Grid Impact of Electric Vehicles with Secondary Control Reserve Capability

Thomas Degner
Division System Technology and Distribution Grids
Fraunhofer IWES
34119 Kassel, Germany
thomas.degner@iwes.fraunhofer.de

Gunter Arnold, Ron Brandl, Julian Dollichon, Alexander Scheidler
Division System Technology and Distribution Grids
Fraunhofer IWES
34119 Kassel, Germany

***Abstract*— In frame of the research project INEES the provision of secondary control reserve by a pool of electric vehicles has been developed, implemented and tested in laboratory environments as well as under realistic operation conditions and in a pilot field test. In this paper the impact on distribution grids were analyzed by means of simulation studies, field measurements and measurements in a realistic laboratory environment:**

A detailed study concerning the effect on distribution grids analyzing possible congestions, violations of static voltage limits and loading of network assets was performed. The analysis show that presently congestions in the network occur only rarely. Measurements at the grid connection point of the charging stations concerning power quality aspects during the operation of a small fleet of electric vehicles were executed over a one year period. The evaluation of the records show, that there is no negative impact on the distribution grid considering power quality. Finally a system of four electric vehicles with experimental bidirectional DC charging stations was tested in one grid feeder together with further distributed generation. Even while operating close to operational limits of the network the system performed well and as expected.

In conclusion, the successful grid integrated of electric vehicles with bidirectional charging station for the provision of secondary control reserve could be demonstrated. Even with a high share of electric vehicles, the impact on the distribution grid is very well predictable and different approaches indicate that the impact can be managed quite well.

Keyword: ancillary services, distribution grid, electric vehicles, pilot test, secondary control reserve

I. INTRODUCTION

In the frame of the project INEES (Smart Grid Connection of Electric Vehicles Enabling Ancillary Services) technical requirements for ancillary services for the transmission network delivered by a pool of electric vehicles, as well as their effect and value have been investigated. Based on this, business processes including required communication interfaces between driver, vehicle, grid operator and utilities has been worked out and turned into corresponding IT solutions [1][2].

As part of the project the impact of electric vehicles and the experimental bidirectional DC-charging stations – which were developed in the project - was analyzed and also the impact of a future extension of electro mobility on the distribution grid was researched. In particular the provision of control reserve, i.e. the simultaneous charging or discharging of a pool of electric vehicles was considered.

The investigated points are the analysis of the impact of electric vehicles on distribution networks in future scenarios with a large amount of electric vehicles (section 2), the analysis of the grid impact in terms of power quality measured during a one year pilot tests (section 3) and performance and operational tests of a group of electric vehicles with bidirectional charging station (section 4). For the simulation studies, as well as for the laboratory investigations, grid situations and configurations in adaptions to German distribution networks are assumed.

II. ANALYSIS OF THE IMPACT ON DISTRIBUTION NETWORKS IN FUTURE SCENARIOS WITH A LARGE AMOUNT OF ELECTRIC VEHICLES

During the project a pool manager was developed. The “LichtBlick-SchwarmDirigent®” is a central instance that decides the actions of every single electric vehicle (EV) contained in a pool of electric vehicles. In order to provide secondary control reserve the pool manager controls (a part of) the EVs in the pool to simultaneously charge or discharge via a bidirectional charging station. Clearly, this may have an impact on the distributions grids which depends on the specific properties of the single grids as well as the number and power level of EVs and charging stations respectively, that participate in providing secondary control reserve.

To identify critical penetration rates of EVs studies of 310 low voltage networks were conducted. In order to assess the EV hosting capacity of a single network 50 probabilistic

EV penetration scenarios were simulated. An EV penetration scenario defines the grid connection points of all considered EVs. More precisely, starting from an empty grid repeatedly single EVs are assigned at random free grid connection points. After every introduction of a new EV a load flow calculation is performed and it is determined if one of the following violations occurs:

- Voltage violations according to DIN EN 50160 (voltages at low-voltage levels must not deviate more than 10 % of the targeted 400 V)
- Overload of cables due to exceedance of thermal current limits
- Overload of transformers due to exceedance of rated power

If no violation occurs, the process is continued until all possible connection points of a grid are occupied. If, on the other hand, a violation occurs the maximal number of EVs that the grid can host is noted and a new scenario is simulated.

Besides the grid connection points of the EVs also the specific load scenario has to be defined. In analogy to the design process of distribution networks used by distribution system operators, two worst-case load cases have been simulated in network calculation software. In the “high-load” scenario all customers consume the maximum power while there is no feed-in by distributed generation (DG). Additionally, all EVs supply negative control energy, which means charging simultaneously at full rated power (10 kW). On the other hand, in the “low-load” scenario consumers consume only a minimum of power while DG feed in maximal power. Moreover, the considered EVs supply of positive control power (-10 kW) means a power feedback at their maximal power rate.

In Fig. 1 an example of a low-voltage network with 91 households (grey rectangles) is depicted. As can be seen, the positions of the bidirectional charging EVs (blue rectangles) can strongly influence the maximal power the grid can absorb before violations occur. The simulations of 50 different randomly generated scenarios provide a statistical distribution of the maximal control energy the network can transmit.

The previously illustrated approach has been applied to 310 models of low-voltage grids located in predominantly rural areas (see Fig. 2). The results show that, following the defined worst-case assumptions, a sixth of the grids would not be able to host any bidirectional feeding EV. The reason is that in many of these networks the number of installed PV plants is already at the limit. This results in high loading in the low-load case, limiting the control reserve the grid is able to absorb. However, the results also show that the majority of the studied networks are able to host EVs that provide bidirectional control reserve even at very progressive predictions of EV penetration rates.

According to the conducted simulations mainly violations of the allowed voltage band and overloading of transformers are expected. Possible solutions for the voltage problems are for example on-load tap changer at the LV/MV substations or power flow dependent target voltage controlling at medium-voltage levels.

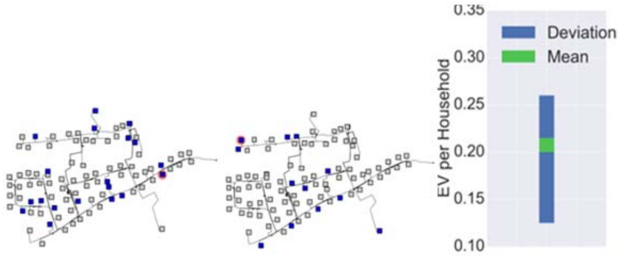

Figure 1. *Determination of the electric vehicle hosting capacity of a LV network with the help of probabilistic simulations. Left: Scenario 1 voltage violation with 25 EV; Middle: Scenario 2 voltage violation with only 12 EV; Right: Estimation of hosting capacity by analysis of 50 different, randomly generated, scenarios. Each scenario is characterized by a different EV distribution.*

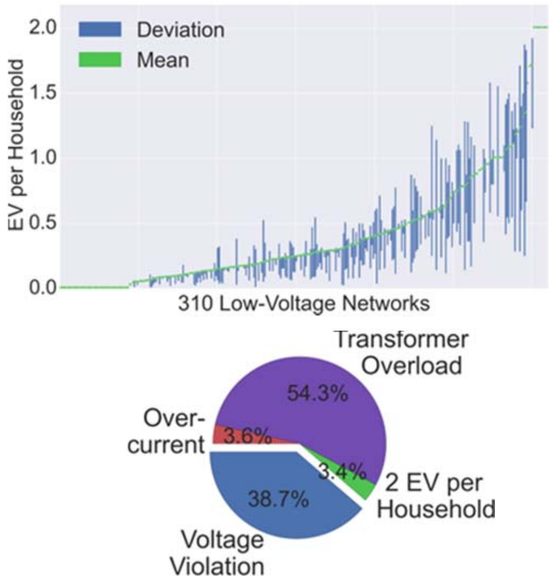

Figure 2. *Hosting capacity and type of expected constraint for 310 analyzed LV networks.*

By default, the simulated EVs provided reactive power according to the German grid connection guide line AR-VDE 4105 [3]. Compared to no provision of reactive power the results show that this increases the hosting capacity of the networks by 0.134 EVs on average for networks with voltage violations.

To assess the influence of the EVs on the medium voltage (MV) level an investigation of 35 distribution grid models was conducted. In contrast to the approach used for studying the low voltage networks, for the medium voltage investigation the future expected increase in power from distributed renewable energy plants was considered. To this end, the scenarios of the German Netzentwicklungsplan 2014 [4] were used to define possible future scenarios. That is, based on the area covered by the MV networks and the number of grid connection points, the prognosticated PV penetration was scaled to fit the network. Clearly, the models reflect the networks in their current state of operation. Therefore, the evolution of the grid that will take place in the next years is not modelled. This explains why the simulations showed massive grid overloading even when assuming only the predicted growth in renewable energy plants without any EV. Two thirds of the networks analyzed cannot be operated in 2024 in their current condition even with deployment of power flow dependent voltage controlling at the HV/MV substation. This is in accordance with different studies that show that long-term network reinforcement will be necessary [5]. Simultaneously in-feeding EVs would additionally increase necessary extent of grid reinforcements, because of sharing network hosting capacity with the EE systems.

Possible measures to prevent EV induced grid reinforcement must limit the provision of secondary control reserve at times of high feed-in by DG. If the Pool Manager would have knowledge of the (expected) network state and it could incorporate this knowledge in its decisions by reducing the number of EVs that participate in the secondary control reserve delivery at certain hot-spots in the distribution system. However, to date there is no possibility to obtain the necessary data to be able to incorporate the exact state of arbitrary networks. Instead, the data is kept by the distribution system operators (DSOs).

A different approach would be to completely refrain from offering positive secondary control at certain times. In the following, an estimation of the number of hours within a year at which one could not take part in the secondary control market is sketched. In Fig. 3 (left) the measured power flow over a HV/MV substation of an example medium voltage network is depicted. Values greater than zero correspond to a power flow toward the higher voltage level, i.e. the generation within the network is larger than the consumption. As can be seen in the selected grid there is already a large amount of DG power installed. However, the grid is able to host these values, as the DSO is obligated to secure the functioning of the network. Clearly, at times where the load flow is less than 30 – 5 = 25 MW it should be save to provide 5 MW secondary control by the EVs (assuming a reasonably even distribution of EVs). Depending on the amount of secondary control reserve one wants to offer, the fraction of hours of the year at which this is feasible varies. In Fig. 3 (right) it can be seen, that for reasonable amounts of offered secondary control reserve the number of hours is in the lower percent area. Clearly, one has to keep in mind, that this analysis is post-hoc. In real operation (day-ahead) estimates would be necessary to be able to apply this approach.

One important note is that the investigation assumes that all present EVs take part in the secondary control provision. However, the project revealed that in reality only a part of cars are available to control by a pool manager.

III. Analysis of Grid Impact During a Pilot Test

A core part of the INEES project was a pilot test in Berlin, where two times 20 participants were supplied with an electric vehicle and bidirectional DC-charging station. As part of the pilot test Fraunhofer IWES performed detailed measurements on the grid side of the charging station in order to monitor in detail any impact on the distribution grid. Three charging stations have been selected for detailed monitoring. Besides measurements of the electrical power (active power, reactive power) also voltages, currents and power quality parameters (voltage changes, flicker, harmonics) where measured and recorded. The subsequent evaluation of the recorded data mainly focused on:

- Provision of control reserve power (5 s-values): temporal evaluation, dynamics, precision.
- Interactions at the grid connection point between charging station and distribution grid (10 min-values)

Fig. 4 shows the provision of secondary control reserve power based on a charge/discharge schedule specified by the pool manager “LichtBlick-SchwarmDirigent®” for one electric vehicle (EV) over a time period of about 11 hours. Positive active power corresponds to energy provided by the grid, charging of the EV storage and a negative control power respectively. On the other hand negative active power corresponds to positive control power, discharge of the storage and active power feed into the grid.

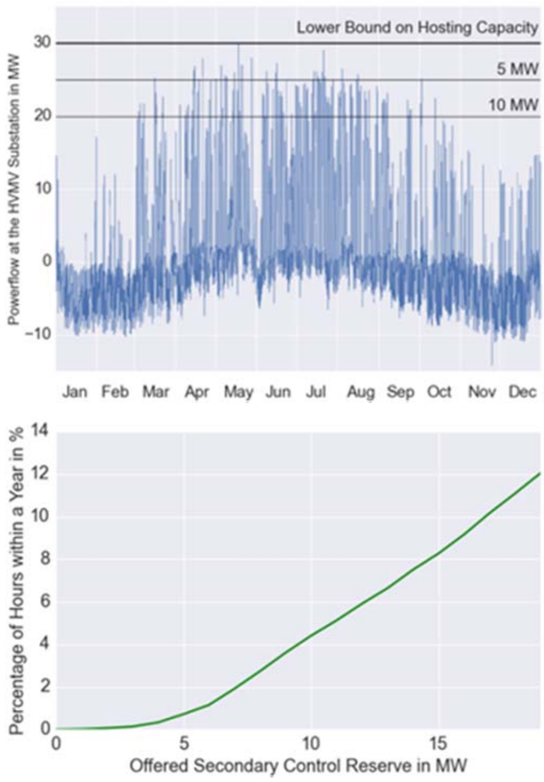

Figure 3. *Top: Measured power flow over a High Voltage / Medium Voltage substation. Bottom: Percentage of hours the offered control reserve could not be provided.*

It can be well observed, that the active power for both conditions is nearly perfectly balanced to the three conducting lines. Furthermore it could be shown, that the active power actual delivered matched very well the set value provided by “SchwarmDirigent®”

Beside measurements concerning the provision of control reserve the power quality characteristics (voltage changes, flicker, harmonics) were a further focus of the analysis. It could be shown, that also in real operation no violation of power quality parameters could be observed (see Fig. 5).

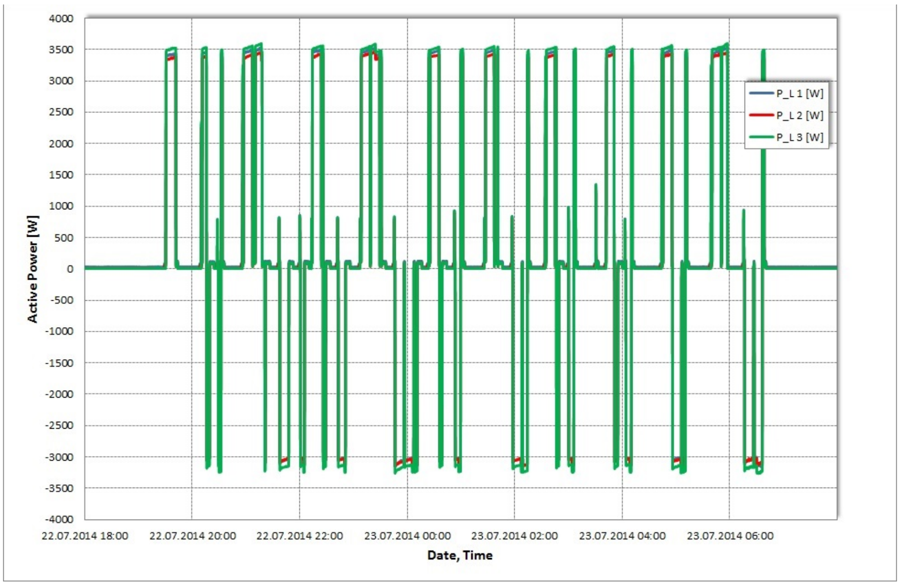

Figure 4. *Provision of control reserve according to a defined charge/discharge schedule from 22.7.2014 to 23.7.2014. Displayed are all 3 phases.*

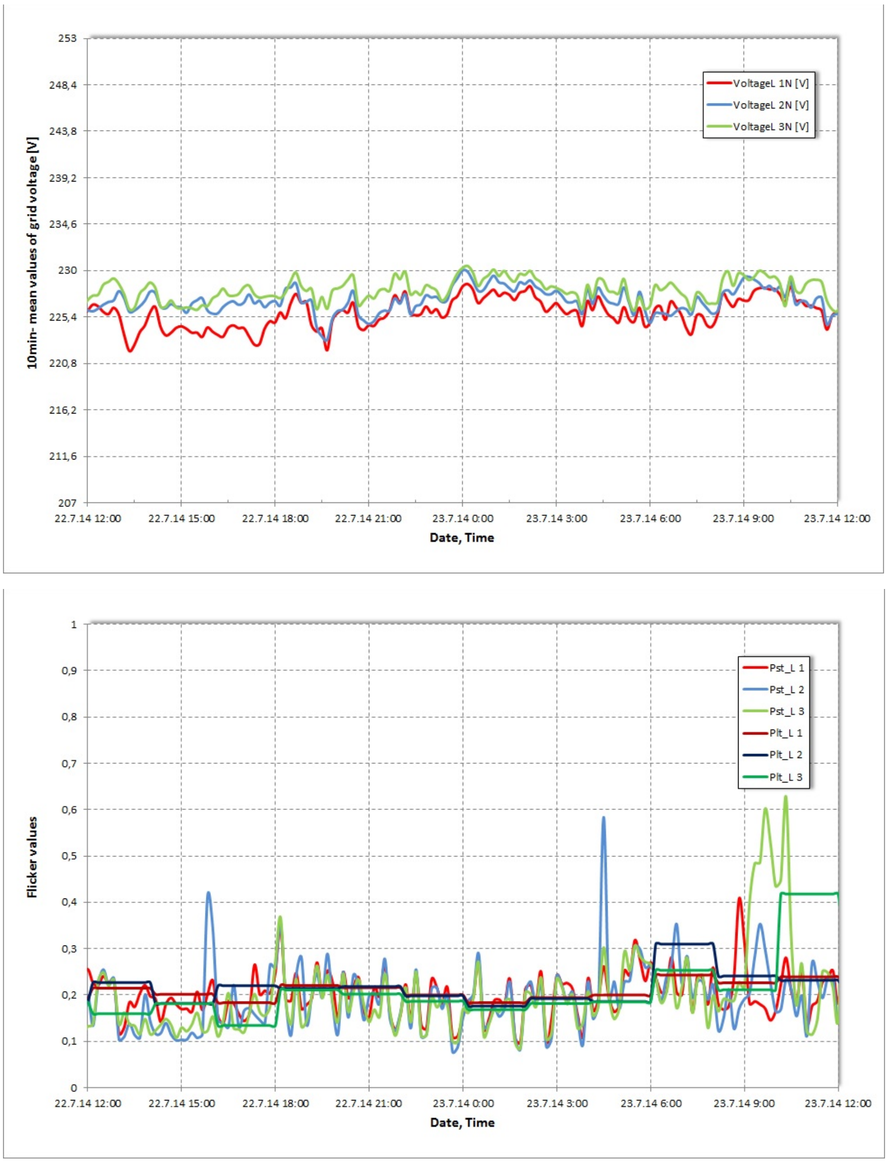

Figure 5. *Measured voltage and flicker values during a 24h period 22.7.2014 to 23.7.2014. Displayed are all 3 phases.*

IV. Performance and Operational Tests of a Group of Electric Vehicles with Bidirectional Charging Stations

In order to perform further functional tests and testing any impact on the grid additional investigations were conducted after the pilot test. These tests were performed at the Fraunhofer IWES Test Centre for Smart Grids and Electro-mobility (SysTec). The setup consisted of four electric vehicles and four bidirectional DC-charging stations, respectively. The charging stations were connected to a physical low voltage distribution grid branch as seen in Fig. 7. In adaptation to the German grid connection guideline AR-VDE 4105 different experiments concerning frequency and voltage limits, flicker and harmonic, set-point precision and power flows were performed. The impact of high electric vehicle penetration was investigated in further experiments.

Considering performance and operational tests, different setups and grid topologies were realized to analyze performance and interactions between charging stations and photovoltaic (PV) systems. Three different network configurations were built-up: a single grid feeder with a homogeneous distribution of charging stations, a grid part with two feeders in parallel and a long feeder with one charging station at the end.

Figure 6. *View of the experimental setup in the Fraunhofer IWES SysTec*

4.1 Provision of secondary control reserve and static voltage change for different network configurations

Fig. 7 depicts a single feeder with homogeneous distribution of four systems consisting of charging stations and electric vehicles. These systems are illustrated as houses.

Highlighting the impact of charging or discharging a group of EVs in low voltage networks, different profiles for the active power set point were applied. Therefore to investigate the relation between voltage change and power variation experiments were carried out where four charging stations injected or consumed power at different active power level.

Fig. 8 (top) shows the total active power flow over the network (blue) as well as the power consumption (neg. power) or injection (pos. power) of each house (charging station) over the time. This experiment was made by using power changes between ±35 kW on one feeder with a 50mm² cable cross section.

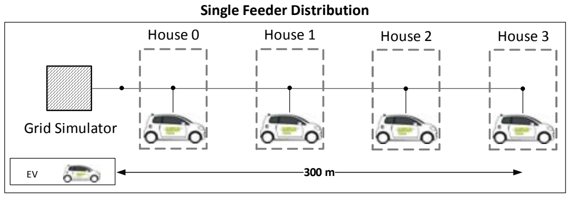

Figure 7. *Setup for a single feeder with a homogeneous distribution*

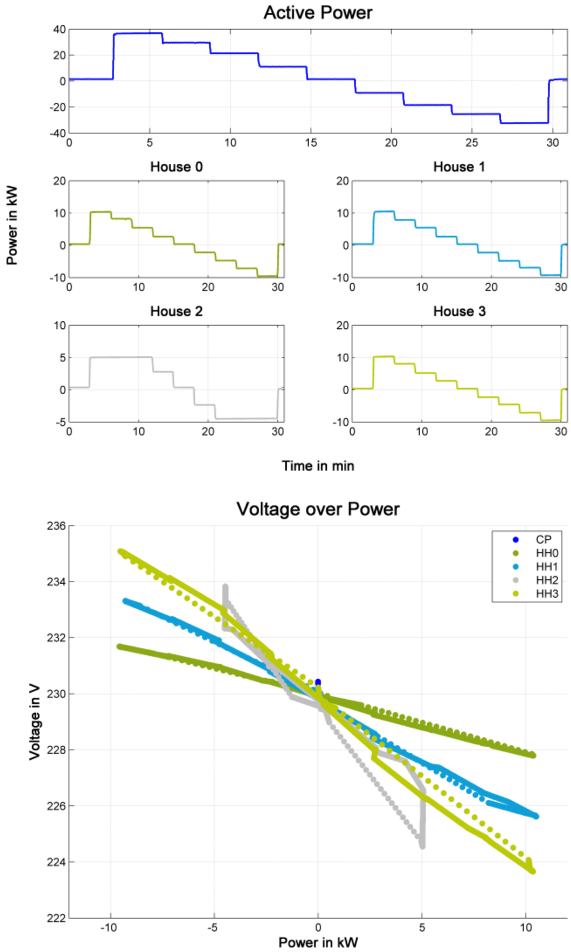

Figure 8. *Voltages to power relation of a low voltage test bench*

As depicted in Fig. 8 (top) the group of four EVs is able to provide nearly instantaneously 35kW active power. This goes along with voltage changes Fig. 8 (bottom), in this case up to 7 V. This experiment also shows that by controlling a pool of EVs positive or negative control reserve can be provided.

Further tests were carried out with different network setups like various lengths of feeders and cable cross sections (50mm², 70 mm², 125 mm²). For instance a long branch with 1.5 km was built-up to emulate rural network conditions. At the end of the branch a charging station was injecting or consuming power up to ± 10 kW, which lead to voltage deviations of ± 11 V.

4.2 Response Time of Active Power Set Point

To analyze the dynamic of all four charging stations a set point of 50% power increase was set in the charging stations. The precision and response time to provide active power according to set point request is given in Fig. 9. The upper diagram in Fig. 9 shows the simultaneous control and dynamic of all four systems, measured as total active power flow over the network. The lower diagram shows a more detailed resolution of the step response. The time to reach the set point was 1000 ms ±300 ms in average.

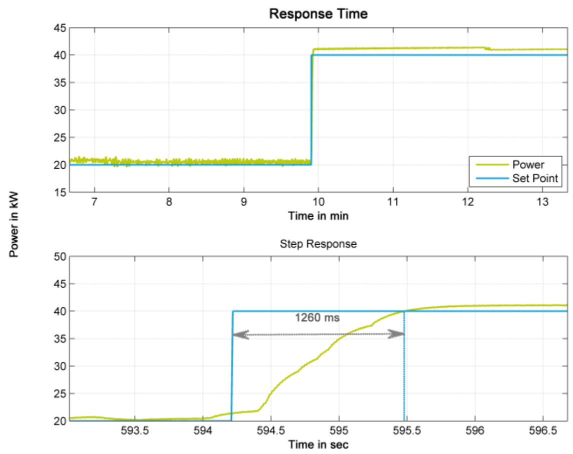

Figure 9. *Experiment to analyze the dynamic settling time of the step request*

In summary, the experiments show the trouble-free operation of a group of electric vehicles with bidirectional charging stations in a weak low voltage grid in parallel with distributed photovoltaic systems. The investigated group of four electric vehicles with bidirectional charging station is able to provide secondary control reserve.

Further experiments of parallel operations between PV systems and charging stations exposed that future smart coupling management can lead to power balancing by controlling power flows from PV systems and charging stations. This reduces not only network influence of both power systems, moreover power balancing can be optimized economically. Other tests presented possible network support by control technologies like power reduction in case of overfrequency (according to guidelines like VDE-AR-N 4105).

V. Conclusions

The analysis concerning the impact of secondary control reserve by a coordinated pool of electric vehicles have shown that to date network congestions may occur only rarely. From this we conclude that the provision of secondary control reserve from a pool of electric vehicles is possible. Only networks which already have high loading may reach their capacity limits, due to further supply of renewable generation or by the simultaneous provision of control reserve from many electric vehicles. In the medium term network reinforcements may become necessary in rural networks with high share of renewable generation. By not offering the full control reserves in affected grid parts at the same time peak power from renewables occurs, any network congestions induced by re-feeding electric cars (positive control reserve) could be nearly completely avoided. It's worth to mention, that e.g. peak power production from renewables occurs to very limited periods only. In the long term a high portion of electric cars may require - even in the case of delivering negative control reserve - extensive network extensions. But future smart grid technologies (e.g. power flow dependent target voltage controlling of the high voltage/medium voltage transformer, controllable transformers in the secondary substations) may generally increase the hosting capacity of the networks and reduce grid expansion costs.

Measurements concerning power quality aspects at the grid connection point of the charging stations during the operation of a small fleet of electric vehicles have shown that the impact on the distribution grid does not lead to violation of limits given in power quality standards.

Performance and operational tests during critical grid conditions in a high penetration scenario were performed at a system of four vehicles which was tested in one grid feeder together with other distributed generation. The system was operated for different grid topologies and different operation conditions (like variations of voltage and frequency). Even while operating close to network limits the system performed well and as expected.

In conclusion, grid integration of electric vehicles with secondary control reserve could be demonstrated successfully. Presently network congestions may occur only rarely. In future, even with a high share of electric vehicles and bidirectional charging stations, the impact on the distribution grid is very well predictable and manageable.

Ackknowledgement

We greatly acknowledge support of the work in the frame of the project "INEES – Intelligente Netzanbindung von Elektrofahrzeugen zur Erbringung von Systemdienstleistungen" by the Federal Ministry for the Environment, Nature Conservation, Building und Nuclear safety, the project agency VDI/VDE Innovation und Technik GmbH (contract number FKZ 16EM1016) and our project partners Volkswagen AG, Lichtblick SE and SMA Solartechnology AG. The authors take the full responsibility for contents of the publication.

References

[1] Degner, T., Arnold, G., Brandl, R., Portula, M., Scheidler, A., Bäuml, G., Bärwaldt, G., Weidauer, V., Baumbusch, K., Eberhardt, T., Führer, O., Andrae, R., Rigbers, K., Leifert, T.: *Smart Grid Connection of Electric Vehicles Enabling Ancillary Services*. ETG-Kongress 2013, Berlin, 5.11.2013 – 6.11.2013.

[2] Bäuml, G., Haupt, H., Weidauer, V., Eberhardt, T., Führer, O., Leifert, T., Degner, T., Brandl, R., u.a.: *Intelligente Netzanbindung von Elektrofahrzeugen zur Erbringung von Systemdienstleistungen – INEES*. Abschlussbericht. Projekt supported by the Federal Ministry for the Environment, Nature Conservation, Building und Nuclear Safety, contract no. FKZ 16EM1016. Technische Informationsbibliothek (TIB), 2016.

[3] *VDE-AR-N 4105:2011-08 Erzeugungsanlagen am Niederspannungsnetz, Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz*, VDE-Anwendungsregel

[4] *Netzentwicklungsplan Strom 2014*. Issued by 50Hertz Transmission GmbH, Amprion GmbH, Tennet TSO GmbH, TransnetBW GmbH

[5] Deutsche Energie-Agentur GmbH - *Verteilnetzstudie - Ausbau- und Inno-vationsbedarf der Stromverteilnetze in Deutschland bis 2030.*, URL: http://www.dena.de/fileadmin/user_upload/Projekte/Energiesysteme/Dokumente/denaVNS_Abschlussbericht.pdf