Impact of Electric Vehicle Charging on Low-Voltage Grids and the Potential of Battery Storage as Temporary Equipment during Grid Reinforcement

Lukas Held
Martin Uhrig
Dr.-Ing. Michael R. Suriyah
Prof. Dr.-Ing. Thomas Leibfried
Karlsruhe Institute of Technology
Karlsruhe, Germany
Email: lukas.held@kit.edu

Eric Junge
Dr.-Ing. Selma Lossau
Dr.-Ing. Martin Konermann
Netze BW GmbH
Stuttgart, Germany
Email: e.junge@netze-bw.de

Abstract—**This paper presents results of a research cooperation between Netze BW GmbH and KIT. The objective of the cooperation is to prepare the integration of electric vehicles in the distribution grid of Netze BW GmbH. A representative test grid is used to investigate the effects of charging infrastructure on distribution grids. High penetration of electric vehicles requires grid reinforcement of the distribution grids. Until grid reinforcement is completed, electric vehicle owners aren't able to charge their new vehicle unrestricted. Battery storage is suggested as a temporary equipment to bypass grid expansion and hence to ensure the satisfaction of the electric vehicle owners. Additionally, placement and requirements for temporary battery storage to optimally compensate the charging process are investigated.**

I. INTRODUCTION

Through the energy transition Germany wants to lower its greenhouse gas emission by 80 % till 2050 in comparison to 1990. Additionally, 60 % of the gross energy consumption shall be produced by renewables in 2050. Electric mobility is seen as one important aspect to achieve these goals [1].

In [2] different scenarios are calculated which predict a range of 50.000 to 1.400.000 electric vehicles (EVs) in Germany by 2020. As the development is difficult to predict the challenge for distribution grid operators is to be prepared for many different scenarios and hence to develop a flexible and intelligent strategy to operate the distribution grid cost-effectively and securely.

The integration of EVs and their charging infrastructure is not expected to cause extensive grid expansion in all voltage levels. However, distribution grids are comparatively small, but a high number exists so that local accumulations of EVs are probable [3]. Problems will arise initially at these accumulations, but their local occurrence is not predictable. The power of charging infrastructure of EVs in households (up to 22 kW [4]) is significantly higher than the average power demand of a household. The charging process stresses distribution grids, especially when considering the fact that the simultaneity factor of the charging process is quite high. Overloading of equipment as well as voltage limits are critical stresses. Furthermore, recent charging infrastructure partially uses one or two phases of the three-phase system to charge an EV, in particular when low charging power (3.7 kW, 4.6 kW or 7.4 kW) is needed. This causes voltage asymmetries which have to be considered in grid planning processes as they can have negative impact on distribution grid operation.

Assuming that a major part of the households has an EV, grid extension will be necessary to maintain grid stability. In recent years grid extension was already necessary in rural areas, because of PV installations. In urban areas this was often not required. Netze BW GmbH expects high shares of EVs especially in urban areas.

Grid extension in a distribution grid takes normally about 3 - 6 months, due to planning and necessary permissions. Owners of EVs want to charge their vehicle as soon as possible after the purchase. Therefore solutions have to be developed which bypass the time till grid expansion is finished.

In this research cooperation Netze BW GmbH is responsible for the practical implementation and the selection of suitable distribution grids that are regarded. The Institute of Electric Energy Systems and High-Voltage Technology at KIT accompanies the project scientifically through theoretical calculations and the development of planning principles.

II. TEMPORARY USE OF BATTERY STORAGE

A. Justification

The Netze BW GmbH decided to face the challenges mentioned in Chapter I using battery storage as a stopgap measure till necessary grid expansion is completed. The main task of a distribution grid operator is to provide sufficient energy to all residents in his supply area. Using battery storage, Netze BW GmbH will be able to connect new charging infrastructure for EVs immediately without having to influence the behaviour of vehicle owners. Thereby possible disputes between EV owner and distribution grid operator are avoided and the distribution operator ensures the fulfilment of his mandate.

B. Practical implementation

A field-test is planned by Netze BW GmbH to test this approach. Therefore several studies are performed. The methodology is introduced in Chapter III. First results will be presented in Chapter IV and V.

As a grid service, only the compensation of the charging process is tackled. Recharging of the batteries will happen whenever there are free capacities in the distribution grid. Lithium-ion batteries will be used as battery storage, because they are commercially available in large quantities and different sizes.

III. POWER FLOW CALCULATIONS

To analyse the impact of electric charging and temporary battery storage on distribution grids, power flow calculations have been performed in this paper using DIgSILENT PowerFactory.

A. Test grid

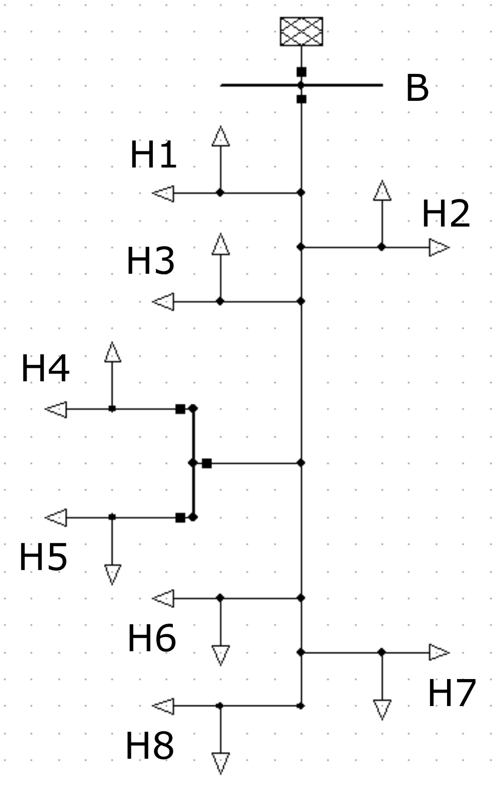

Fig. 1. Used test grid

The structures of distribution grids are rather different. Therefore, it is difficult to generalize results of one grid for all other distribution grids. Nevertheless, in [5] sample grids which are typical for Netze BW GmbH distribution grid have been developed using clustering methods. In comparison to population density based methods technical parameters are used to cluster different grid topologies. One of this sample grids is used in this paper (Fig. 1). It consists of eight households with a load demand of 16 kW. The closest household to the low-voltage (LV) busbar (B) is named Household 1 (H1). The other households are named in order following the respective distance to the LV busbar. Each household consists of two loads. One represents the load demand of this household and the second load is the EV. The power of the EV is adjusted for different simulations. It was assumed that each household would connect maximally one EV. The maximum distance between the LV busbar and a household (H8) is 280 m. The voltage at the LV busbar is set to 1.0 pu. The test grid is a comparatively small low-voltage grid. Nevertheless the effect of the integration of charging infrastructure can be studied on this grid as it has representative characteristics.

B. Symmetric and asymmetric power flow calculations

For power flow calculations different options exist. In a symmetric power flow all phases are considered to have equal loads and line parameters and therefore equal power flowing on it. Hence it is adequate to use a single phase equivalent circuit (Fig. 2). The neutral line can be neglected as no power is flowing there in a symmetric load case.

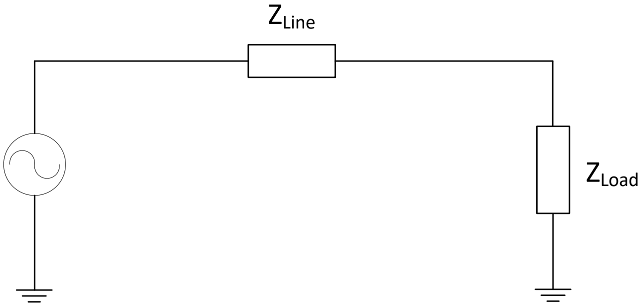

Fig. 2. Equivalent circuit for a symmetric power flow

Assuming an unbalanced power flow all three phases (Fig. 3) have to be simulated with their unique conditions. Apart from this another difference is that the neutral line has to be regarded as power is flowing on this line. These calculations are normally performed using symmetrical components. This method simplifies the analysis of unbalanced grids. A three-phase system can be indicated by three components, the zero, positive and negative sequence component. In a symmetrical system only the positive sequence component exists [6]. Voltage unbalance, which is defined in [7] as the voltage of the negative component V_2 divided by the voltage of the positive component V_1, is a measure for the asymmetries in a grid.

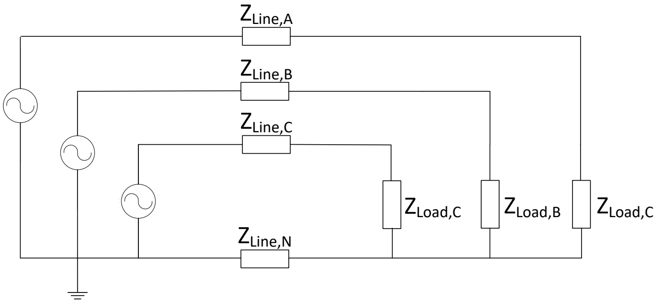

Fig. 3. Equivalent circuit for an asymmetric power flow

C. *Limits for grid operation*

Three limits for the operation of the distribution grid have been verified during the power flow calculations:

- Voltage drop from the LV busbar to each point in the low-voltage grid has to be lower than 4 % of the nominal voltage [8]
- Equipment may never be overloaded ($\leq$ 100 %)
- The voltage unbalance $\frac{V_2}{V_1}$ has to be lower than 2 % [7]

IV. GRID INTEGRATION OF CHARGING INFRASTRUCTURE

A. *Simultaneously chargeable EVs*

As a first step, the capacity of a test grid to integrate charging infrastructure was investigated. The aim was to see which concept of charging infrastructure causes which type of problems in the grid.

Different connection concepts of charging infrastructure are investigated. Charging infrastructure connected to only one phase with 3.7 kW (16 A fuse) and 4.6 kW (20 A fuse) is simulated as well as two phase charging with 7.4 kW (16 A fuse). Additionally, symmetric charging on all three phases with 11 kW (16 A fuse) and 22 kW (32 A fuse) is investigated. For each concept it was determined how many EVs are able to charge at the same time without violating grid operation limits. Moreover, the maximum utilization of a line, minimum voltage in the grid and the maximum voltage unbalance in these cases, have been calculated.

The effect of the position of households with a charging point in the grid is considered regarding two cases. In the first case the order of the households is chosen starting with Household 1 (H1) and ascending to Household 8 (H8) (Table I). So at first charging infrastructure is connected to the households that are close to the LV busbar.

TABLE I
CHARGEABLE EVS IN THE TEST GRID (FIRST CASE)

Case: Description	Chargeable EVs	Max. Utilization	Min. Voltage (pu)	Max. Unbalance
1:1 ph, 3.7 kW	7	50.6 %	0.961	0.63 %
1:1 ph, 4.6 kW	5	45.7 %	0.966	0.54 %
1:2 ph, 7.4 kW	7	50.6 %	0.962	0.64 %
1:3 ph, 11 kW	8	56.1 %	0.978	0.00 %
1:3 ph, 22 kW	7	92.5 %	0.964	0.00 %

In the second case the opposite scenario is performed. The order of households is chosen that the EVs far from the LV busbar are equipped with charging infrastructure primarily (Table II).

TABLE II
CHARGEABLE EVS IN THE TEST GRID (SECOND CASE)

Case: Description	Chargeable EVs	Max. Utilization	Min. Voltage (pu)	Max. Unbalance
2:1 ph, 3.7 kW	5	38.9 %	0.962	0.61 %
2:1 ph, 4.6 kW	4	38.7 %	0.961	0.64 %
2:2 ph, 7.4 kW	5	38.8 %	0.963	0.62 %
2:3 ph, 11 kW	8	56.1 %	0.978	0.00 %
2:3 ph, 22 kW	6	81.2 %	0.961	0.00 %

In the first case more EVs can be connected in comparison to the second case. The reason for that is that voltage sag caused by a charging EV is less, because the line between the LV busbar and vehicle is shorter.

In the asymmetric charging scenarios, the restricting quantity is voltage drop. When charging with 3.7 kW (one phase), 7.4 kW (two phases) and 11 kW (three phases) the maximum charging power per phase and EV is equal. Nevertheless, the maximum voltage drop is significantly lower when charging with 11 kW although more EVs are charging. The reason is the current flowing in the neutral line during asymmetric loading which causes an additional voltage drop in comparison to symmetric load cases. In the scenarios with a charging power of 22 kW voltage drop and also line loading are critical parameters. Voltage unbalance was within the given limit in all simulations.

Another observation is that the results for charging powers of 3.7 kW (one phase) and 7.4 kW (two phases) are similar. The explanation for that is that the charging power per phase is 3.7 kW in both scenarios and the current flowing on the neutral line is similar.

In [9] voltage sag is identified as an important aspect regarding grid operation under given limits which confirms the results in this paper. In [10] and [4] overloading of the MV/LV-transformer was identified as major limitation. A MV/LV-transformer was not part of the investigated test grid in this paper.

B. *Errors by neglecting asymmetries*

To prove the necessity of the asymmetric power flow in this chapter the results for a symmetric and an asymmetric power flow are compared for one-phase charging with 3.7 kW. The results can be seen in Table III.

TABLE III
DIFFERENCES IN THE RESULTS BETWEEN SYMMETRIC AND ASYMMETRIC POWER FLOW CALCULATIONS

Description	Charged EVs	Max. Utilization	Min. Voltage (pu)	Max. Unbalance
1 ph, 3.7 kW, asym.	8	56.9 %	0.955	0.71 %
1 ph, 3.7 kW, sym.	8	56.1 %	0.978	0.00 %

Obviously the voltage unbalance cannot be determined in a symmetric power flow. Additionally, the maximum utilization is slightly different. Furthermore, the minimum voltage in the grid is significantly different. As voltage sag was derived as major reason for violation of grid limits this is an important difference. Using a symmetric power flow the voltage is in compliance with the voltage limit, although when calculating an asymmetric power flow this is not the case. Through symmetric power flow calculation, a review of the voltage limit is therefore not possible.

In Fig. 4 the voltages at the different households are displayed for the symmetric and asymmetric power flow. The asymmetric charging causes a current on the neutral line and therefore also a voltage sag on the neutral line which is neglected when calculating a symmetric power flow.

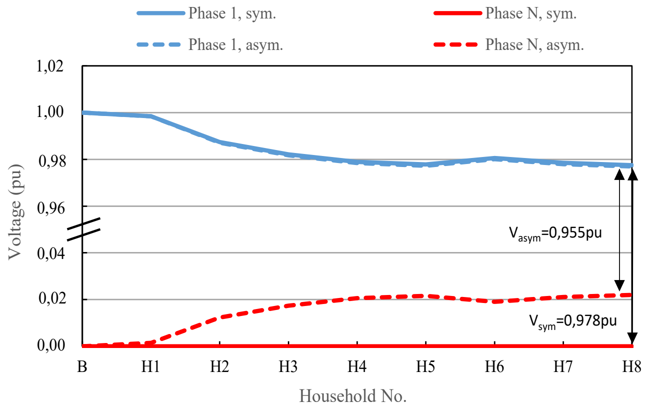

Fig. 4. Voltages at the households in a symmetric and asymmetric power flow calculation

In case of a three-phase charging with 11 kW or 22 kW symmetric and asymmetric power flow calculations generate equal results.

V. REQUIREMENTS, DIMENSIONING AND PLACEMENT OF THE TEMPORARY BATTERY STORAGE

A. *Requirements*

The temporary battery storage has to be able to compensate the impact of the charging of the EV. This dimensions required power and energy that can be stored in the battery. For several scenarios the rated power is determined in the next section. Furthermore, the battery storage should be able to control the phases independently. As battery storage will be used temporarily a stand-alone control is necessary to prevent installation of additional equipment.

B. *Positioning*

1) Distributed approach: In this approach the temporary battery storage is placed in a household that wants to connect new charging infrastructure, but only when this charging infrastructure will lead to a violation of the limits. Alternatively, the EV owner would have to wait until grid extension is completed. Hence for each household connecting charging infrastructure an additional battery storage has to be installed. This battery will compensate the share of the charging process of the EV that causes violation of the limits. The point of installation of the battery storage depends on the order of installation of charging infrastructure in this approach.

Results of simulations of this approach can be seen in Table IV and Table V. The power requirements of the different battery storages are calculated. For the results in Table IV the order of the connection of the EVs is chosen that H1 is the first household and H8 the last.

TABLE IV
RATED POWER OF BATTERY STORAGE IN A DISTRIBUTED APPROACH (FIRST CASE)

Case: Description	Chargeable EVs	Storage Placement	Rated power of storage
1:1 ph, 3.7 kW	7	-	-
1:1 ph, 3.7 kW	8	H8	2.9 kW

For the results in Table V the order of the connection of the EVs is chosen that H8 is the first household and H1 the last.

TABLE V
RATED POWER OF BATTERY STORAGE IN A DISTRIBUTED APPROACH (SECOND CASE)

Case: Description	Chargeable EVs	Storage Placement	Rated power of Storage
2:1 ph, 3.7 kW	5	-	-
2:1 ph, 3.7 kW	6	H3	1.7 kW
2:1 ph, 3.7 kW	7	H3	1.7 kW
		H2	3.7 kW
2:1 ph, 3.7 kW	8	H3	1.7 kW
		H2	3.7 kW
		H1	3.7 kW

Depending on the order of the connection of the infrastructure the results are quite different. In case 1 already seven EVs can be charged without battery storage (Table I). So only one storage has to be installed at the farthest household (H8). In case 2 (Table II) only 5 EVs can be charged. So three additional battery storages have to be installed until all 8 EVs can charge at the same time. They are installed at the closest three households to the LV busbar (H1, H2, H3).

The battery storage in the first household, that needs a storage, requires a rated power that is maximum the charging power of the EV. That depends on the spare capacity of the low-voltage grid. The battery in the second and further households needs exactly the charging power of the EV as rated power. Hence the charging power of the EV dimensions the rated power of the battery essentially.

2) Centralized approach: Here only one temporary battery storage is placed in the low-voltage grid. This battery storage will be placed like conventional grid infrastructure. Therefore, an appropriate place has to be found which depends on local circumstances. The battery storage has to be able to compensate the charging power of all EVs in the regarded distribution grid that will be installed before grid expansion is completed. Only the peak charging power has to be compensated which is lower when not all EVs are charging simultaneously. Therefore an advantage of this approach is that it is economically beneficial as the overall power and energy requirements are lower.

In Table VI the required power of the battery to charge all eight EVs simultaneously at different places in the grid can be seen. It is assumed that the battery storage will be placed close to one of the households.

An operation under compliance with the given limits is not possible when installing a battery at Household 1 (H1). The requirements for the rated power are the lowest when installing the central battery storage as far as possible from the LV busbar. Again only charging on one phase with 3.7 kW is considered.

Previously voltage sag was derived as major issue concerning operating limits in this case. If the battery storage is connected on a far household power transfer over a longer distance is avoided and hence less voltage sag occurs.

TABLE VI
RATED POWER OF BATTERY STORAGE IN A CENTRALIZED APPROACH

Description	Storage Placement	Rated power of Storage
1 ph, 3.7 kW	H1	Not possible
1 ph, 3.7 kW	H2	6.5 kW
1 ph, 3.7 kW	H3	4.2 kW
1 ph, 3.7 kW	H4	3.4 kW
1 ph, 3.7 kW	H5	3.4 kW
1 ph, 3.7 kW	H6	3.3 kW
1 ph, 3.7 kW	H7	2.9 kW
1 ph, 3.7 kW	H8	2.9 kW

The requirements for the energy capacity of the battery storages in both approaches depend on the rated energy of the batteries inside the EVs.

VI. ALTERNATIVE CONCEPTS TO REDUCE THE IMPACT OF EV CHARGING ON LOW-VOLTAGE GRIDS

In this paper battery storage is suggested as an equipment to bypass times of grid reinforcement. Nevertheless, also other concepts exist to reduce the impact of EV charging on low-voltage grids.

A controllable distribution transformer is able to influence the voltages in the low-voltage grid through the integrated tap changer. As voltage sag was derived as a major problem during EV charging a controllable distribution transformer could be a possible solution. Unfortunately to prevent overloading of equipment this type of transformer does not help in comparison to a battery storage. Additionally the replacement of the transformer also lasts several weeks. Therefore, Netze BW GmbH does not consider the controllable distribution transformer as an universal alternative to battery storage during necessary grid extension. In particular use cases a controllable distribution transformer is seen as a useful possibility to improve the integration of electric vehicles.

Another option would be load management. This option was already studied extensively in [3], [10], [4] and further publications. Different approaches exist like centralized or decentralized controls. An advantage is that these systems can be installed quickly. Additional equipment has to be installed to measure the controlled variables and perhaps communication between different controller is required. One possibility is to provide reactive power whenever the converter of the battery in the EV is able to do that. Furthermore, the active power can be controlled. This leads eventually to longer charging times.

One possibility to enforce load management are specifications in grid codes. A regulatory framework to force EV owners to use load management does not exist at the moment in Germany. The second possibility is that load management is economically beneficial for the owner of electric EVs. Here the distribution grid operator can not influence the decision of the EV owner to use load management. However, an economically beneficial load management can have negative impact on the low-voltage grid e.g through same price signals [10]. Consequently, the installation of load management is not considered as an universal possibility to bypass grid reinforcement by Netze BW GmbH. Nevertheless, load management is seen as one important aspect to improve grid integration of electric vehicles by Netze BW GmbH.

VII. CONCLUSION & OUTLOOK

The research cooperation started recently and already first results are shown in this publication. Regarding the integration of charging infrastructure voltage sag can be derived as a major reason for a necessary grid expansion in the analysed distribution grid. In this paper a limit of 4 % of the nominal voltage was used as permitted voltage sag [8] in the low-voltage grid. Different distribution grid operators are using different limits for the voltage sag in their planning principles, which can influence the significance of voltage sag as major limit.

In the simulations, using a three phase charging system with 22 kW, the thermal rating of the cables was a limiting parameter. A MV/LV-transformer was not considered in the used test grid. It is an additional possible limitation.

Furthermore, simulations have shown that charging infrastructure which uses only one or two phases lead to asymmetries of the voltages in the distribution grid. To calculate these asymmetries and their consequences it is necessary to perform an asymmetric power flow. To calculate only symmetric power flow simulations is not sufficient as voltage unbalance as well as voltage sag on the neutral line can't be reviewed properly. Asymmetric power flow calculations are not state of the art in grid planning processes for distribution grid operators.

For local accumulations of EVs in distribution grids grid reinforcement can be necessary. Battery storage was discussed in this paper as temporary equipment till the grid reinforcement is completed as it can be installed quickly and ensure grid operation under compliance with the given limits. Hence EV owner can charge their EVs immediately at their home, even when grid expansion is necessary. Thereby the distribution grid operator can fulfil his supply mandate.

Different approaches to position the battery in the distribution grid have been studied. One approach is to place a battery in the households that install new charging infrastructure. The second approach is to place one battery storage in a central position of the distribution grid. The position in the grid influences the required rated power of the battery.

At the moment a suitable distribution grid is searched for the field-test. This grid will be also analysed regarding the capacity to integrate EVs and requirements for the used battery storage. Planning principles for distribution grids with a high share of EVs and the installation of battery storage as temporary equipment will be deduced. Furthermore, the autonomous control for the charging and discharging of the battery system will be developed.

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