Hot-spot Scenarios of Electrical-Vehicles on the Low Voltage Grid

including Statistics and Effect of decentralized Battery Storage

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***Abstract*—This paper analyzes the impact of simultaneous charging events from battery electrical vehicles (BEVs) on samples of suburban networks. Voltage drop is more significant than transformer and network loading. As the BEV penetration increases, a probabilistic view reduced the requirement for network upgrade. Furthermore, local battery energy storage of as low as 5 kWh at each charging station will reduce the likelihood of simultaneous charging from the network.**

Keywords- battery electrical vehicle; private charging station; low voltage grid; transformer load; voltage drop; peak load of households; statistic of arrival time; distribution of daily driving distance; dezentral battery electric storage

I. Introduction

Citizens of towns and suburban areas with high density of single and two-family houses have the possibility to charge their BEV at private parking spaces and are assumed to be the 'first movers' towards battery electric vehicles (BEVs)

For grid stability the load on substation transformers and the voltage level of the grid has to remain within appropriate limits. Due to the European standard EN 50160 a voltage range of ±10 % over all voltage levels is permitted. A range of 5 % is used as boundary for the voltage drop on power lines of the last leg of low voltage distribution network.

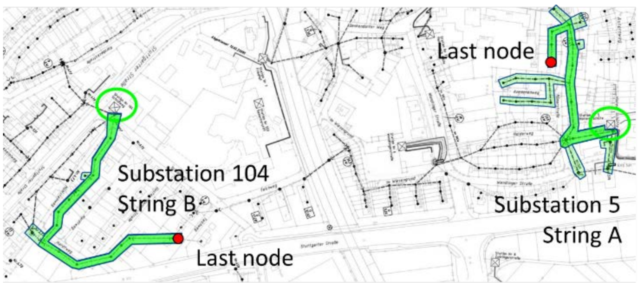


Figure 1. The additional voltage drop caused by BEVs is analyzed on two overhead power lines of the low voltage grid of a town in southern Germany – string A has a branched structure while string B is essentially a single line.

This paper analyzes the impact of BEVs on both, the substation transformers and the power lines of the low voltage grid. The impact of BEVs has been calculated using PowerFactory® for a suburban grid in Southern Germany.

II. System Description

A. Load on substation transformers

Distribution System Operators estimate the total load P_{total} at substation transformers by summing up all connected loads including the load of households (HH) and the load of all charging BEVs:

$$\sum P_{total,\ substation} = \sum P_{HH,\ substation} + \sum P_{BEVs,\ substation}$$

For the study, it is assumed that the BEVs are charged exclusively at private charging stations (CS) with 11 kW, 22 kW power or as combination with 14.7 kW (based on an assumed ratio of 2:1 on 11 kW and 22 KW CS, respectively). The charging stations are connected to the house connection points. Thus the charging load has to be added to the power demand of the households (HH). In this paper the load on eleven substation transformers is calculated with a BEV penetration of up to 21 %.

B. Additional voltage drop

The additional voltage drop created by all CS on a power line $\Delta U\ (BEVs)_{node}$ is the difference between (a) voltage drop during peak load of the HH plus load of charging BEVs $\Delta U\ (HH + BEVs)_{node}$ and (b) the voltage drop during peak load of the HH $\Delta U\ (HH)_{node}$.

$$\Delta U\ (BEVs)_{node} = \Delta U\ \ (HH + BEVs)_{node} - \Delta U\ (HH)_{node}$$

The additional voltage drop is calculated in PowerFactory® for two sample strings with over-head power lines. As in Fig. 1 shown String 'A' has a branched structure while String 'B' is essentially a single line. The analysis includes penetrations of 5, 10 and 21 % BEVs which are charged by 11 kW CS.

To show the range of encountered additional voltage drop, the positions of the charging stations are varied. Results are shown for the CS clustered at the household with largest distance to the feeding transformer (last node), next to the transformer (first node) and equally distributed at the households. All the assumptions are listed in Table I.

III. Cases

The impact on the substation transformer and the low voltage grid is analyzed for three different cases: worst case, probabilistic case and battery electrical storage case.

A. *Worst case*

The worst case assumption is used as the starting point. In this case the maximum load on the substation transformer results from all BEVs charging simultaneously in addition to the peak load of all connected households. In a first scenario the maximum simultaneous peak load is estimated by the conservative formula for grid sizing by Kaufmann [1] and Kerber [2]. The formula converges at 2.1 kW/ HH for a large number of HH. For comparison, the maximum simultaneous peak load is assumed to converge at 1 kW/ HH according to Probst [3]. Counteracting PV plants are neglected due to the assumption that the combined peak of HH-load and charging will take place during the evening hours, where during part of the year, no solar radiation is available.

The worst case of additional voltage drop caused by BEVs is occurring, if all BEV owner reside at the end of the string and thus CS are pooled at the last connected household of the strings.

Table I. Assumptions

Low voltage Grid	Transformers: 630 kVA power Power Lines – overhead lines (type N2XRY 4 x 50 mm²) - String A: branched structure of 243 m length (trunk line) serving 62 HH - String B: single line of 373 m length and 31 connected HH.
House-hold (HH)	Peak load for 30 – 60 HH - conservative peak load: ~ 2.8 kW/ HH - reduced peak load: ~ 1.4 kW/ HH
Battery Electric Vehicles (BEVs)	- 1.27 BEVs per HH - Up to 21 % BEV penetration (leads to 17 and 8 BEVS in string A and B) - Consumption: 0.2 kWh/ km
Charging stations (CS)	- CS/BEV ratio: 1 CS for each BEV - Power: 11, 14.7 (mixture ratio 2:1) or 22 kW - Distribution: pooled at first node/ last node or equally distributed - Charging process: rectangular
Li-Ion Battery storage	- Support for CS: first charge from battery then use the grid - 5/ 10/ 15/ 20 kWh capacity

Table II. Survey Results For Daily Driving Distance [4]

Maximum Driving Distance (km)	0	1	10	20	40	65	100	200	300
Probability (%)	29,9	2,5	17,1	12,7	14,7	9,1	6,1	4,7	3,2

B. *Probabilistic view taking statistics into account*

Due to different driving behavior of BEV owners the used battery capacity will vary as well as the starting time of recharging. Case B takes the statistics of arrival times and distribution of daily driving distances into account. Therefore, the maximum number of simultaneously charging vehicles is reduced significantly with a high confidence. The household load is calculated by the above mentioned conservative formula.

The summary provided by Probst [4] on the daily driving distance (Table II) and arrival times of cars (Fig. 2), based on the survey of German vehicle owners [5] are used in this paper to characterize the driving behaviors of BEV owners. The study of driving distance showed that only 70% of the cars are moved at least once a day and have an average driving distance of 50 km per day in Germany. The distribution of daily driving distance is shown in Table II.

With 50 km of average driving distance an average of 10 kWh is needed for daily recharging with a conservative assumption of 0.2 kW/km according to [6, 7]. Assuming also a simplified, rectangular charging profile at a charging station with 11 kW power, 71 % of the individual charging events have a duration less than an hour. By doubling the CS power to 22 kW the duration is halved and more than 86 % of all charging events are finished within one hour. Additionally, the last arrival time of a day is between noon and 1.00 h in the morning. Its probability density function has its maximum between 17:30 h and 18:30 h with probability p=0.1927 per hour. It is assumed that the arrival time coincides with the start

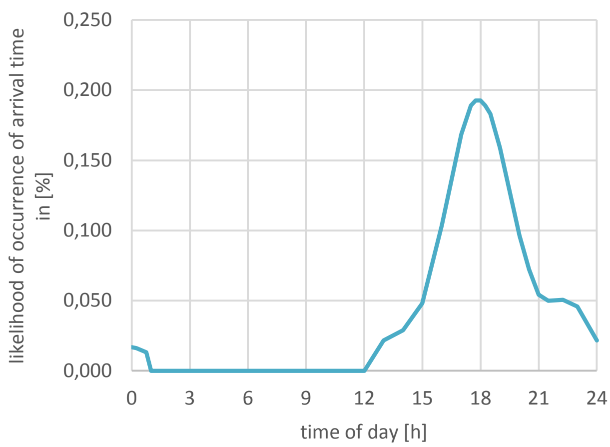


Figure 2. Probabilistic density of arrival time of German car owners [4]

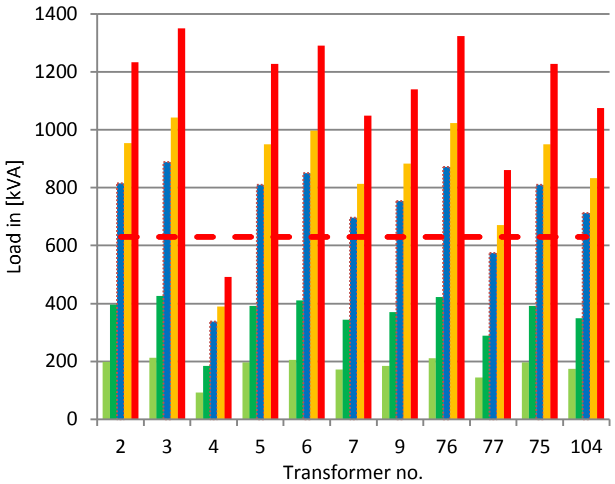


Figure 3. Maximum load on the transformer caused by peak loads of households (HH) by itself and including the load of charging BEVs (21%) with all BEVS charging simultaneously (Case A) and different power rating of the charging stations (same legend as Fig. 4).

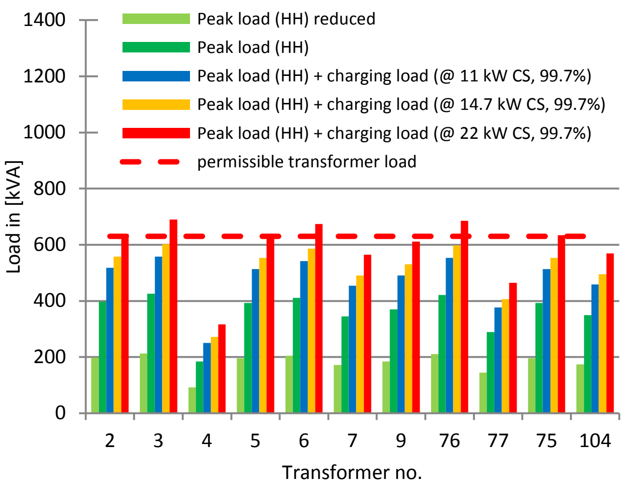


Figure 4. Maximum load on the transformer caused by peak loads of households (HH) by itself and including the load of charging BEVs (21%) with different power ratings of the charging stations using a probabilistic view (Case B – confidence level of 99,7%)

time of the charging event. For covering a high likelihood of occurrence a confidence level of 99.7 % is chosen (i.e. an exception occurs approx. once in a year).

C. Probalistic view with assisting battery storages

In addition to the previous case 'B' this case analyzes the effect of Li-Ion battery electric storages systems on the grid impact of BEVs if the related CSs are supplied by stored energy first, then using the grid as power supply. The analysis uses stored energy of 5, 10, 15 and 20 kWh respectively. The available discharge power is assumed to match the power of the charging station.

IV. Results

A. Worst case

In the worst case all BEVs are charging simultaneously at the same time. The highest investigated penetration of BEVs is 21 %.

Fig. 3 shows the maximum load on the transformer caused by peak loads of all connected households by itself or including the load of all BEVs. Due to the charging BEVs the load on the transformer (blue line) doubles or triples compared to the load caused by the households itself using a conservative design (dark green columns) or a reduced design (light green columns). Thus the transformer rating is exceeded at nearly all transformers. Only the load on transformer 4 remains within the limits which is due to the small number of connected households and BEVs accordingly. Corresponding to the power of the used CS the load on the transformer is even higher if CS with 14.7kW or 22 kW power (orange and red columns) are used to charge all BEVS at the same time.

The additional voltage drop caused by BEVs is shown in Fig. 5 as a range between the BEV pooled close to the feeder (green bars) and pooled at the end of the string (red bars). The blue dots symbolize the additional voltage drop caused by equally distributed BEVs. With more than 8 BEVs in String 'A' or 4 BEVs in String 'B' (10% BEV penetration) the additional voltage drop exceeds the acceptable range. Fig. 5 shows clearly that the placement of charging stations along the string influences the observed voltage drop to a large extend. Only for the case of 5% penetration of BEVs the additional voltage drop stays in all placements of CS below 5%.

B. Probabilistic view taking statistics into account

Taking the statistics of arrival time and the duration of individual charging events into account, the maximum number of simultaneously charging vehicles is reduced significantly with a high confidence level. The results shown for this case B are for a confidence level of 99.7 %.

Considering the statistics for 21 % BEVs, the maximum load does not reach the rating of the eleven transformers if CS with 11 kW or 14.7 kW power are used (as shown in Fig. 4). Only if CS with 22 kW are used some transformers have to be upgraded.

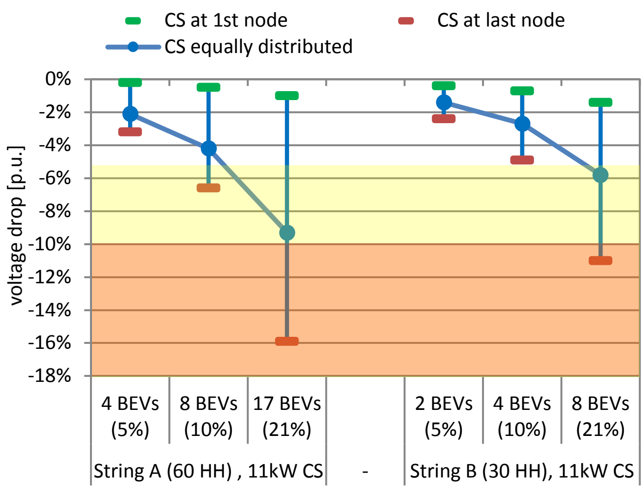
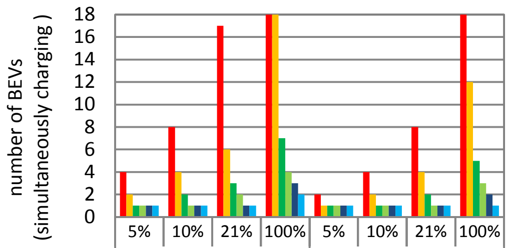


Figure 5. Range of the additional voltage drop on two strings caused by simultaneously charging BEVs using 11kW charging stations (CS) with different assumptions of the distribution of the connection points of the CS within the strings



	BEV penetration String A				BEV penetration String B			
	5%	10%	21%	100%	5%	10%	21%	100%
BEVs total	4	8	17	79	2	4	8	40
BEVs (probabilistic view)	2	4	6	19	1	2	4	12
BEVs (probabilistic view with 5kWh storage)	1	2	3	7	1	1	2	5
BEVs (probabilistic view with 10 kWh storage)	1	1	2	4	1	1	1	3
BEVs (probabilistic view with 15 kWh storage)	1	1	1	3	1	1	1	2
BEVs (probabilistic view with 20 kWh storage)	1	1	1	2	1	1	1	1

Figure 6. Maximum number of simultaneously charging BEVs from the grid – in worst case, with probabilistic view itself (arrival time at 18.00h, distribution of daily driven distances and confidence level 99.7%) or if the related charging stations are supported by battery storages

On the further analyzed string 'A' the statistics reduce the number of simultaneously charging BEVs to 6 out of 17 BEVs (at 21 % BEVs penetration) with 99.7 % confidence. On string 'B' there will charge 4 out of 8 BEVs simultaneously.

Therefore, the maximum load caused by 21 % BEVs at 99.7 % confidence diminishes to a level equal to the voltage drop according to the case of a 10 % BEVs charging all at once (worst case). The case of 100 % BEVs at 99.7 % confidence reduces to approx. 20 % of all BEVs charging all at once.

The additional voltage drop on the strings declines with the statistics similarly. In the statistic case the voltage drop is comparable or even less than in worst case with 10 % BEV penetration (see Fig. 5). Further examples up to 100 % penetration are shown Fig. 6.

C. *Probalistic view with assisting battery storages*

Significant reduction of likely simultaneous charging events can be achieved by adding batteries to each charging station. Due to the low average daily driving distance in Germany only 34% BEVs remain to be charged from the grid after using up 5 kWh of battery supplied energy.

For the example of 17 BEVs in string 'A', a 5 kWh storage reduces the maximum number of simultaneously charging BEVs from 6 to 3 vehicles (out of 17) with equal or more than 99.7 % confidence. In case of 10 kWh or 15 kWh capacity it leads to a maximum of 2 or 1 vehicle(s).

V. SUMMARY

The assumption of simultaneous charging of all existing BEVs leads to excessive transformer loading and voltage drop on string in the distribution network even for low penetration of BEVs.

Taking the statistics of arrival times and driven distance over the day into account (for an example string with 62 households with 21% penetration of BEVs), not more than 7 out of 17 BEVs in this string will charge simultaneously at 99.7 % confidence level.

Small decentral batteries of 5 kWh at each CS further reduce significantly the maximum number of vehicles to be expected for simultaneous charging from the grid.

In conclusion: it will not pay to extend the grid for low probabilities of high demand. Therefore, communication to limit charging for the unlikely event of a high number of simultaneous charging requests seems the most economical option.

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