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Electric car charging stations in the power grid

PhD dissertation thesis booklet

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1 Introduction

An important step in the alteration of the power system is the spreading of electric vehicles (EVs): they are intelligent consumers and might act as distributed energy storages in the future. To investigate the impact this technology will have on the grid, one has to estimate the charging needs and the chargers themselves in terms of power quality. The capacity planning of charging stations for EVs is a widely researched topic and in my dissertation I aim to consent to this common goal with the creation of stochastic models for charging station planning. Such simulations are required due to the absence of existing infrastructure for electric vehicle charging: real-life impacts can only be measured when the charging stations are built, but for capacity planning the DSOs must have a tool in advance.

Meanwhile, the electronics used in the chargers and other grid-connected loads are becoming increasingly sensitive to power quality, while reliability requirements are becoming more stringent. A large proportion of chargers are expected to be fast or quick chargers: these devices draw a considerable amount of power from the grid, while as yet no standard sets limits to inrush currents of switching of these chargers. Large inrush currents cause short-time voltage sags on the grid, which can adversely affect charger electronics or cause the tripping of sensitive instruments. For infrastructure with high power quality requirements, adequate metrics are required for DSOs to be able to monitor and evaluate their grid compliance in terms of power quality in a simple and reliable way. I present a new voltage sag evaluation method in accordance with the aforementioned requirements in the second part of my thesis.

2 Stochastic modelling of electric car charging

In Chapter 2. I presented my research regarding the stochastic modelling of electric car charging stations. In the beginning of the chapter I reviewed the literature upon electric car charging station sizing, especially those with a similar approach to mine, investigating the charging procedure with stochastic modelling, using the mathematical apparatus of queuing theory.

The stochastic model I created for charging station sizing defines three possible states for every vehicle: the car either moves, parks and not charges, or parks and charges. Transition probabilities between these states are given by a state transition matrix for every discrete time step, as seen in (1):

$$\underline{\underline{A}}_{i,j}^{l}[k] = \begin{bmatrix} a_{11}[k] & a_{12}[k] & a_{13}[k] \\ a_{21}[k] & a_{22}[k] & a_{23}[k] \\ a_{31}[k] & a_{32}[k] & a_{33}[k] \end{bmatrix} \tag{1}$$

where i and j are row and column indices, l is the vehicle number, while k denotes the discrete time step applied during the simulation, in this case 5 minutes. The state of a given car in the next time step can be determined from the actual state by multiplication with the transition matrix. The structure of the matrix is actually much simpler than shown generally in (1): cars don't get into parking or charging states by chance (this means that a_{13} and a_{23} equal to 0, while a_{33} is 1, for the matrix to remain stochastic), but various - hereinafter to be presented - constraints override matrix elements. Mathematically this is as follows: let us denote

$$cs^{l}[k] = \begin{cases} 1, if\ the\ car\ is\ moving \\ 2, if\ the\ car\ is\ parked\ and\ not\ charging \\ 3, if\ the\ car\ is\ parked\ and\ charging \end{cases} \tag{2}$$

the state of car no. l (moving, parked and charging, parked and not charging) in the kth time step, and let $SOC^{l}[k]$ be the state of battery charge of the same car in the same moment. If the car is moving, then the prescribed travel time for it, denoted with $dist^{l}[k]$ decreases according to (3):

$$dist^l[k+1] = dist^l[k] - cons^l[k] \tag{3}$$

where $cons^l[k]$ is the actual consumption of the vehicle, determined by (4):

$$cons^l[k] = 1 - \frac{cap^l - c^l[k] \cdot t_{step}}{cap^l} = \frac{c^l[k] \cdot t_{step}}{cap^l} \tag{4}$$

where $c^l[k]$ is the consumption of the car in kWh/100km for the given time interval, cap^l is the battery capacity of the car in kWh, and t_{step} is the discrete time step applied during the simulation, in our case 5 minutes. We can construct the parameter $m[k]$ as seen in (5):

$$m[k] = \begin{cases} 0, if\ cs^l[k-1] = 2 \\ 1, if\ cs^l[k-1] = 1\ \&\ dist^l[k] > 0 \\ 2, if\ cs^l[k-1] = 1\ \&\ dist^l[k] = 0\ \&\ SOC^l[k] > 0{,}3.\ This\ means\ m[k+1] = 0 \\ 1, if\ SOC^l[k] \le 0{,}3.\ This\ means\ m[k+1] = 3 \\ 3, if\ cs^l[k-1] = 3\ \&\ SOC^l[k] < 1 \\ 2, if\ SOC^l[k] < 0{,}3\ and\ there\ is\ no\ available\ charger. Tries\ again\ in\ [k+1] \\ 1, if\ cs^l[k-1] = 3\ \&\ \lfloor SOC^l[k] \rfloor = 1. This\ means\ m[k+1] = 0 \end{cases} \tag{5}$$

where $\lfloor SOC^l[k] \rfloor$ denotes the entire function of $SOC^l[k]$. Furthermore,

$$\underline{\underline{S}} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \tag{6}$$

is a summation matrix and

$$\underline{\underline{P}} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \tag{7}$$

is a permutation matrix. Let us denote with

$$\delta_{m[k]0} = \begin{cases} 0, ha\ m[k] \neq 0 \\ 1, ha\ m[k] = 0 \end{cases} \tag{8}$$

the Kronecker delta. With all these notations, the evolution of $\underline{\underline{A}}^l_{i,j}[k]$ transition probability matrix during the simulation can be given according to (9):

$$\underline{\underline{A}}^l_{i,j}[k] = \underline{\underline{A}}^l_{i,j}[k-1] \cdot \underline{\underline{S}}^{(1-\delta_{m[k]0})} \cdot \underline{\underline{P}}^{m[k]} \tag{9}$$

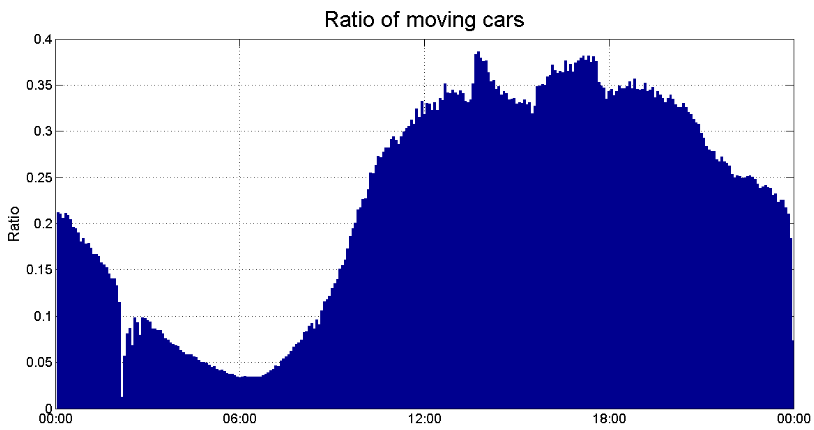

Fig. 2-1: Ratio of moving cars during the day, a fleet of 10357 taxis

To demonstrate how the algorithm works, I conducted simulations for a taxi fleet composed of 100 electric cars. To simulate the motion of the electric cars, GPS data for more than 10000 taxis was available in the literature, so I was able to determine how (see Fig. 2-1) and for how long (Fig. 2-2) cars move. I could also calculate the transition probabilities (Fig. 2-3) for the algorithm.

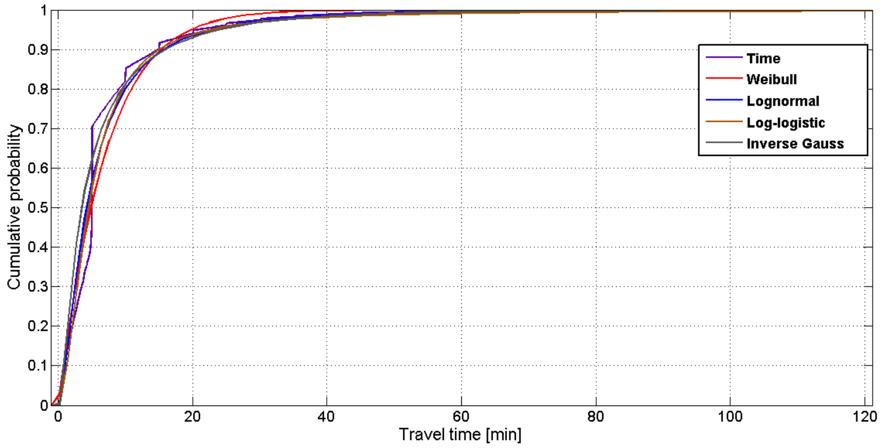

Fig. 2-2.: The fitting four investigated distributions (Weibull, lognormal, log-logistic, inverse Gauss) to travel time, cumulative distribution function (CDF)

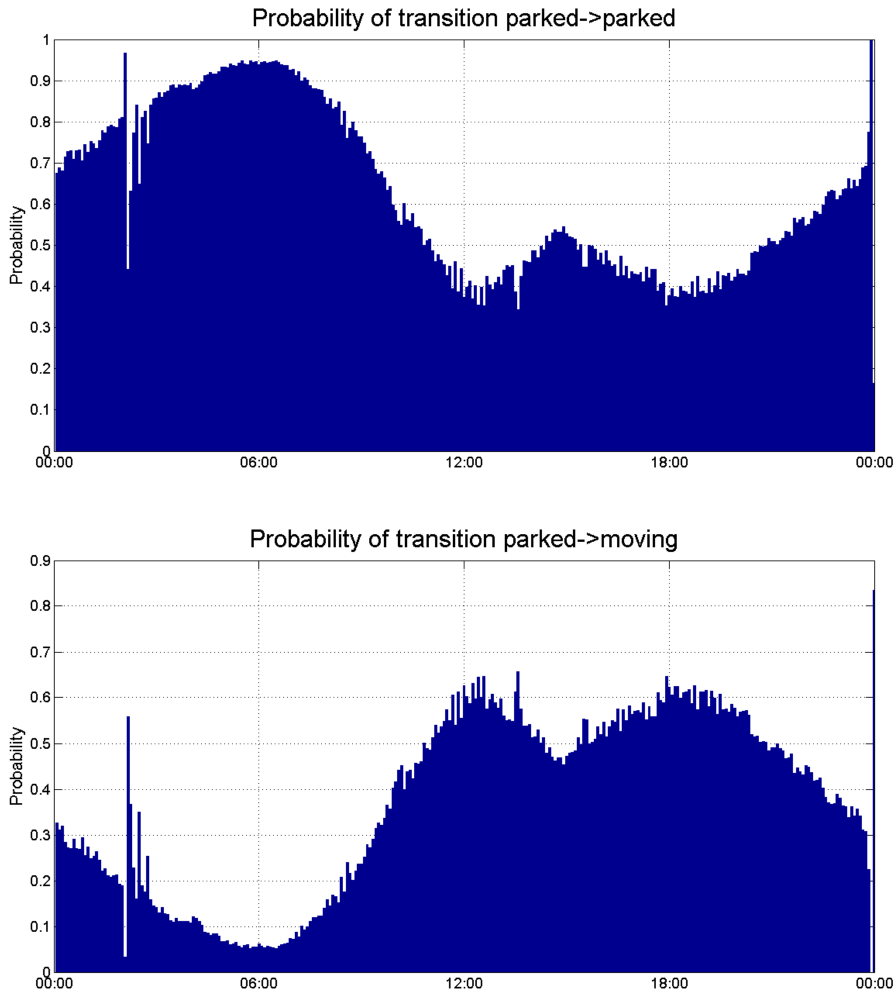

Fig. 2-3.: Graphical interpretation of transition probabilities

I determined vehicle motion parameters, such as travel time, travel distance, vehicle consumption with Monte Carlo simulation. For this, I fitted distribution functions to every parameter, as shown in Fig. 2-2. Besides the fitting procedure, I validated the chosen distribution functions with literature research.

The model is capable of determining the required number of slow and fast chargers in a charging station for given traffic conditions, assuming that both slow and fast chargers are homogeneous. The aim of the investigations is to have enough chargers, so that the number of waiting cars is smaller than a predefined threshold. Fig. 2-4 and Fig. 2-5 depicts simulation results for a homogeneous taxi fleet of 100 cars.

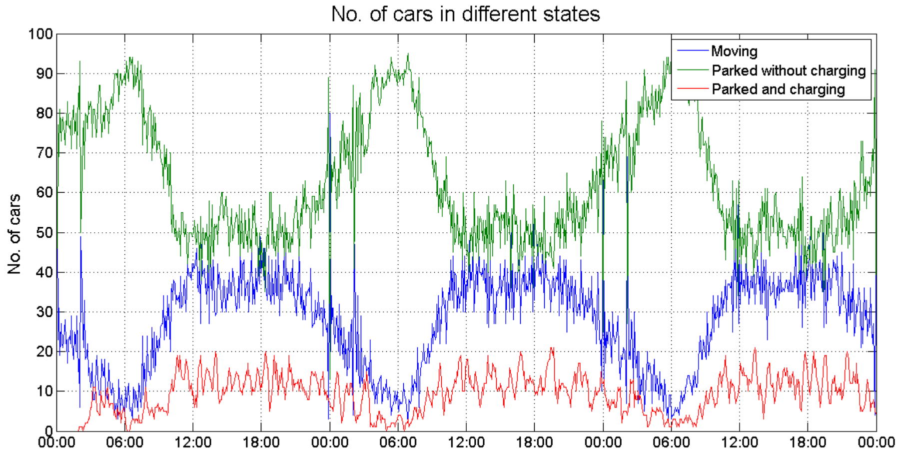

Fig. 2-4.: Cars in different states during the simulation (example)

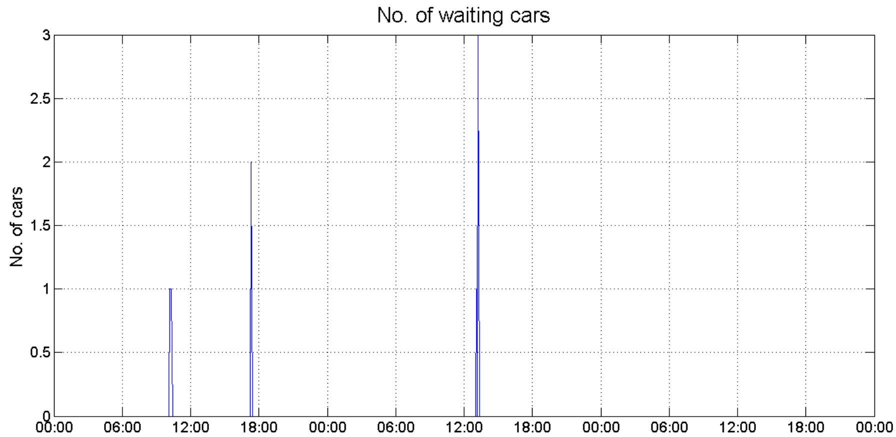

Fig. 2-5.: Number of cars that have to wait (example)

Charging station sizing can be viewed from an opposite viewpoint as well, namely we set a threshold for the maximum allowed number of waiting cars and we determine the number of slow and fast chargers required to fulfil this need. Fig. 2-6 depicts this approach, where I depicted the average of multiple simulation runs. There is no optimization here in its classic sense, as the optimization problem could not be formulated, let alone solved, due to the stochastic nature of the problem.

Based on the results of the research I formulated the following thesis:

***Thesis I:** I elaborated a stochastic model for electric vehicle charging based on statistical data and probabilistic estimations. The model is capable of determining the required number of slow and fast chargers in a charging station from available traffic data.*

Publications of the author, related to the research presented in Chapter 2: [S12]-[S15].

The contribution in Chapter 2 is the model itself, with which similar databases for buses, community cars, etc. can also be treated and the required number of chargers for these vehicles determined.

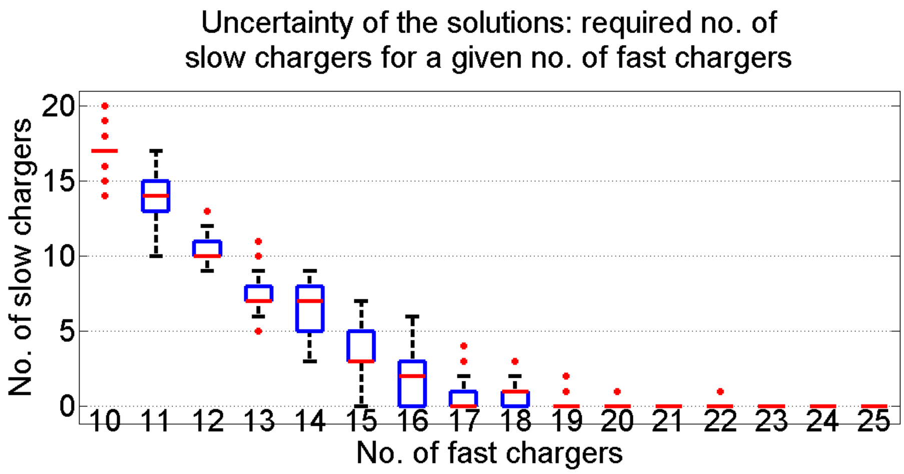

Fig. 2-6.: Uncertainty of the solutions

3 A queuing theory based investigation of the required number of chargers in electric car charging stations

While the model introduced in Chapter 2. incorporated vehicle motion, the model presented in Chapter 3. uses only arrival and service time statistics (in the latter the initial battery state of charge is explicitly included) for determining the required number of fast chargers in a charging station.

The queuing model introduced in Chapter 3. uses Markov arrival processes (MAP), which is a point process where the arrivals are determined by a continuous time Markov chain. The literature review, summarized in Chapter 2. indicates that the car arrival process was almost exclusively considered to be a Poisson-process, a fact that is not supported by any measurements. However, the MAP model proposed in Chapter 3. is more general in nature compared to the Poisson-process, and can be used under circumstances when the latter cannot be (e.g. sojourn times are exponentially distributed). I used second-order MAPs in my simulations due to their convenience with numerical calculations, and because they have canonical representation, as seen in (10). I also compared the proposed MAP model with an M/M/c model described in the literature.

The canonical form of the proposed MAP model can be seen in (10). I used second-order forms.

$$D_0 = \begin{bmatrix} -\lambda_1 & (1-a)\cdot\lambda_1 \\ 0 & -\lambda_2 \end{bmatrix}, \quad D_1 = \begin{bmatrix} a\cdot\lambda_1 & 0 \\ (1-b)\cdot\lambda_2 & b\cdot\lambda_2 \end{bmatrix} \tag{10}$$

The D_0 matrix in the canonical form represents the hidden transitions, where there is no arrival, while D_1 contains the observable transitions, where the phase process has no state change, but an arrival takes place. For the charging station sizing procedure we have to determine the values of the four unknown parameters (a, b, λ_1, λ_2) for a given traffic data. This is done using a z-transform polynomial (11) obtained from the histogram of the arrival process (the procedure is similar for the service process as well), as depicted in Fig. 3-2. This polynomial must be fitted to the z-transform polynomial of the distribution of the arrivals in the case of MAP, see (12). The correlation of the arrival data must also be taken into account by calculating the lag-1 correlation of the original dataset and the correlation coefficient of the MAP and equate each other.

$$A(z) = \sum_i p_i \cdot z^i \tag{11}$$

$$p(\Delta, z) = \alpha \cdot e^{(D_0 + D_1 \cdot z) \cdot \Delta} \cdot \mathbf{1} \tag{12}$$

The p_i values in (11) denote the probability that during one time step a number of i cars arrive to charge, while in (12) $\alpha = [\alpha_0 \quad \alpha_1]$ is the time stationary phase distribution vector and $\mathbf{1} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ is a summation vector. Δ denotes the time step, which is 5 minutes in my example. After obtaining the missing parameters a, b, λ_1, λ_2 the MAP process can be simulated according to Fig. 3-1.

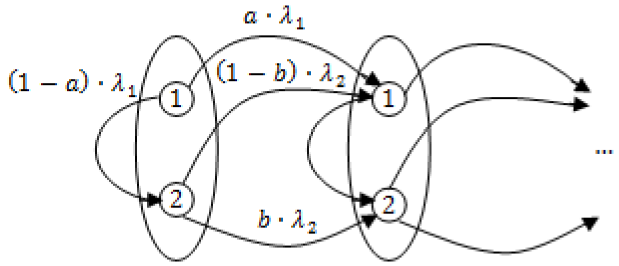

Fig. 3-1.: Process behaviour of MAP(2)

Based on the arrival (see Fig. 3-2) and the service histogram, I determined the required number of homogeneous fast chargers in a charging station using the proposed MAP model. As traffic data about electric cars, as well as real measurement data about battery charging stations was missing in the literature, I compared the MAP model with the stochastic model described in Chapter 2. (in fact, this stochastic model was used to generate the arrival histogram in Fig. 3-2 as well).

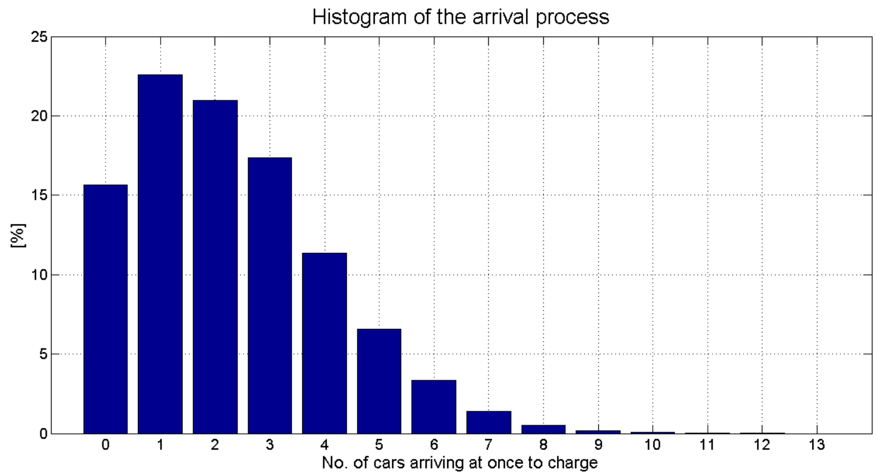

Fig. 3-2.: Histogram of the arrival process

I also investigated the M/M/c model proposed in the literature and - as Fig. 3-3 indicates - showed that the MAP model is more accurate in determining the required number of chargers in a charging station.

The findings of the research done in Chapter 3. are not the numerical values, but the general model that can be used for any kind of traffic data, even for cases that cannot be characterized as Poisson-processes.

Based on the results of the research I formulated the following thesis:

<u>Thesis II.:</u> I elaborated a queuing model based on Markov arrival processes to investigate the sizing of electric car charging stations. Unlike the M/M/c model widely used in the literature, the proposed MAP(2)/MAP(2)/c model is capable of modelling the arrival and service processes of electric cars at a charging station even if they are not Poisson-processes; in this sense, the proposed model is a generalisation of the existing ones.

Publications of the author, related to the research presented in Chapter 3: [S14]-[S17].

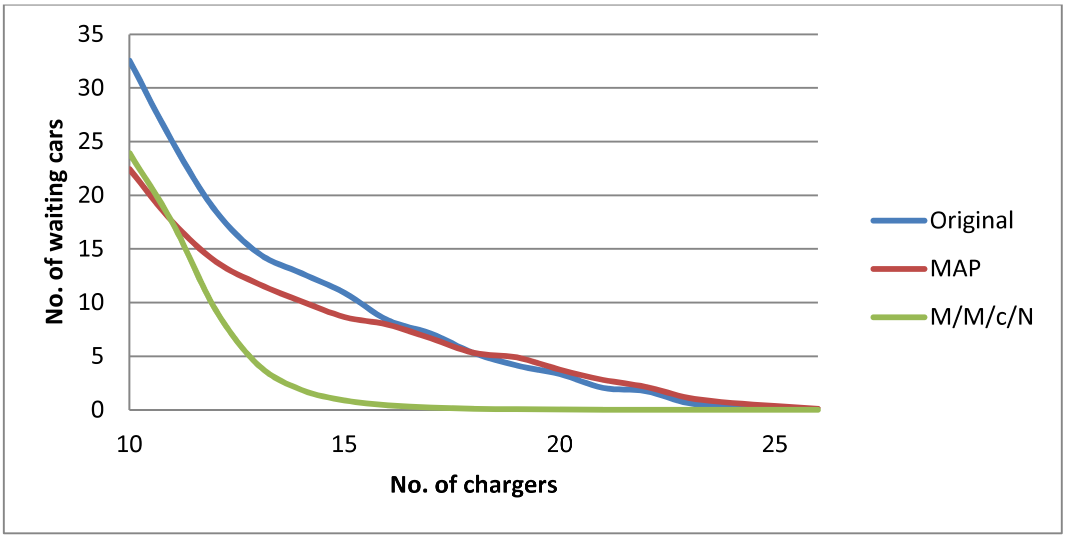

Fig. 3-3.: Number of waiting cars as a function of the number of fast chargers, 100 runs

4 Voltage sag evaluation

The electronics used in the chargers and other grid-connected loads are becoming increasingly sensitive to power quality, while reliability requirements are becoming more stringent. This means that for infrastructure with high power quality requirements, adequate metrics are required for DSOs to be able to monitor and evaluate their grid compliance in terms of power quality in a simple and reliable way. In Chapter 4. of my dissertation I present a new voltage sag evaluation method in accordance with the aforementioned requirements.

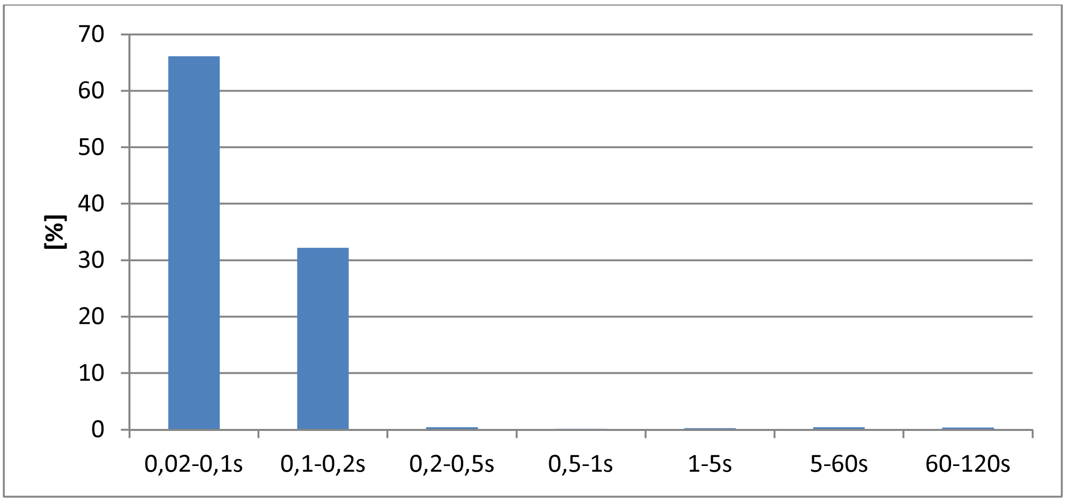

Fig 4-1.: Voltage sags considered to be critical

The most widely used method to evaluate voltage sag is the ITIC curve, but - as the literature clearly states - this curve is defined for only a limited set of devices and not for every voltage level and frequency, hence the applicability of the curve is questionable. The literature review disambiguates that most of the household appliances have L-shaped sensitivity curve to voltage sag on the voltage-time plane. This finding justifies the use of the ITIC curve and evaluation methods similar to this curve. However, the operational time of modern protection devices must also be taken into consideration when evaluating voltage sag. I did statistical analysis to measurement data in my dissertation, and showed that voltage sag duration does not exceed 200ms in LV distribution grids (as depicted in Fig 4-1), while it is less than 100ms for modern protection devices, as Fig. 4-2 depicts for voltage sags registered in an automotive industrial facility.

I investigated several evaluation method in Chapter 4., as can be seen in equations (13)-(15), calculating the lost energy of the voltage sag, and (16), the method proposed by me.

$$E = \left(0{,}9 - \left(\frac{V_{pu}}{V_{névl}}\right)^2\right) \cdot t \tag{13}$$

$$E = \left(\left(0{,}9 - V_{pu}\right)^2\right) \cdot t \tag{14}$$

$$E = \left(\left(0{,}9 - V_{pu}\right)^{3{,}14}\right) \cdot t \tag{15}$$

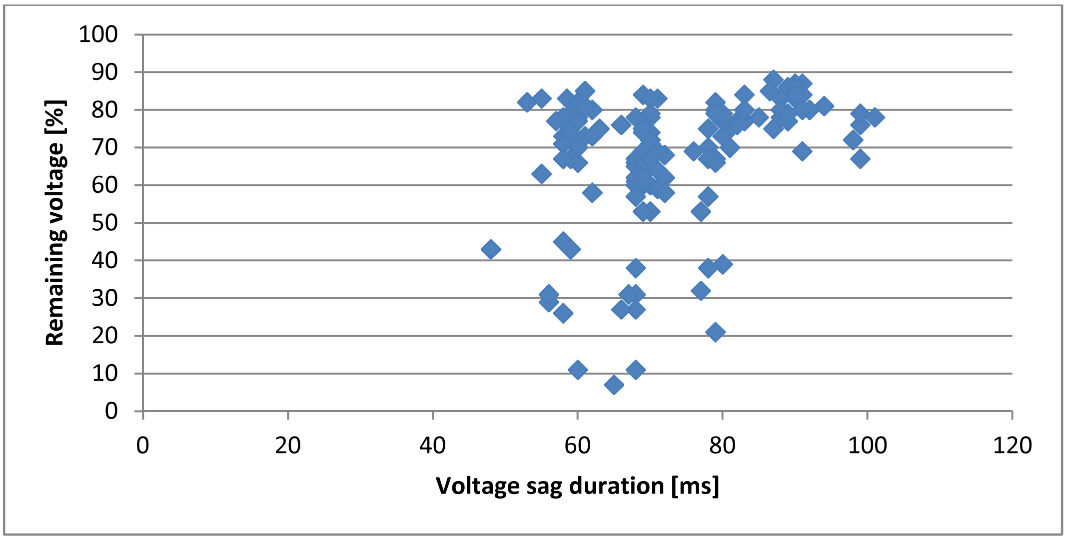

Fig. 4-2.: Voltage sags registrated in an automotive industrial facility

I also constructed an evaluation method on my own, similar to those of equations (13)-(15), calculating the lost voltage-time area of the sag, as seen in (16).

$$T = \left(0{,}9 - V_{pu}\right) \cdot t \tag{16}$$

When using these methods for evaluation, I considered so-called corner points as base values characterising the criticality of voltage sag events. These corner points were determined based on the ITIC curve, measurement results from the literature, and from the automotive industrial facility as follows:

- if the duration of the voltage sag is less than 20ms, it is not considered to be critical, as - according to the literature - devices have a ride-through capability for this duration;
- the first corner point is characterised by $0{,}7V_{pu}$ remaining voltage and 100ms duration;
- the second corner point is characterised by $0{,}8V_{pu}$ remaining voltage and 200ms duration.

Taking the aforementioned into consideration, the energies and voltage-time areas for which larger values are considered to be critical and smaller values not critical, can be determined (for example for voltage-time areas, $20Vpu \cdot ms$ is this value for the whole region above 20ms).

I compared the evaluation methods against each other using measurement data from the automotive industrial facility. The obtained results are depicted in Fig. 4-3 and Fig. 4-4. The results indicate that for different evaluation purposes, we can use different methods to determine the criticality of voltage sags:

- if we would like to have the highest hit ratio among all voltage sags (so including the safe ones as well), then the lost voltage-time and or the first energy based method should be used based on 70% remaining voltage as corner point;
- if we would like to have the highest hit ratio for only the truly critical voltage sag events, then we should use the lost voltage-time and or the first energy based method should be used based on 80% remaining voltage as corner point;
- if we would like to have a high hit ratio for both aspects, the ITIC curve is a good choice.

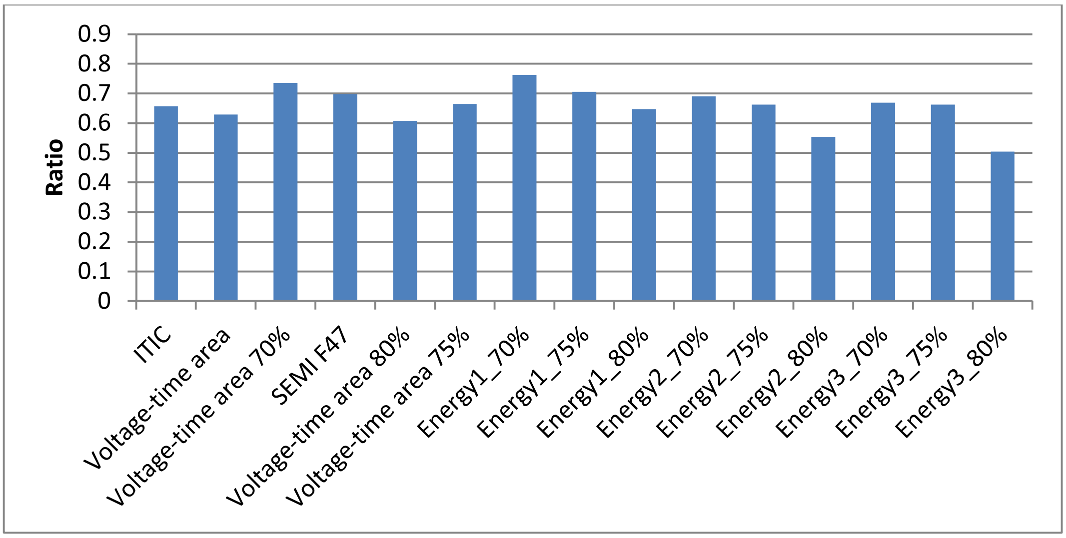

Fig. 4-3.: Hit ratio of various evaluation methods, all sag events

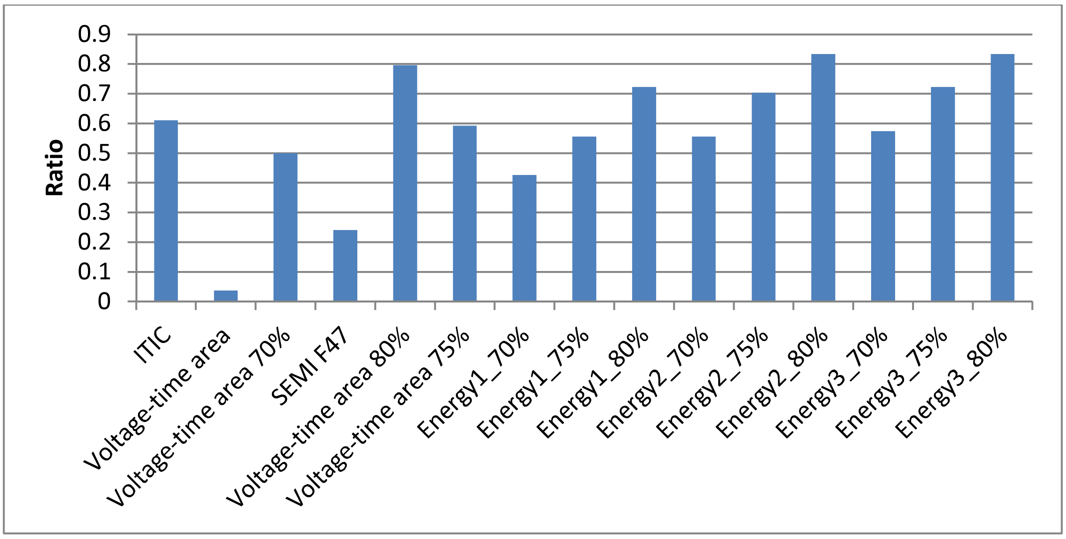

Fig. 4-4.: Hit ratio of various evaluation events, only critical voltage sags

Neither of the evaluation methods, however, take into consideration whether there were any household devices turned on at all during a particular voltage sag. It is obvious, that if the number of devices on during a sag event is small (e.g. during the night), then the criticality of that particular voltage sag is less than that of the voltage sag during which many devices are on. To also take this aspect into consideration, I created the on-period curve (Fig. 4-5) with which the criticality of voltage sag events can be drawn nearer to their real extent, as shown in Fig. 4-6, which depicts the ratio of not critical sags to all sags.

It is worth noting that by taking the on-period curve into account, not only the criticality of voltage sags can be evaluated, but all the other short or long timed voltage drops, disturbances, etc. can be treated, as the use of the on-period curve allows for more accurate predictions. It even has an impact on the evaluation of SAIDI and SAIFI values.

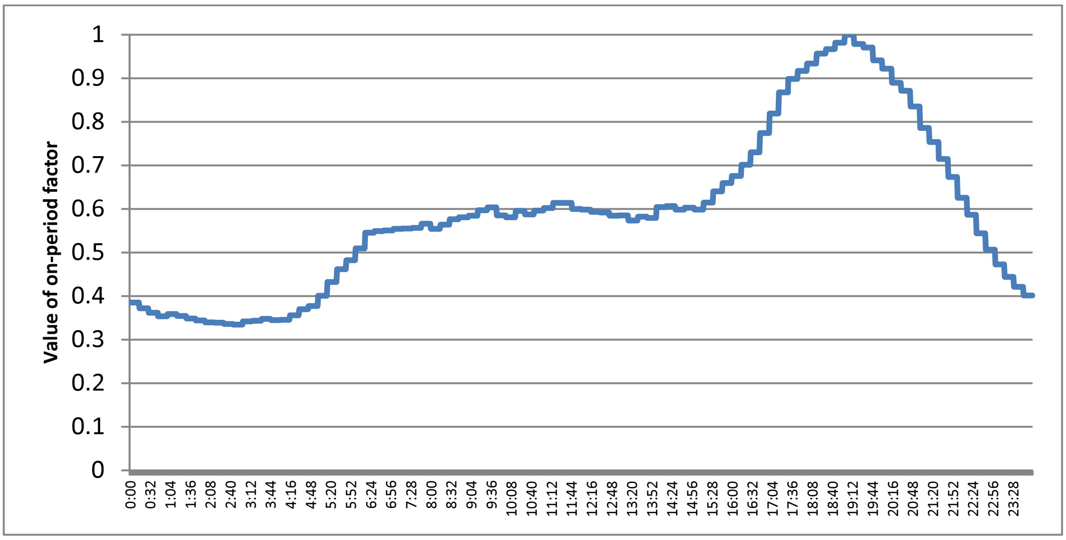

Fig. 4-5.: The on-period curve in 1-minute resolution

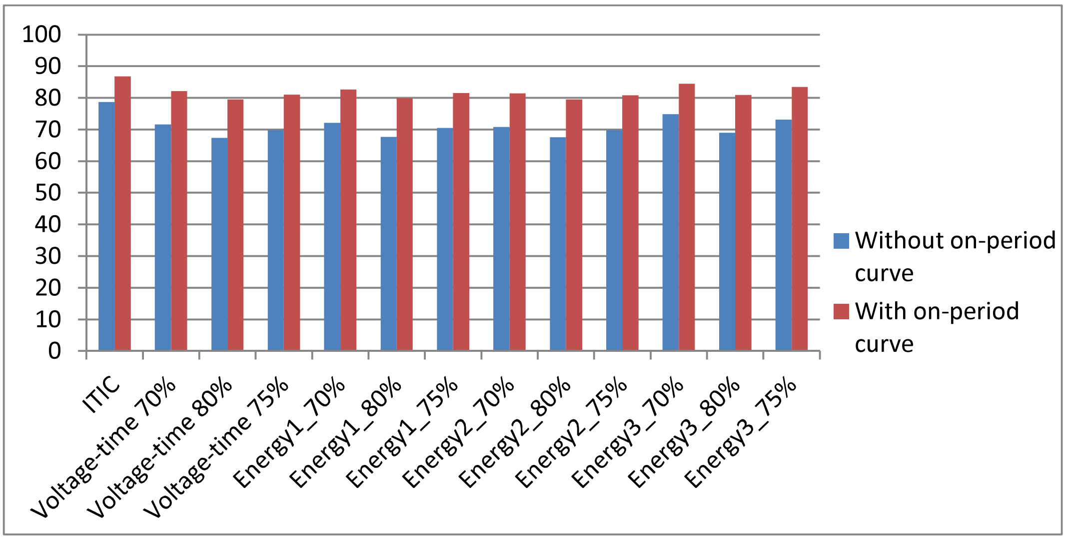

Fig. 4-6.: Degree of criticality of voltage sags with and without taking the on-perod curve into consideration. The figure shows the ratio of not critical sags

To summarize the results obtained in Chapter 4. we can state that the proposed evaluation methods characterise the criticality of voltage sag events better than the existing ones, while the use of the on-period curve enables us to make even more accurate predictions.

Based on the results of the research I formulated the following thesis:

Thesis III.: Based on the widely used ITIC curve and using measurement data with lost energy-based methods from the literature also taken into consideration I elaborated a new voltage sag evaluation method based on the lost voltage-time area associated to the voltage sag. Using measurement data I defined corner points that can be used as base values for the evaluation of voltage sag severity, making the evaluation more accurate compared to the older methods.

Sub-thesis of thesis III.: I created the on-period curve to further improve voltage sag evaluation accuracy. The probability of household devices been turned on can be taken into consideration with this curve, thus drawing voltage sag criticality closer to its real extent.

Publications of the author, related to the research presented in Chapter 4.: [S19]-[S24].

5 List of publications

[S1] Pintér László, Farkas Csaba, "Impacts of Electric Vehicle Chargers on the Power Grid", 2015 5th International Youth Conference on Energy (IYCE), Pisa, Olaszország, 2015.05.27-2015.05.30., pp. 10-16.

[S2] Farkas Csaba, Dán András, Prikler László, "Villamos autók integrálása a villamosenergia-rendszerbe", Tavaszi Szél 2014 Konferenciakötet: VII., Debrecen, Magyarország, 2014.03.21-2014.03.23. Debrecen: Doktoranduszok Országos Szövetsége, 2014. pp. 321-339.

[S3] Dán András, Farkas Csaba, Prikler László, "V2G effects on frequency regulation and under-frequency load shedding in a quasi-islanded grid", IEEE PowerTech 2013 Grenoble: Towards carbon free society through smarter grids, Grenoble, Franciaország, 2013.06.16-2013.06.20.pp. 1-6.

[S4] Farkas Csaba, Prikler László, "Aggregált villamos autó teljesítmény felhasználási lehetőségei", VII. Klímaváltozás - Energiatudatosság - Energiahatékonyság (KLENEN) Konferencia, Mátraháza, Magyarország, 2012.03.08-2012.03.09.pp. 1-5.

[S5] Farkas Csaba, Prikler László, "Impact of electric vehicle charging on cable and overhead line distribution systems", JOURNAL OF ELECTRICAL AND CONTROL ENGINEERING 2:(4) pp. 1-6. (2012)

[S6] Farkas Csaba, Vereczki György, "E-mobility - A villamos autók hatása a villamos hálózatra III. rész: V2G - Villamos autók visszatáplálásos üzemmódja", ELEKTROTECHNIKA 105:(10) pp. 5-9. (2012)

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[S8] Farkas Csaba, "Az e-mobilitás várható hatása a villamosenergia-elosztó és -átviteli hálózaton", ELEKTROTECHNIKA 105:(11) pp. 10-11. (2012)

[S9] Farkas Csaba, Szabó Kristóf, Prikler László, "Impact Assessment of Electric Vehicle Charging on a LV Distribution System", III. International Youth Conference on Energetics (IYCE2011), Leiria, Portugália, 2011.07.07-2011.07.09.pp. 1-8.

[S10] Farkas Csaba, Szabó Kristóf, Prikler László, "E-mobility - A villamos autók hatása a villamos hálózatra 1. rész", ELEKTROTECHNIKA 104:(2011/04) pp. 9-13. (2011)

[S11] Farkas Csaba, Prikler László, "A villamos autók hatása a villamos hálózatra II. rész", ELEKTROTECHNIKA 104:(12) pp. 11-16. (2011)

[S12] Dán András, Farkas Csaba, "Villamos autók töltöttségének sztochasztikus modellezése", ELEKTROTECHNIKA 107:(12) pp. 15-19. (2014)

[S13] Farkas Csaba, Dán András, "Villamos autók töltöttségének sztochasztikus modellezése - II. rész - Villamos autók számára létesítendő töltőállomások optimalizálása", ELEKTROTECHNIKA 108:(5) pp. 5-7. (2015)

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[S15] Julian Rominger, Csaba Farkas, "Public charging infrastructure in Japan - a stochastic modeling analysis", International Journal of Electrical Power and Energy , Elsevier, under review (submitted 18. February 2016.)

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[S17] Jayakrishnan Harikumaran, Vereczki György, Pavol Bauer, Farkas Csaba, "Comparison of Quick Charge Technologies for Electric Vehicle Introduction in Netherlands", IECON 2012: 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, Canada, 2012.10.26-28.pp. 1-8.

[S18] Csaba Farkas, Gergely Szűcs, László Prikler, "Grid impacts of twin EV fast charging stations placed alongside a motorway", 4th International Youth Conference on Energy (IYCE'13), Siófok, Magyarország, 2013.06.06-2013.06.08., pp. 1-6.

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