Development of a Tool for the Determination of Simultaneity Factors in PEV Charging Processes

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***Abstract*—In this paper, an open-source Tool for the calculation of simultaneity factors of Electric Vehicles (EV) (i.e. battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)) charging processes is presented. In addition, the peak loads of EV and households can also be displayed, taking into account the EV and household specific simultaneities. In the following, the underlying input parameters and calculations of the Tool are explained. Based on this, different results are generated and discussed in detail.**

I. INTRODUCTION

One challenge of electric vehicles (EV) is the relatively high additional load compared to other domestic appliances and the resulting effects on the power grid. This effect of EV (i.e. battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)) have already been analysed and discussed in numerous studies ([1], [2], [3], or [4]). One factor that has been often neglected in previous analyses is the simultaneity of charging processes [5]. It is often assumed that all EV are charged simultaneously at a constant charging rate throughout the entire charging process. However, this reflects an empirically unrealistic simultaneity factor for EV. In other studies, the simultaneity factor is based on current mobility behaviour or is limited to selected applications (e.g. EV can only charge with a charging rate of 3.7 kW), see for instance [2] and [6].

If the simultaneity of the charging processes is analysed, a distinction must be made between two different simultaneity factors. Firstly, there is the simultaneity factor which describes the percentage of EV charged at the same day. This considers the fact that not each EV is charged on a daily basis. On the other hand, the simultaneity of the charging processes taking place within one day must also be taken into account.

With regard to the simultaneity of the charging processes taking place within one day, a Tool is developed which will be offered as an open-source Tool to download from a public website (https://doi.org/10.5281/zenodo.3364366). The Tool calculates the simultaneity of the charging processes within one day taking into account the number of EV, arrival and departure time, vehicle class (small, medium, or large), various charging rates (3.7 kW, 7.4 kW, 11 kW, 22 kW and 44 kW), battery capacity, and State of Charge (SoC) at arrival as well as desired SoC at departure. The percentage of EV charging on the same day might be included, too. The user of the Tool can chose to either use the included data or individual adjusted data. Thus, it is also possible to consider future trends. Especially for analysing the resulting grid impacts (e.g. transformer or cables), household loads with the specific simultaneities in combination with the associated simultaneities of EV charging play a decisive role and are therefore incorporated in the Tool. Hence, using the Tool, different simultaneity factors (i.e., EV alone or EV plus household) can be easily displayed.

The paper is structured as follows. Chapter II gives an overview of the default input data on which the Tool is based. Chapter III presents the calculations of the Tool in detail. The results generated by the Tool are analysed and discussed in Chapter IV. Chapter V concludes our contribution.

II. INPUT DATA

The default data set is based on different sources (e.g. [3], [4], or [7]) and each value can be modified by the user. Most values can be changed directly in the user interface. Specific input data (e.g. average charging durations) can only be changed in the program code.

All input profiles in this paper have time intervals of 15 minutes as the household load profiles used are only available in 15 min intervals. This can be changed in the code, but makes the according adjustment of the time resolution of input load profiles necessary.

One input parameter is the number of simulated days. The Tool calculates the maximum simultaneity factor on a daily basis. This calculation is then repeated to determine the probability of the occurrence of a specific simultaneity factor. Consequently, a higher amount of simulated days increases the accuracy of the results, but also increases the simulation time. The influence of the number of repetitions on the results is examined in Chapter IV.

A. Households

For the households in the regarded power grid, only the number of households and the yearly energy consumption per household in kWh have to be entered as input data. To represent the load of a household, a profile is chosen randomly out of a database with 365.000 profiles. This database was generated using [8]. All profiles in the database have a yearly energy consumption of 1000 kWh. Hence, the chosen profile is scaled according to the yearly energy consumption per household. The preset value is 3216 kWh, which was the average yearly energy consumption of a two-person household in Germany in 2017 according to [9] and in the basic settings 10 households are considered.

B. Electric vehicles

Regarding the EV many different parameters influence the calculations. One main parameter is the number of EV considered. The Tool differentiates between PHEV and BEV and three vehicle classes (small, medium, big). The share of the individual vehicle classes was calculated from [7]. The battery capacity data for BEV and PHEV for the underlying setting are taken from [10]. The default data is presented in Tab. I.

Table I: Default values for EV.

	BEV		
	small	medium	big
Share EV class [%]	7	3	5
Battery capacity [kWh]	30.46	37.9	75
	PHEV		
	small	medium	big
Share EV class [%]	5	40	40
Battery capacity [kWh]	8.4	12.26	8.4

As already mentioned, the Tool distinguishes between two simultaneity factors. The simultaneity factor, which describes the percentage of EV charged at the same day is set to 78%. This value is based on [11] and is preset for the basic setting. The arrival time is randomly assigned to the EV according to the distribution of [3]. It was assumed, that every used EV is charged as soon as it arrives at home. During the charging process, a distinction is to be made between 2 variants. Either the SoC limits (SoC at the beginning and SoC at the end of the charging process) are set individually or the SoC at the beginning of the charging process is determined according to the distribution of [12]. For the latter, the final SoC is always set to 100%.

Since different charging rates occur simultaneously in reality, an additional aspect covered in the Tool is the possibility taking into account simultaneously different charging rates. The default charging power distribution follows [4] and the calculations are performed on the average charging rate. In the presettings, the Tool differentiates between 3.7 kW, 7.4 kW, 11 kW, 22 kW and 44 kW with a share of 73.7%, 0%, 21.5%, 3.5% and 1.3%, respectively.

III. CALCULATIONS IN THE TOOL

A. Start

The number of vehicles per vehicle class i is calculated by multiplying the given share of each vehicle class i $S_{\text{Veh,i}}$ with the total number of EV $N_{\text{EV,Total}}$ (see Equation 1).

$$N_{\text{EV,i}} = N_{\text{EV,Total}} \cdot S_{\text{Veh,i}} \tag{1}$$

The main part of the Tool is the calculation of the different maximum simultaneity factors and peak powers on a daily level. For example, the calculation of the simultaneity factor of EV for one day k $SF_{\text{EV,k}}$ is repeated accordingly to the entered number of simulated days N_{Days}.

B. Daily simultaneity factor for electric vehicles

First, an arrival time $\text{T}_{\text{Arrival}}$ is assigned to each EV randomly accordingly to the distribution in Chapter II. As the accuracy of the distribution is one hour, we assume a uniform distribution in each hour.

Next, the charging duration $\text{T}_{\text{Charging}}$ for each EV is calculated. If the EV is charging on the considered day, the SoC before $\text{SoC}_{\text{Char.,Start}}$ and after $\text{SoC}_{\text{Char.,End}}$ the charging process are determined.

The formula for the calculation of the average energy capacity of all EV's batteries is given in Equation 2.

$$E_{\text{EV,Avg.}} = \sum_{i=1}^{6} E_{\text{EV,i}} \cdot S_{\text{EV,i}} \tag{2}$$

In Equation 2, $\text{E}_{\text{EV,i}}$ is the average energy capacity of vehicle class i. $\text{E}_{\text{EV,i}}$ and $\text{S}_{\text{EV,i}}$ are input parameters.

The necessary charging energy $\text{E}_{\text{Charging}}$ is calculated as given in Equation 3.

$$E_{\text{Charging}} = (SoC_{\text{Char.,End}} - SoC_{\text{Char.,Start}}) \cdot E_{\text{EV,Avg.}} \tag{3}$$

The charging time $\text{T}_{\text{Charging}}$ is calculated by multiplying the necessary charging energy $\text{E}_{\text{Charging}}$ and the average charging duration per kWh $\text{T}_{\text{Char.,Avg.}}$ (see Equation 4).

$$T_{\text{Charging}} = E_{\text{Charging}} \cdot T_{\text{Char.,Avg.}} \tag{4}$$

$\text{T}_{\text{Char.,Avg.}}$ is defined as given in Equation 5.

$$T_{\text{Char.,Avg.}} = \sum_{j=1}^{5} S_{\text{Char.Power,j}} \cdot T_{\text{Char.,j}} \tag{5}$$

$\text{S}_{\text{Char.Power,j}}$ is the share of charging power j on the total amount of EV and $\text{T}_{\text{Char.,j}}$ is the corresponding average charging duration per kWh for charging power j.

Using the charging duration $\text{T}_{\text{Charging}}$, the end time of the charging process can then be calculated using Equation 6.

$$T_{\text{End}} = T_{\text{Arrival}} + T_{\text{Charging}} \tag{6}$$

Finally, the charging profile of each EV is defined. The profile contains the information whether the EV is charging or not for each time step of the day (e.g. 96 time steps per day for a 15 min resolution).

In order to obtain the collective profile $\text{N}_{\text{EV,Collective}}$, the profiles of all individual vehicles are summarised. This delivers the number of maximum simultaneously charging EV $\text{N}_{\text{EV,Simul.}}$. $\text{N}_{\text{EV,Simul.}}$ is then used to calculated the maximum daily simultaneity factor $\text{SF}_{\text{EV,k}}$ (see Equation 7).

$$SF_{\text{EV,k}} = N_{\text{EV.,Simul.}} / N_{\text{EV,Total}} \tag{7}$$

The arrival time $\text{T}_{\text{Arrival}}$ and the SoC (depending on the option chosen) are assigned randomly (see Chapter II for more information). In contrast to that, for the energy capacity of the EV $\text{E}_{\text{EV,Avg.}}$ as well as the charging duration per kWh $\text{T}_{\text{Char.,Avg.}}$ average values are used and the values are not assigned randomly. The reason for that is that these values are EV dependend and should be constant for all simulated days.

C. Unbalanced charging

If the option that considers unbalanced charging is chosen, the calculation for the daily simultaneity factor is equal until Equation 6. Here, the profiles are not added to get the collective profile $\text{N}_{\text{EV,Collective}}$, but divided between the different

phases. If the charging power is 3.7 kW one-phase charging is assumed, for 7.4 kW two-phase charging and for all additional charging powers three-phase charging (which is provided by the German electricity grid). If less than three phases are used, the selection of the phases is uniformly distributed. Now, the profiles for each phase ($\mathrm{N_{EV,Ph1}}$, $\mathrm{N_{EV,Ph2}}$, and $\mathrm{N_{EV,Ph3}}$) are generated by adding up the profiles of the EV charging for each phase individually. The profiles are multiplied with a weighting factor (1 for one-phase charging, 1/2 for two-phase charging, 1/3 for three-phase charging) before adding up the profiles.
Out of the profiles $\mathrm{N_{EV,Ph1}}$, $\mathrm{N_{EV,Ph2}}$, and $\mathrm{N_{EV,Ph3}}$ the maximum number of simultanously charging vehicles for each phase $\mathrm{N_{EV,Simul.,Ph1}}$, $\mathrm{N_{EV,Simul.,Ph2}}$, and $\mathrm{N_{EV,Simul.,Ph3}}$ are determined.
These results are then used to calculate the maximum daily simultaneity factor $\mathrm{SF_{EV,k,PhO}}$ for each phase O (see Equation 8).

$$SF_{\text{EV,k,PhO}} = N_{\text{EV.,Simul.,Ph0}}/N_{\text{EV,Total}} \tag{8}$$

D. Load profile of the households

For each household l, a randomly chosen energy consumption profile $\mathrm{E_{Household,1000,l,k}}$ is applied. This profile is scaled to an annual electricity consumption of 1000 kWh. Accordingly, the profile has to be scaled according to the average annual electricity consumption of households considered $\mathrm{E_{Con}}$ (cf. Equation 9).

$$E_{\text{Household,l,k}} = E_{\text{Household,1000,l,k}} \cdot \frac{E_{\text{Con}}}{1000} \tag{9}$$

Finally, the profiles of all households are added to a collective profile $\mathrm{E_{Household,Collective}}$. For this profile, the peak power is determined and saved in $\mathrm{P_{Household,k}}$.

E. Total peak power on daily level

To determine the total peak power, a collective profile $\mathrm{E_{Total}}$ including the EV and households is calculated using Equation 10.

$$E_{\text{Total}} = E_{\text{Household,Collective}} + E_{\text{EV,Collective}} \tag{10}$$

with

$$E_{\text{EV,Collective}} = N_{\text{EV,Collective}} \cdot P_{\text{Char.,Avg.}} \tag{11}$$

and

$$P_{\text{Char.,Avg.}} = \sum_{j=1}^{5} S_{\text{Char.Power,j}} \cdot P_{\text{Char.,j}} \tag{12}$$

With $\mathrm{E_{EV,Collective}}$, the collective profile of EV, $\mathrm{P_{Char.,Avg.}}$, the average charging power, and $\mathrm{P_{Char.,j}}$ the individual charging power j.
The maximum power of the collective profile $\mathrm{E_{Total}}$ is the total peak power $\mathrm{P_{Total,k}}$.

Finally, the daily maximum values for $\mathrm{SF_{EV,k}}$, $\mathrm{P_{Household,k}}$, and $\mathrm{P_{Total,k}}$ are determined for day k.

F. Calculation of the final results

As the last step, the result on a daily level ($\mathrm{SF_{EV,k}}$, $\mathrm{P_{Household,k}}$, and $\mathrm{P_{Total,k}}$) for each of the $\mathrm{N_{Days}}$ days are sorted in order to determine the maximum value as well as the quantiles. Additionally, the result plots are generated.

IV. RESULTS

In the following exemplary results for the default data are provided (see Chapter II).

It is assumed that each of the 10 households (with an annual energy consumption of 3216 kWh/a) is endowed with an EV. The probability that a car is charged on the selected day amounts 78% and the simulation considers 1000 days. The distribution of the charging power, the share of EV classes, and the energy capacity can be found in Chapter II. The following results assume that $SoC_{\text{Char.,Start}} = 0\%$ and $SoC_{\text{Char.,End}} = 100\%$. This represents an extreme scenario and explains the (possibly) higher simultaneity factors. Based on the default data and especially caused by the high share of PHEV, the average battery capacity per EV amounts to 15.7 kWh. The average charging power based on the preset charging rates is 6.43 kW. These values are used for further calculations.

A. Simultaneity factor of EV

The main objective of the Tool is to calculate the simultaneity of EV charging processes. In Fig. 1, an exemplary distribution of the simultaneity factor of EV is presented. The x-axis describes the simultaneity factor of EV and the y-axis the number of simultaneities occurred per year.

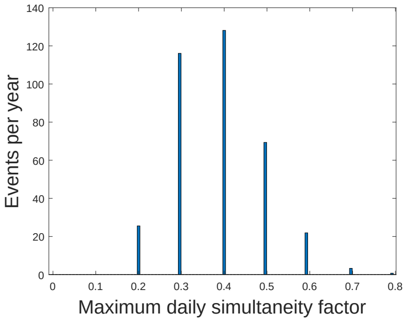

Figure 1: Distribution of the simultaneity factor of EV.

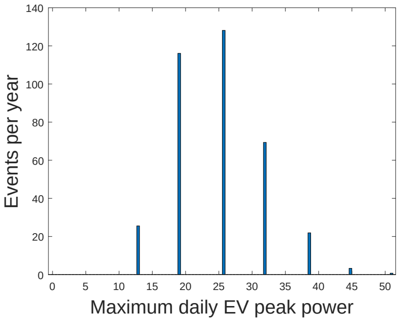

Figure 2: Distribution of EV peak power.

In addition to the simultaneity factor for EV, various percentiles are also mapped, see Tab. II. In the exemplary results, the maximum simultaneity factor amounts 0.8. Since 10 vehicles were assumed in the example, in maximum 8 EV charge in parallel. However, this case only occurs with a probability of 0.2%.

Table II: Results of simultaneity factor of EV.

	Tool Results
Max. simultaneity factor	0.8
Prob. max. simult. factor [%]	0.2
99.9th percentile	0.8
99th percentile	0.7
95th percentile	0.6
90th percentile	0.5
50th percentile	0.4

Considering the different percentiles, it can be seen that the 50th percentile is already at 0.4 and thus significantly below the maximum simultaneity factor.

B. Peak power of EV and household

In addition to the EV specific simultaneity factor, the EV peak power and the household peak load are calculated within the Tool, see Fig. 2 and Fig. 3. Since EV loads are affected by different simultaneities than household loads, these different simultaneities are explicitly taken into account.

The EV peak load in this exemplary calculation is 51.44 kW. This is calculated by the maximum simultaneity factor, the number of EV and the average charging power.

The household peak power results from the summation of the individual load profiles and amounts for the default values to 30.95 kW.

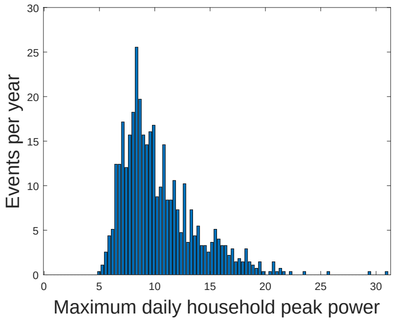

Figure 3: Distribution of household peak power.

In addition to the calculations of the household peak power, the 99th, the 90th and the 50th percentile are also calculated.

C. Total peak power

For grid analyses, it is important to consider the total peak load, i.e. both the EV and household loads. In order to calculate the total peak load, the individual household and EV loads are summated. It must be mentioned, that for both load curves the specific simultaneities are included. Therefore, total peak load is calculated from the sum of these two load curves. The distribution of the exemplary total peak load is presented in Fig. 4.

Tab. III shows the different peak loads. As the peak load times of EV and households diverge, the total peak load is lower than the sum of the individual peak loads.

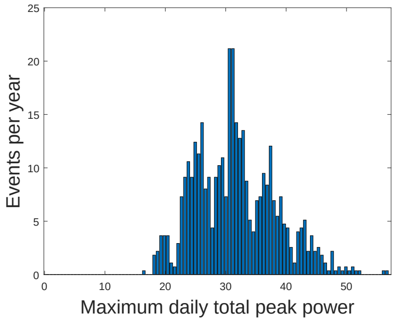

Figure 4: Distribution of total peak power.

Table III: Peak Loads.

	EV	Household	Total
Peak Power [kW]	51.44	30.95	56.70

D. *Sensitivity analysis*

Within the framework of this subchapter IV-D, the number of simulated days, the number of EV, and the distribution of the charging rate is varied and the corresponding results analysed.

In Tab. IV the results for a different number of simulated days is presented. A differentiation is made between 1000, 10,000, and 100,000 days.

Table IV: Tool Results for various numbers of simulated days.

Simulated days	1,000	10,000	100,000
Max. simultaneity factor	0.8	0.8	0.9
Prob. max simult. factor [%]	0.2	0.09	0.007
99.9th percentile	0.8	0.7	0.8
99th percentile	0.7	0.6	0.7
95th percentile	0.6	0.6	0.6
90th percentile	0.5	0.5	0.5
50th percentile	0.4	0.4	0.4
EV peak load [kW]	51.44	51.44	57.87
Household peak load [kW]	30.95	31.97	36.72
Total peak load [kW]	56.70	60.06	66.73

As it can be seen in Tab. IV, the maximum simultaneity factor and the relative percentiles are quite similar. However, the probability of the maximum simultaneity factor decreases significantly. The household peak load is 30.95 kW, 31.97 kW, and 36.07 kW, respectively. The associated total load peak differ between 56.70 kW, 60.06 kW, and 66.73 kW.

Second, the number of EV is varied. Fig. 5 shows the simultaneity factor if just one EV is considered. In this case, the simultaneity of the charging processes is either 1 or 0.

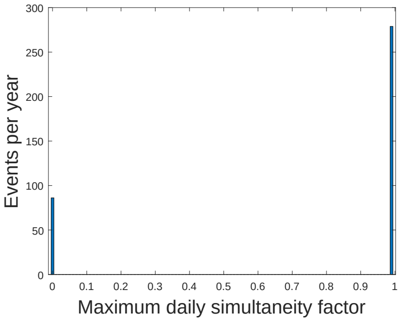

Figure 5: Distribution of the simultaneity factor for one EV.

Table V: Results for different number of EV.

Number of EV	1	10	20
Max. simultaneity factor	1	0.8	0.6
Prob. max simult. factor [%]	78	0.2	0.1
EV peak load [kW]	6.43	51.44	77.16
Household peak load [kW]	24.40	30.95	25.59
Total peak load [kW]	30.83	56.70	85.71

By increasing the number of EV, the simultaneity factor decreases, but the total load increases, see Tab. V.

Third, since the limitation of the charging power is seen as a possibility to reduce the network loads, the simultaneity factors at different charging rates are shown in the following. Fig. 6 shows the corresponding simultaneities if EV can only be charged with a charging power of 3.7 kW. In comparison, Fig. 7 shows the simultaneities when all EV are charged with 11 kW. It can be seen that due to the shorter charging duration at 11 kW, the maximum simultaneities decrease.

However, the change in average charging power also influences the EV peak load. Compared to the default charging rate distribution (see II-B) the EV peak load decreases from 51.44 kW to 33.30 kW at a charging rate of 3.7 kW and increases to 77 kW at a charging rate of 11 kW. Consequently, the

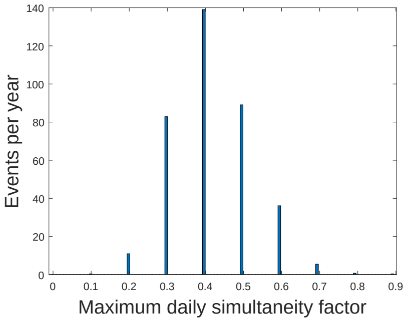

Figure 6: Distribution of simultaneity factor of EV if EV can only be charged with 3.7 kW.

charging power is a very decisive parameter for the grid impact, which can be seen also on the level of total peak load (see Tab. VI).

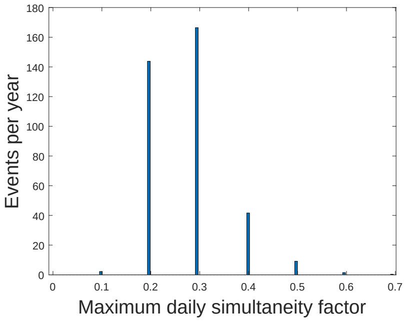

Figure 7: Distribution of simultaneity factor of EV if EV can only be charged with 11 kW.

Table VI: Results for different distributions of charging rates.

Charging rate [kW] (100%)	3.7	11
Max. simultaneity factor	0.9	0.7
Prob. max simult. factor [%]	0.1	0.1
EV peak load [kW]	33.30	77
Household peak load [kW]	29.28	27.32
Total peak load [kW]	40.38	82.18

E. Unbalanced charging

An additional feature of the Tool is the differentiation between balanced and unbalanced charging of EV. At previous results it was assumed, EV are loaded symmetric at all phases. Now, we assume a three-phase system like it exists in Germany and other countries. In order to represent the more realistic case that the individual EV are distributed unbalanced over the three phases, this can be explicitly taken into account in the Tool. However, due to the lack of data, the household loads remains symmetrically spread over the three phases.
If the unbalanced charging setting is selected, the simultaneity factors for the individual phases are calculated (cf. Fig. 8).

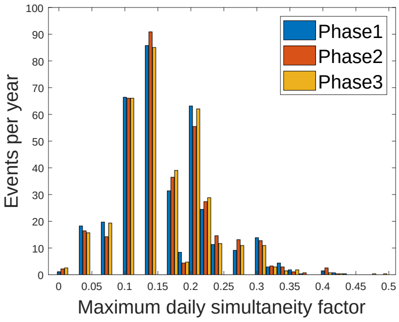

Figure 8: Distribution of simultaneity factor in a three-phase system (unbalanced charging).

As can be seen in Fig. 8, the simultaneities for each of the three phases are now shown (see Tab. VII). Due to the unbalanced distribution of the EV between the three phases, the load on the individual phases is different. This is also reflected in Fig. 9, which represents the EV peak power per phase.

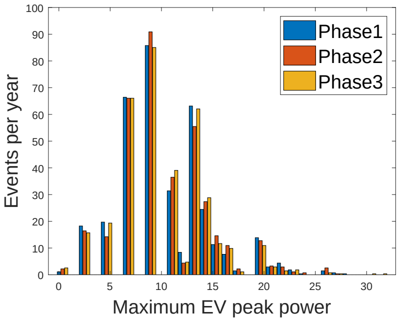

Figure 9: Distribution of EV peak power in a three-phase system (unbalanced charging).

If one compares the results between unbalanced and balanced charging (cf. Tab. VII), considerable differences can be identified. If the maximum simultaneity factor of the individual phases are summed up (0.43/ 0.43/ 0.5), they rise above the maximum value for balanced loading (0.8).

Table VII: Balanced vs. unbalanced charging.

Charging	Unbalanced	Balanced
Max. simultaneity factor	0.43 / 0.43 / 0.5	0.8
Prob. max sim. factor [%]	0.1 / 0.1 / 0.1	0.2
99.9th percentile	0.43 / 0.4 / 0.47	0.8
99th percentile	0.37 / 0.37 / 0.33	0.6
95th percentile	0.3 / 0.3 / 0.3	0.6
90th percentile	0.23 / 0.27 / 0.23	0.5
50th percentile	0.13 / 0.13 / 0.13	0.4

The consideration of the unbalanced distribution is particularly important for the network analyses with regard to grid voltage and cable limitations.

V. CONCLUSION

In summary, the simultaneity of charging processes plays a significant role in the analysis of the network effects of EV. However, it is important to consider whether the EV are distributed balanced or unbalanced between the three phases. In general, it can be said that the simultaneity of the charging processes is in any case below the empirically unrealistic but frequently assumed simultaneity factor of 1. As can be seen in the results, concurrences of 0.8 occur sporadically, but with a very low probability for 10 EV. Since the total peak load is important for grid analyses, the household loads should also be included in the analysis in addition to the EV loads. However, since the times of household peak loads and EV peak loads fall apart, this should also be taken into account in the calculation of the total peak load. Due to the time difference between EV peak loads and household peak loads, this peak load is lower than the sum of the individual peaks. As shown, in particular the charging power and the number of EV taken into account have a strong influence on the simultaneity factors. However, when using the Tool and the resulting simultaneities or peak loads, it should be noted that extreme values can occur empirically by accident.

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