötzer
Otto-von-Guericke University Magdeburg
Magdeburg, Germany
martin.stoetzer@ovgu.de

Przemyslaw Komarnicki
Fraunhofer Institute IFF
Magdeburg, Germany

Zbigniew A. Styczynski
Otto-von-Guericke University Magdeburg
Magdeburg, Germany

Abstract— **In the coming years electric vehicles will become a part of the transportation system in Europe. This contribution considers the impact of a penetration of electric cars on a distribution grid. For computations load profiles of electric cars (EC) are used by means of real battery measurements. A real low voltage grid data is used to show that security of supply could be ensured when there is a high penetration of electric cars. To forecast a certain charging demand reasonable scenarios are defined. Some conclusions and final remarks summarize the investigation presented in this paper.**

Keywords- distribution grid, electric car; security of supply; load profile

I. INTRODUCTION

The German government set a political goal to have one million electric cars in Germany by 2020. The potentials of electric driving are mainly seen in the following points [1]:

- Reduction of CO_2 and local emissions (NO_x, SO_2)
- Reduced dependency on fossil fuels
- Mobile storages to improve grid efficiency and facilitate the integration of renewable generation
- New mobility concepts for urban areas

Various studies have shown that the forecasted amount of electric vehicles needs to be viewed not only from a generation but from a grid side point of view. In [2] two scenarios were applied to estimate the market penetration of electric cars in Germany in 2020, substituting them for medium-sized vehicles. The objective was to calculate the associated energy demand and peak power demand regarding the different customer classes (typical yearly driving performance). The key findings are summarized in TABLE I.

TABLE I. FORECAST AMOUNT OF EC IN GERMANY IN 2020 [2]

Scenario	No. of EC [in Mill.]	Energy demand [TWh/a]	Peak power demand [GW]
Pessimistic	0.85	3,3	1
Optimistic	8	22,5	7

The results for the optimistic scenario show that the energy demand for electric cars would imply about 4% of the current annual electrical energy consumption in Germany. If we regard the forecasted development of the renewable generation in 2020 in Germany (from 35% [3] up to 47% [4] of total generation) and the possible operation time of the thermal power plants, the more important issue will be how to shift the load (household, industry, EC as well) to times of excess generation compared to average load profiles. In 2020 the excess generation of renewable energies at the time of low demand (night and weekend) is estimated to be about 20% in the European Union. [5]

The second aspect is the forecasted peak power demand. The electric vehicles will be charged primarily on the low voltage grid. If there is a high number of ECs being charged simultaneously the limits of the cables and, in particular, the transformers (typically 630kVA) will probably be exceeded. The peak power demand for 2020 with up to seven GW (about 8% of current peak load in Germany) will not be distributed equally in the German transmission and distribution grid. In the short and medium term ECs will be mostly used in urban areas with a high penetration in upper class residential and commercial areas. The reasons for this can be seen in the investment price for an electric car being significantly higher than for conventional vehicles and the shorter driving distance than in rural areas. Further, the specific costs to install a close charging infrastructure are lower for areas with a high population density. From what is known today it is difficult to give a general conclusion about the capability of the distribution grid to integrate electric cars. The low voltage grids in particular were dimensioned to ensure security of supply even if the consumption were to grow. In the last few decades some regions have lost a significant part of their population. It could be assumed that in those areas there are free capacities for ECs compared to cities with increasing population. Further, the grid topology should be taken into consideration to estimate the amount of ECs that could be charged at the same time.

This paper contributes to the discussion about the impact of a significant number of EC in the distribution grid. For a certain low and medium voltage grid reasonable scenarios were defined based closely on the realistic daily behavior of drivers. In the second chapter an overview about battery systems and standardized charging capacities is given. The following chapter describes how the distribution power system was modeled. This includes the distribution grid and the load profiles derived from battery testing and a statistical analysis of the driving performance of average car drivers. Finally, the simulation results are shown in chapter 4.

II. BATTERY SYSTEMS OF ELECTRIC CARS

A. Battery Technology

The most crucial aspect of electric vehicles is the quality of the applied storage. In the last two decades some promising steps were made to develop new battery technologies in particular for automotive application. Currently the nickel-metal hydride (NiMH) is the most common battery system applied in electric cars globally. The most important advantage of NiMH over other technologies can be seen in durability and safety issues. Nevertheless, there are still manufacturers offering electric cars with lead acid batteries, mainly due to their low costs and availability. The lack of cycle-life anticipates a relevant market penetration on a medium term perspective. Currently the nickel-metal hydride (NiMH) is the most common battery system applied in cars that are fueled partly by an electric powertrain (hybrid cars). The most important advantage of NiMH over other technologies can be seen in durability and safety issues. The energy density is higher than in lead acid batteries but lower than in modern lithium based batteries [6]. A further technology being applied is the so called ZEBRA battery (Na-NiCl). The sodium-nickel chloride batteries operates at about 300°C, which means that energy must be used to maintain the high temperature in times of no or low power operation. Further, ZEBRA batteries are characterized by a high discharge rate. The main advantage of these batteries is an insensitive behavior towards temperature and high cycle efficiency. The energy density is about 120Wh/kg which is higher than for lead acid batteries. [7]

But in the long run the lithium based batteries (lithium-polymer, lithium-air, and other material combinations) will establish themselves as the leading battery technology for electric cars. They have three main advantages: the energy density could be increased by further engineering (up to 200Wh/kg in the short term [1]), self discharge per month is very low (5% for Li-ion vs. 30% for NiMH [8]) and the costs could be dropped under the level of NiMH by large-volume production (economies of scale) [9].

The following items must be achieved by all battery manufacturers to meet the requirements of the OEM [10].

- Low cost
- High cycle-life
- High power delivery and fast recharge capabilities

In [9] the applicability of Li-Polymer (Li-Po) batteries (146Wh/kg, 3.7V, 100Ah) for electric cars was investigated. They concluded that Li-Po batteries are fully capable of application in electric cars. The battery works in a wide temperature range with high efficiency. The high energy density and the fast chargeability fulfill mostly the requirements described above.

B. Standardized charging capacities

For grid planning issues it is necessary to estimate the load to charge the electric cars. The related standard IEC 61851-1 describes four types of connection between the EC and the grid. In this regard the most important aspect is the maximum power being consumed (see TABLE II). Connection type one and two are applied in the private area (charging in the garage). Types three and four belong to charging spots that could be placed in the city core or other point of interests (POI).

TABLE II. CONNECTION TYPES FOR ELECTRIC VEHICLES [11]

Connection type	Loading power
House connection (type 1) Max. 16A per phase	Up to 3.7kW (single phase) Up to 11kW (three phases)
Home connection (type 2) Max. 32A per phase	Up to 7.4kW (single phase) Up to 22kW (three phases)
Charging spot (type 3) Max. 32A per phase	Up to 7.4kW (single phase) Up to 22kW (three phases)
Fast charging (type 4)	Up to 400A (DC)

For type 4 the battery charger will be installed in the charging spot. The EC needs to be fitted up with the proper ICT to communicate with the charging point. The battery charger is controlled by a remote signal that is sent by the EC; regarding the peak power the charging spots are to be connected directly to the medium voltage level (15-20kV). From what is known so far there are currently no large-scale installations.

III. CASE STUDY MODEL

A. General remarks

The modeled power system consists of a 10 and 0,4-kV distribution power network at the Otto-von-Guericke University Magdeburg and the determined load profiles. The entire network was reduced down to the amount of loads which can be modeled by means of measured load profiles within the time range of 24 hours. The network topology and the included electrical equipment as well as their parameters were implemented within the simulation software. The different scenarios of electric car penetration were taken into consideration through determination of real arrival times in relation to a specific parking lot and the estimated distances of the arriving cars. Furthermore, a traction battery was modeled with reference to the charging characteristic. Hence instantaneous charging processes of electric cars were mapped to different EC penetrations. The intended scenarios were adapted in each case to a resulting load profile for the connection point near the chosen parking lot.

B. Distribution Network

The modeled distribution power network in Figure 1 consists of a 10kV cable system connected to an urban distribution network. The loads are each presented by the amount of individual loads of a building and are connected over a 0.4kV three-phase system to the 10kV power system by means of intermediated transformers. The distribution network contains seven low-voltage nodes connected to their loads and five medium-voltage nodes. The eight medium-voltage lines have been modeled according to the transmission line Pi-equivalent circuit. As already mentioned, the modeled topology derives from a more complex system but implies a similar structure due to the fact that the neglected lines were mostly connected to the medium-voltage node west (cp. Figure 1). The network was reduced including the measured load profiles at the low-voltage nodes b1 to b7 taken from [12].

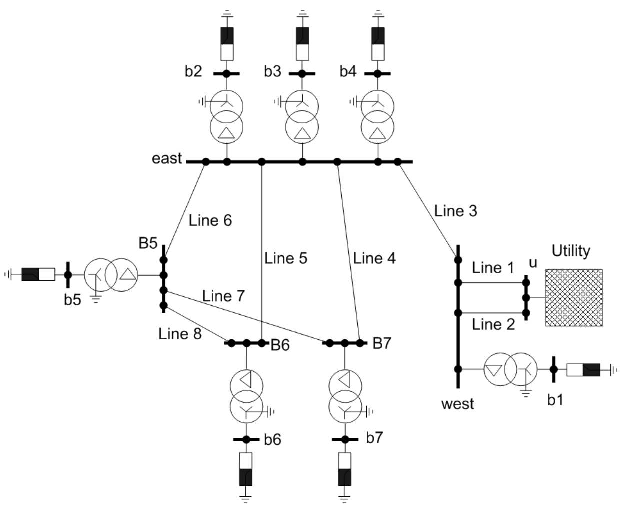

Figure 1. Topology of the modeled distribution power system

C. Scenarios of Electric Car Penetration

First, a well suited parking lot for a meaningful future electric car application was chosen near the node b6. The parking lot at the particular building enables optimal distances to all important buildings. The amount of individual parking places was determined to be 74. The applied scenarios are distinguished between low and high penetration of electric cars within the quantity of parked cars. The average utilization of the parking lot was estimated at 95%. Thus, the quantity of used parking places correlates finally to 70. The percentages and amounts of arriving electric cars were set as shown in TABLE III corresponding to the estimated 70 parking places being used.

TABLE III: DEFINED SCENARIOS OF DIFFERENT EC PENETRATION

Parameter	Scenario compositions	
	Minimal EC penetration	***Maximal EC penetration***
Percentage of EC at parking lot / University	15.7% / 2.6%	95.7% / 15.7%
Quantity of EC	11	67

To estimate the different arrival times of the future EC fleet the total number of arriving cars were counted in regard to their arrival times in the morning at the entries of parking lots at the Otto-von-Guericke University. The total number of cars arriving between 6:30 a.m. and 9:00 a.m. were counted within time intervals of 10 minutes at the entries to the parking lots at the university. The amount of arriving cars and their associated arrival times for the simulation scenarios were then downscaled to the 70 parking places of the modeled parking lot. The calculated EC penetrations related to the total amount of arriving cars at the university achieve approximately the percentages of the expected optimistic and pessimistic scenarios in TABLE I oriented to the total number of 41.7 million cars in Germany (cp. [13]). Figure 2 shows the counted cars in relation to their arrival times within the day of the count (white bars), whereby cars that exited the parking lot during counting were subtracted from the amount of counted arriving cars at University.

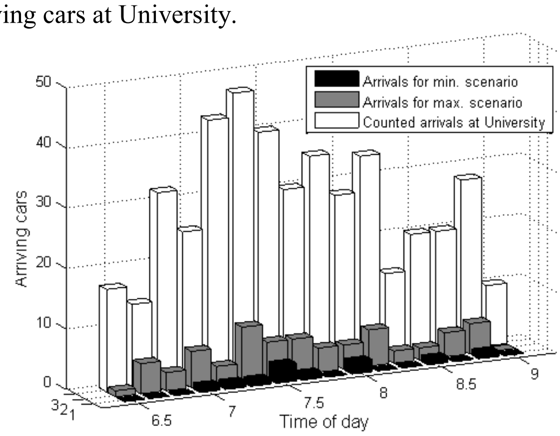

Figure 2. Counted arrivals at the University and downscaled arrivals for the simulation scenarios

The arrivals were downscaled to the total number of arriving EC by means of a randomized algorithm within the defined scenarios shown in TABLE III and shown by means of black and gray bars in Figure 2. It should be mentioned that the arriving cars were counted during morning of a test working day and the defined scenarios assume no leaving cars, so that all EC would be able to fully charge their batteries during the day. The charging time and the related power consumption of an EC are closely related to the previously estimated distance. Therefore, the covered distances of the arriving cars were allocated to each EC with regard to the statistical analysis of the average driving performance for a typical city [14], which defines the current state of charge of the associated ECs. Finally, the model of the used traction battery and its charging characteristic determines the individual load profile depending on the state of charge and the arrival time.

D. Charging Characteristic of Electric Car

The traction battery was sized within the modeling to an energy content of 20kWh. This amount was fixed to ensure a range about 100km for an assumed middle-class car with an average energy consumption of 20kWh per 100km [6]. In this respect an already investigated Lithium Polymer battery (LiPo) was modeled. The active and reactive power consumption in relation to charging characteristic was determined considering the efficiency and the power factor (cosφ) of the chosen battery charger [15].

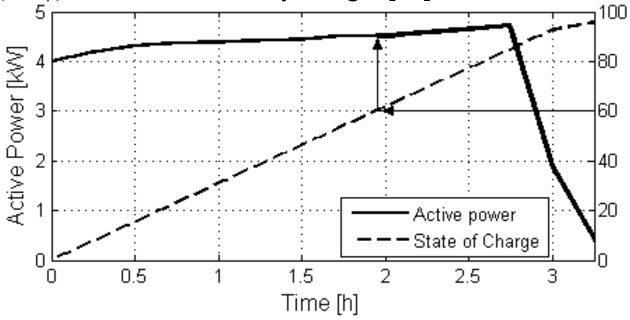

Figure 3. Modeled charging characteristic of an EC

Figure 3 shows the relationship between the charging power and the state of charge (SoC) of the modeled electric vehicle. Depending on the SoC the analyzed EC the respective charging characteristic and the charging time can be determined using this figure. As an example 60% SoC need about 2.5 hours to reach the fully charged state, whereas the resulting load profile derives from the curve section of active power marked bold (cp. clarifying arrows in Figure 3). The resulting charging characteristic and the corresponding SoC are the basis of the further computed load profiles related to the estimated state of charge of the arriving cars.

E. Computation of load profiles

The measured load profiles from the case study network, which were allocated to the low-voltage nodes without charging stations for EC's at node b6. The downscaled arrivals (see Figure 2), the assumed charging characteristic (respectively the state of charge) were added to the measured load profiles of the b6 node depending on the scenarios.

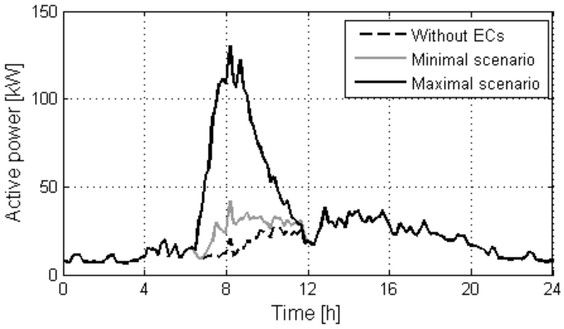

Figure 4. Load profiles for active power at node b6 (at parking lot)

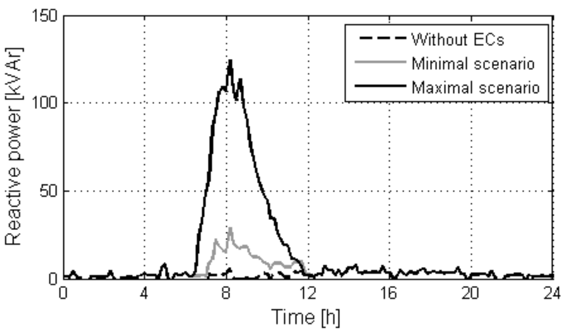

Figure 5. Load profiles for reactive power at node b6 (at parking lot)

The resulting load profiles in Figure 4 and Fig. 5 show that the scenario of maximal EC penetration causes an expected several times higher peak demand between 7:00a.m. and 12:00 noon in comparison to the normal load profiles. The active power consumption reaches a 7 fold higher value in comparison to the measured load profile. The reactive power consumption in Fig. 5 was calculated considering the cosφ=0.68 of the chosen battery charger. The relatively low power factor of the charger leads to a considerable higher reactive power load profile in comparison to the active power load profile (cp. Figure 4 and Fig. 5).

IV. SIMULATIONS AND DISCUSSION

A. Background of the simulations

The previously described modeling was implemented within the simulation software. That will be used to study values such as line currents in the medium voltage section and voltage profiles of chosen nodes. Concerning the high elevated reactive power consumption induced by instantaneous charging processes (cp. Fig. 5), the voltage stability at node b6 will be investigated beforehand.

B. Voltage stability

Reactive power consumption induces a decreasing voltage at the specific node without equipment for power factor correction. Due to the used transmission line Pi-equivalent model the reactive power demand (capacitive manner) of the 10kV cables is proportional to the current squared. Hence, the ramp wise elevation of active and reactive power at node b6 indicates the stability limit of the power system. In terms of the chosen battery charger the ratio between active a reactive power was fixed by cosφ for the ramp wise elevation at bus b6. The other loads were fixed to their averaged power consumptions (cp. TABLE IV) to keep an estimated operation point during ramp wise elevation of active and reactive power.

TABLE IV. AVERAGED POWER CONSUMPTIONS OF LOADS

Load	Active power [kW]	Reactive power [kVAr]
b1	17	4
b2	64	10
b3	62	11
b4	25	6
b5	53	21
b7	40	1

The line properties (cp. TABLE V) of the 10kV cable system and the load characteristic were considered within the simulation model for an exemplary simulated P-V-curve. The P-V-curve in Figure 6 reveals the influence of power demand caused by multiple charging processes by means of the chosen battery charger and its power factor.

TABLE V. CABLE PARAMETERS OF THE SIMULATION MODEL

Line	Line length [km]	R' [Ω/km]	X' [Ω/km]	Cb' [nF/km]	Co' [nF/km]
1	1.157	0.326	0.083	350	192
2	1.288	0.167	0.077	478	262
3	0.385	0.167	0.077	478	262
4	0.294	0.200	0.091	350	192
5	0.256	0.200	0.083	350	192
6	0.245	0.167	0.077	478	262
7	0.074	0.153	0.081	392	215
8	0.070	0.170	0.077	478	262

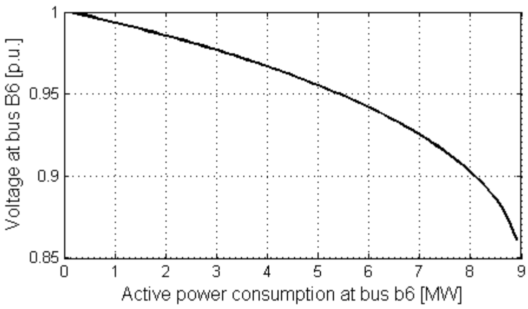

Figure 6. Voltage instability at 10kV bus B6 due to rising power consumption (cosφ=0.68) at bus b6

The simulated voltage stability limit is closely located at 9MW active and 10MVAr reactive power consumption. Taking into consideration the load profiles of both scenarios (see Figure 4 and Fig. 5) the point of voltage instability is located far above the expected active and reactive power consumption. Thus, the distribution power system appears robust in terms of elevated power consumption induced by multiple charging processes at the same time.

C. Voltage profiles

Despite the robust properties of the distribution power system the voltage profiles of chosen nodes has been simulated to disclose the impact of multiple charging processes, whereby tapped transformers were not considered. The simulation of the voltage profiles was done for the medium voltage node u, directly connected at the supply of the urban power distribution system and the low voltage node b6 directly located at the parking lot of the ECs.

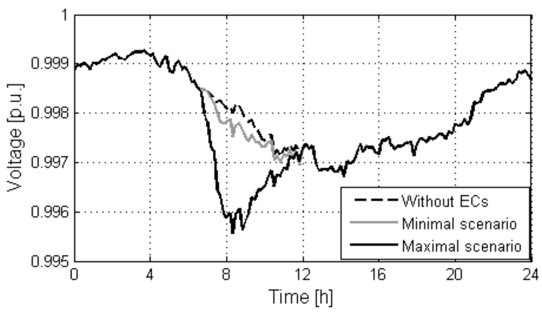

Figure 7. Voltage profile at node b6 (at parking lot)

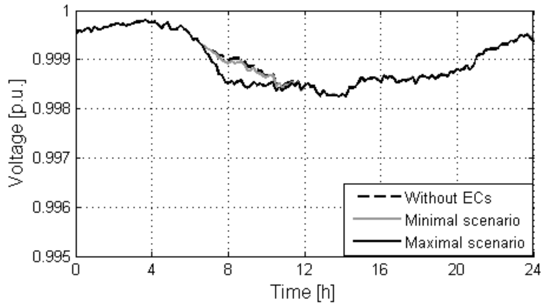

Figure 8. Voltage profile at node u (at power supply)

The comparison of the simulated voltage profiles in Figure 7 (node b6) and Figure 8 (node u) shows that node b6 is much more strongly exposed to a decreased voltage profile. Node u at the power supply benefits from the network topology but is also affected by voltage dropping. Referring to [16] the limitations of voltage characteristic for slow and fast voltage variations (±10%) were not exceeded. In this regard we could conclude that the distribution network appears to be properly dimensioned for the intended scenarios.

D. Line Currents

The simulated line currents reveal the elevation of loading. Furthermore, the losses caused by the line currents can be evaluated in relation to the different scenarios within the medium-voltage cable system. No-load losses and losses referring to power factor correction as well as according to the low-voltage system were not focused on in the further studies.

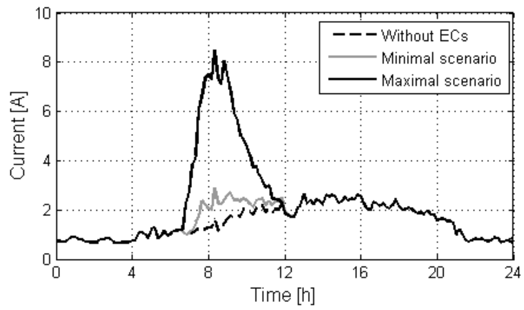

Figure 9. Currents in Line 5 for different scenarios

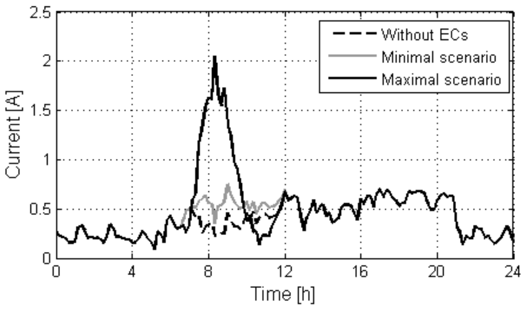

Figure 10. Currents in Line 8 for different scenarios

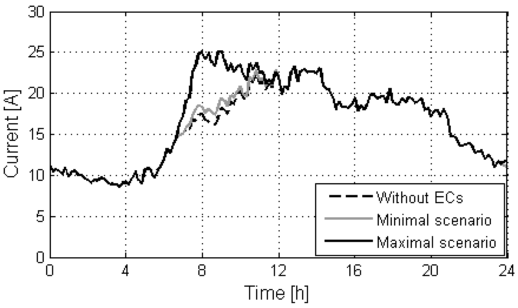

Figure 11. Currents in Line 3 for different scenarios

Figure 9 and Figure 10 show that the connection over two medium-voltage nodes from supply node u to node b6 using line 8 is more strongly affected than line 5. Nevertheless, the proportions between the current curves for the simulated scenarios are preserved. The current curves in Figure 11 reveal that the maximal current for the scenario with maximal EC penetration surpasses slightly the maximal value of the simulation without ECs.

The current dependent losses of the lines can be calculated through the simulated currents by the use of (1) and (2). To achieve a well suited comparison the total losses of energy through the line currents was set into relation to the value of the conditions of the power network without ECs.

$$P_{loss} = 3 \cdot I_{line}^2 \cdot R'_{line} \cdot l_{line} \tag{1}$$

$$W_{loss} = \int_0^t P_{loss} \cdot dt \approx \sum_{i=1}^n P_{loss}(i) \cdot \Delta t \tag{2}$$

The current dependent losses of the medium voltage lines without charging ECs was calculated to a total amount of 4.39kWh. The minimal penetration of ECs would cause comparatively 1.9% higher losses, whereas the maximal scenario would produce 12.4% more losses as compared to the conditions without ECs.

V. CONCLUSION

The future energy demand and the impacts on power systems caused by charging traction batteries of ECs were studied within a modeled distribution power system. The impact of multiple charging ECs on the distribution power system was studied by means of defined scenarios related to the arrival times and the state of charge, which result in cumulated load profiles consisting of individual charging curves and the measured load profile of the chosen low-voltage node. In general the distribution grid is suitable to integrate the significant number of ECs that has been forecasted.

An initial determination of the voltage-stability limit within the distribution power system showed that the assumed scenarios would not cause a voltage-instability. In this case the point of voltage-instability would occur at an almost ten times higher active and reactive power peak demand at the chosen node. Hence, the distribution network appears robust and suitable in case of EC applications within the defined scenarios.

Voltage profiles simulated for the chosen nodes revealed relatively low voltage dropping as a result of multiple charging processes. This statement can be seen in context to the previously specified voltage-stability limit. Nevertheless, maximal EC penetration causes a comparatively larger voltage drop, down to 0.996p.u. Moreover, simulations showed that the node at the power supply would be less affected or rather the maximal voltage drop induced through EC charging is negligible in comparison to the total load within the power system.

Further studies are needed to investigate the grid more deeply as well as the quality of supply. Firstly, the virtual EC limit will be ascertained in terms of not tolerable grid conditions. An estimation will be done between grid enhancement and reducing the number of EC that charge at the same time (concurrency factor). A second issue will be the quality of supply. Battery chargers have typically no power factor correction. The impact of the increasing demand of reactive power will be studied.

REFERENCES

[1] German Federal Government, "Nationaler Entwicklungsplan Elektromobilität", http://www.elektromobilitaet2008.de/, accessed March 10th, 2010.

[2] T. Blank, "Elektrizitätswirtschaftliche Einbindung von Elektrostraßenfahrzeugen", study for E.ON Energie AG, 2007.

[3] Pilot Study 2009, German Federal Environment Ministy, www.bmu.de, accessed April 20th, 2010.

[4] "Stromversorgung 2020 – Wege in eine moderne Energiewirtschaft", German Association of Renewable Energies (BEE), 2008.

[5] German Association for Electrical, Electronic and Technologies - VDE, "Smart Distribution 2020", study, 2008.

[6] M. Kromer, J.B. Heywood, "Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet", Sloan Automotive Laboratory (MIT), 2007.

[7] German Association for Electrical, Electronic and Technologies - VDE, "Elektrofahrzeuge – Bedeutung, Stand der Technik, Handlungsbedarf", study, 2010.

[8] C.D.Dustmann, "Advances in ZEBRA batteries", Journal of Power Sources, vol. 127, 2004, pp. 85-92.

[9] B.G. Kim, F.P. Tredeau, Z.M. Slameh, "Performance Evaluation of Lithium Polymer Batteries for Use in Electric Vehicles", IEEE Vehicle and Propulsion Conference, China, 2008.

[10] A. Du Pasquier, I. Plitz, S. Menocal, G. Amentucci, "A comparative study of Li-ion battery, supercapacitors, and nonaqueous asymmetric hybrid devices for automotive applications", Journal of Power Sources, vol. 115, 2003, pp.171-178.

[11] DIN Deutsches Institut für Normung e.V., "Electrical equipment of electric road vehicles, Electric vehicle conductive charging system" German version IEC 61851-1:2001, Beuth Verlag, Germany, 2001.

[12] C. Dzienis, "Ersatzmodelle nichtlinearer Lasten in elektrischen Verteilungsnetzen," Doctorial Thesis, Otto von Guericke University Magdeburg, Magdeburg, Germany, 2007.

[13] Kraftfahrt-Bundesamt (KBA) – Federal Motor Transport Authority, "Jahresbilanz des Fahrzeugbestandes am 1. Januar 2010," http://www.kba.de, accessed Mai 7th, 2010.

[14] German Federal Ministy of Transport, Construction and Housing; BMVBW, 2003.

[15] ZIVAN S.r.l., "BATTERY CHARGER NG3 – Installation and User Manual," Second Edition, D01058-02, Sacramento, Canada, 2003.

[16] DIN Deutsches Institut für Normung e.V., "Voltage characteristics of electricity supplied by public distribution networks," German version EN 50160:2007, Beuth Verlag, Germany, 2008.