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Managing risk for unbalanced load situations of three-phase supply systems in charging facilities providing single-phase charging for electric vehicles

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Summary

Multi-point charging facilities for electric vehicles often use single-phase connections sufficient for ordinary charging demands. Without an even distribution of charging points across the 3-phase electrical supply, a severe load unbalance could occur, caused by an unfavorable parking pattern and charging time. Users' behaviors affect these patterns, influenced by the physical layout or obstacles. We investigate the load unbalance based on random distribution as well as on simulated parking behaviors assuming varying attractiveness of points. We also examine load unbalance in real-life data from a charging facility in Oslo. We suggest practical considerations for minimizing unbalance situations.

Keywords: *Infrastructure, Load management, Regulation, Smart charging, User behavior.*

1 Introduction

Can charging of electric vehicles (EV) cause unbalances in the low voltage distribution network? Recent research claims to verify this. Allocating enough clean energy for charging the many EVs is one challenge, sharing the power available in the existing distribution networks, is another. As EVs will continue to grow in popularity, in parallel, the awareness and knowledge about the resulting load impacts will increase.

In general, uneven loads are what causes all unbalances between the phases in electrical 3-phase power systems, where they may influence the efficiency of generators, as well as setting limitations to connected inductive devices. AC voltage unbalance ratio (VUR) defines the percentage of asymmetry in 3-phase systems, and is defined in different ways by NEMA, IEEE, and IEC, and contain information by only the voltage difference or both the voltage difference and the phase angle. Typically, the phase voltages will differ by a few volts or more, but if voltages differ excessively it threatens stability and efficiency of 3-phase generators and motors, where need for derating of power or over-dimensioning are sometimes necessary. A nominal maximum limit of phase voltage unbalance rate (PVUR) is 2% between phase voltages. Perfect conditions at all times are not possible, therefore all 1-phase loads connected the 3-phase supplying network should be kept as even as possible across the phases.

In this paper, we discuss load situations caused by charging facilities for EVs that can lead to a voltage unbalance in their supplying point thus risking to threaten the stability of other connected devices and/or the supplied power quality. We describe the severity of a load unbalance situation, but only expressed as a load in comparison to the number of charging points (sockets) available, where the characteristics of the supplying conditions (transformer and line impedances) are not considered because these will vary from location to location depending the local supplying network.

Previous studies of the impact on the electrical supply network of mass EV charging, have addressed an aggregated level [1] (e.g., neighborhoods or cities). To our knowledge, there are to date no studies that focus on the impact of one charging facility in isolation.

Patterns of parking are influenced by the user's behaviors, which again may be influenced by many factors, including the physical layout or obstacles in the area or building. We investigate the risk of load unbalance using data simulations based on random distribution as well as on simulated parking behaviors assuming varying attractiveness of points.

1.1 Definintions

Load unbalance: Analogous to the IEEE definition [2] of voltage unbalance, we defined load unbalance as:

$$\%\, Load\ unbalance\ = \frac{Max\ load\ devation\ from\ the\ average\ phase\ load}{Average\ phase\ load\ at\ maximum\ load} \times 100 \qquad (1)$$

where the denominator uses the average phase load at the maximum load of the facility, that is, when all charging points are in full use, equaling the dimensioned load of the facility. The amount of load unbalance that may cause a critical voltage unbalance, and which should therefore be regarded as severe, will depend on the size and characteristics of the supply and local conditions, and will thus be different for different facilities.

1.2 Research issues

We investigate load unbalance in EV charging facilities designed with 1-phase charging only. Specifically, we set out to study:

- The average level of load unbalance, as well as occurrence of severe unbalance, depending on the number of the charging points, assuming a random distribution of EVs to points;
- The average level of load unbalance, as well as occurrence of severe unbalance, in real-life data from an existing charging facility, under different phase distribution patterns;
- Preferences for charging points in real-life data from an existing charging facility; and
- The average level of load unbalance, as well as occurrence of severe unbalance, in a simulated hypothesized large charging facility with preferences for charging points resembling real-life data, under different phase distribution patterns.

1.3 Distribution of randomized data

1.3.1 Method

We used random generated data sets to investigate the average level of phase unbalance, as well as the proportion of occasions with an unbalance exceeding certain levels, in charging facilities of varying sizes.

10,000 data sets were random generated for each combination of number of charging points and occupancy. We varied the number of charging points from 3 to 96, and the underlying probability of occupancy of each point from 0% to 100%. For the generation of randomized data, we modeled occupancy as the probability of each charging point being occupied, not as a fixed proportion of points charging in a data set.

1.3.2 Results

Fig. 1 shows how the average unbalance in data sets varies with the number of charging points in a facility and occupancy. The unbalance is lesser when the number of charging points is greater. On average, unbalance is always naturally maximally high at 50% occupancy, falling sharply toward 0 as occupancy nears 0% or 100%.

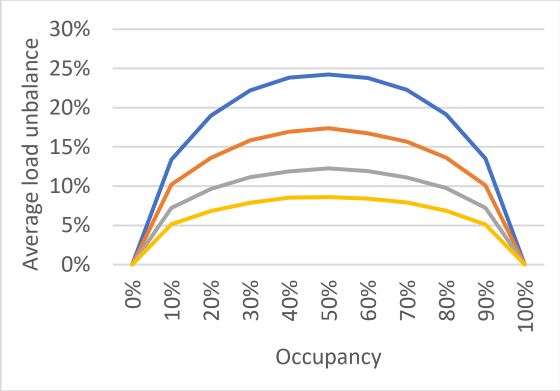

Figure 1. Average load unbalance by occupancy and number of charging points.

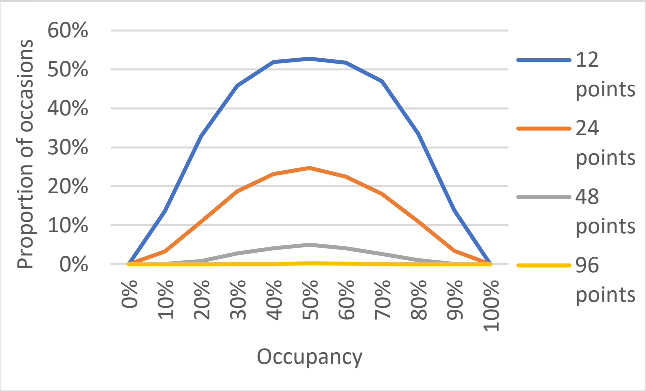

Figure 2. Proportion of cases with ≥25% load unbalance by occupancy and number of charging points.

Fig. 2 shows how the proportion of data sets with an unbalance of at least 25% varies with the number of charging points in a facility and [underlying] occupancy. The proportion diminishes drastically with an increased number of data points. At 96 charging points, an unbalance of 25% almost never occurs (0,2% of data sets).

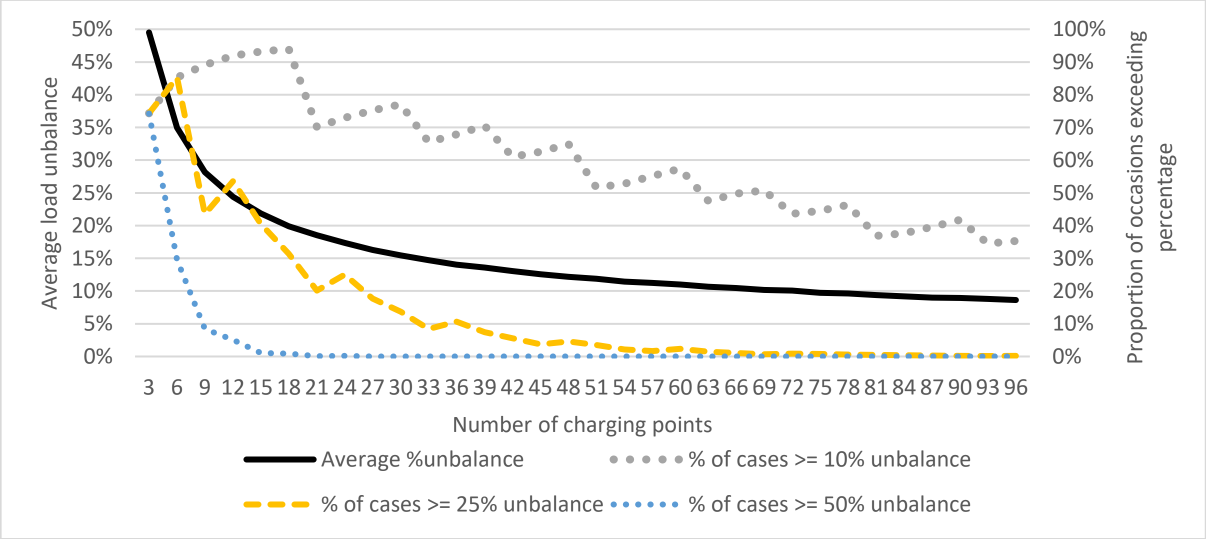

Figure 3. At 50% occupancy, average load unbalance and proportion of occasions exceeding 10%, 25%, and 50% unbalance by number of charging points.

Fig. 3 shows how, at an occupancy rate of 50%, the average unbalance in data sets, as well as the proportion of data sets with at least 50%, 25% unbalance, and 10% unbalance, diminish with the number of charging points.

2 Real life data

2.1 Method

The City of Oslo kindly provided data for the entire year of 2016 for one of their online charging facilities. We chose this location for several reasons. First, it is one of the larger public charging locations in Oslo with 12 online points, a number that can be evenly distributed over three phases. Second, it is a purely work/city location that fills up and empties completely almost daily, creating frequent periods with partial occupancy, which bring with them the potential for load unbalance. Third, it is a popular location, which both by formal control and informal social pressure brings with it few cases of abuse (i.e., non-chargeable vehicles, or chargeable vehicles parked without charging). Fig. 4 shows a picture of the facility.

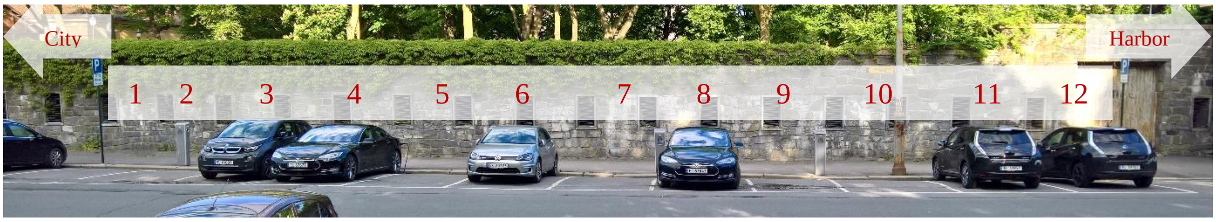

Figure 4. Oslo, Kongens gate, city center charging facility, with 6 double socket poles and 12 parking slots.

Date and time of connection and disconnection was recorded in the data set. Prior to analysis, we removed data entries where the time between connection and disconnection was less than 5 minutes, which for the most part would have been due to connection troubles or other error situations.

Charging of an EV started at the time of connection. However, termination of charging, which can occur before the time of disconnection when the car is charged up to its pre-set level, was not recorded in the data set, due to technical limitations within the communication protocol used. Assuming that cars would be charging for the entire time of connection would much of the time lead to a gross overestimation of the number of points charging, since EVs normally would be fully charged after a few hours based on typical commuting distances in the Oslo area, as well as typical sizes of EV accumulators. We assumed a skewed distribution of actual charging times and random generated charging times in hours according to a distribution with a mean of 5.2, standard deviation of 3.0, skewness of 1.2, and kurtosis of 2.7. We assigned these random generated charging times to data points in the data set and assumed that cars had been charging from connection to the assigned random generated time, or to the time of disconnection, whichever came first. While this procedure gave a more realistic estimate of the pattern of cars charging at any given time point, it did add randomness in charging times to the data, and to the extent that our assumption of charging times was incorrect, may have contributed to a shift in times of day with a higher unbalance created by EVs' charge termination. However, assuming shorter or longer times would likely have contributed to changes in the time when unbalances occur, not in amount.

The charging points were supplied by 1-phase 230 Vac, all fixed to supply 16A. We investigated unbalance assuming that all charging EVs pulled equally amount of currents. Points were assumed to be evenly distributed over the three phases in a phase-to-neutral order, as is common for TN-networks in Europe. We investigated unbalance in four possible distribution patterns of the facility's charging points' connection to phases: 1. Cycling through phases every 3rd point (1, 2, 3, 1…); 2. Cycling through phases by pairs of points (1, 1, 2, 2, 3, 3, 1…); 3. Groups of four points (1, 1, 1, 1, 2…); 4. Cycling through phases by pairs of points, reversing the cycle half-way (1, 1, 2, 2, 3, 3, 3, 3, 2, 2, 1, 1).

The raw connection time data was transposed to represent states of occupancy where each charging point could be free, charging, or occupied but not charging. We recorded the state of occupancy every five minutes.

Visual inspection of the data strongly suggested that drivers' choices of charging points were not random. For example, when most of the places were free, drivers tended to choose either point 1 or point 12. On early weekday mornings, most points would be unoccupied, and then fill up within about an hour. A representative weekday sequence of filling up the facility that occurred on the morning of June 1, 2016, shown in Fig. 5.

The non-randomness in the patterns of occupancy that result from drivers' preferences in real life may create greater unbalance than a random pattern.

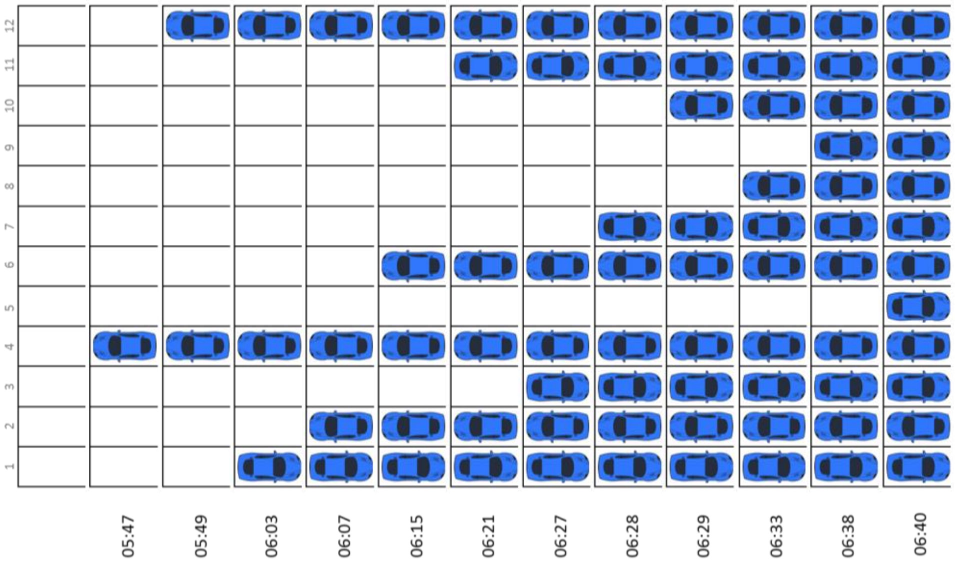

Figure 5. How the charging points fills up in the morning of June 1, 2016.

For the results concerning unbalance, we considered only the 253 workdays of the year, when the connection and disconnection patterns were consistent over days, with the facility more or less filling up and emptying at similar times. (Saturdays, Sundays, and holidays showed a less consistent pattern, and on these days the facility was not always fully occupied.) For the results concerning drivers' preferences for charging points, we used data for all choices upon arrival throughout all days of the year.

2.2 Results

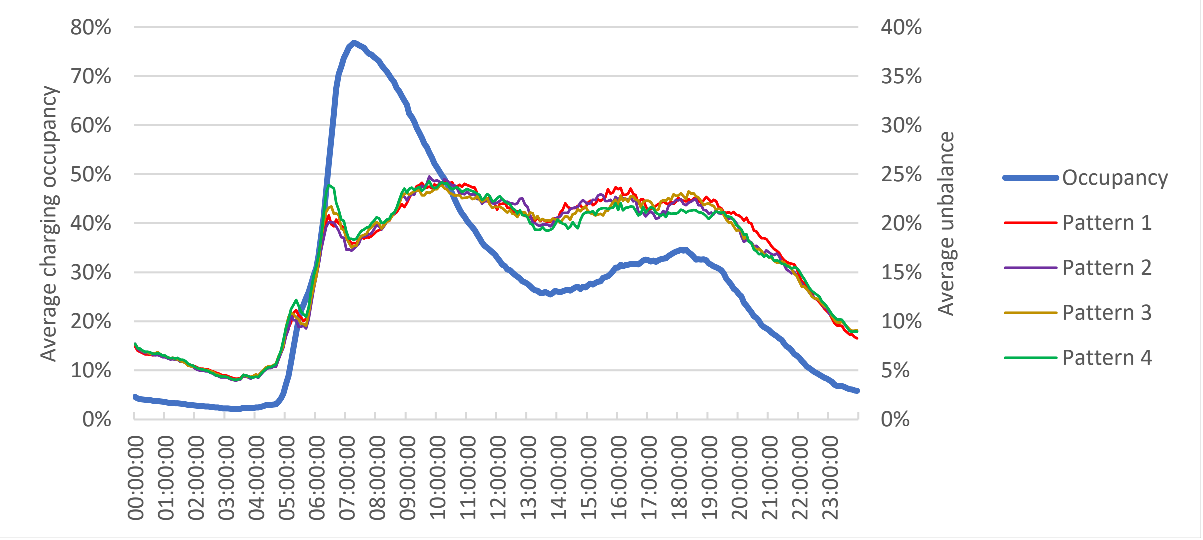

Figure 6. Average charging occupancy and average load unbalance in four phase distribution patterns by time of day in 253 working days.

2.2.1 Unbalance

Fig. 6 shows the average percentage of charging by time of day, as well as the average unbalance assuming the connection patterns 1-4. The average occupancy across the 253 working days was close to 0 in the early morning, rose quickly to a high of about 75% of points at about 07:00 when typically all points were occupied (but not all charging), declined to about 13:00 as a function of end of charging and leaving, increasing to about 18:00 and then declining again. The average unbalance did not differ greatly across connection patterns, and was as expected highest at about the times when occupancy was close to 50%. However, the average unbalance did not decline with the average occupancy in the afternoon, and sank only in the evening hours.

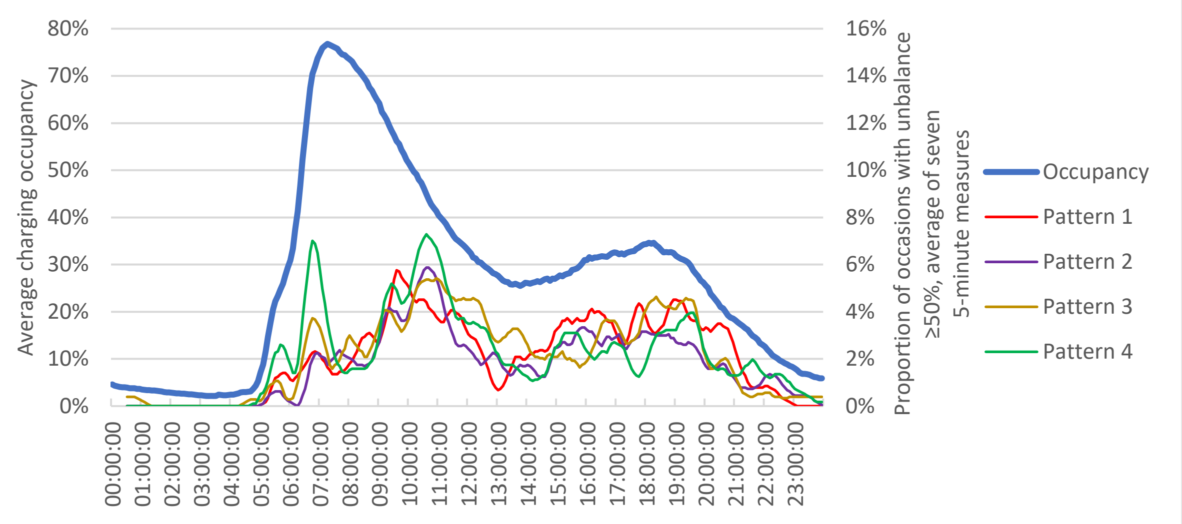

Figure 7. Average charging occupancy and proportion of severe (≥50%) unbalance
in four phase connection patterns by time of day in 253 working days.

Fig. 7 shows the proportion of days when the unbalance was severe at 50% or more at each time. The occurrence of severe unbalance followed a similar pattern over the day as average unbalance. Pattern 4 seemed to create higher proportions of severe unbalance (about 7%), particularly around times of 50% occupancy. Pattern 2 seemed to give slightly lower occurrence of severe unbalance across the day.

2.2.2 Preferences for points

Drivers' choices of charging points within this facility was inspected in all patterns of occupancy involving places 4-8 not being occupied, separately for points 1-6 and 6-12. Proportion of choices was converted to Rasch-scaled preference measures anchored at a preference of 0 for charging point number 6. A linear multiple regression model through the origin weighted for number of cases in each pattern was used to predict preference measures from properties of points in parking patterns. The significant preference rules, expressed in logits relative to the preference for charging point 6, with lower numbers expressing more preference and higher numbers expressing more avoidance, were:

Static rules
1. Avoid the five points furthest from city (0.9).
2. Avoid point 10 (plausible reason: a close light pole) (1.0).
3. Avoid point 4 (plausible reason: uneven ground or sewage lid) (0.4).

Dynamic rules
4. Prefer the first free point nearest to harbor (-2.2).
5. Prefer the first free point nearest to city (-1.6).
6. Prefer the point nearest to city with both adjoining points free (-1.0).
7. Prefer the point nearest to harbor with both adjoining points free (-0.5).
8. Avoid any point with both adjoining points occupied (1.2).

We also tested the preference for points with the charging outlet to the left versus right side, for points with one adjoining point occupied, and for each individual point except for the reference point (no. 6); none of these preferences were statistically significant.

3 Simulation

3.1 Method

We built data simulation models to reproduce the 12-point real-life data set and to simulate a hypothesized 96-point charging site. The simulations were modeled in scripts with a simple programming tool (ToolBook Instructor 9.5).

In the replication simulation, we used approximations of the observed real-life data for time between arriving cars by hour of day and durations of connection. We assumed the same distribution of duration of charging as in the real-life data set. We used the preference rules from the real-life data findings to generate choices of points in a Rasch-scaled probability model, and further assumed that every 15th arriving car parked without connecting.

3.2 Results

3.2.1 Replication of 12-point charging site findings

The replication simulation consisted of one single set of simulated data for 253 working days for 12 points.

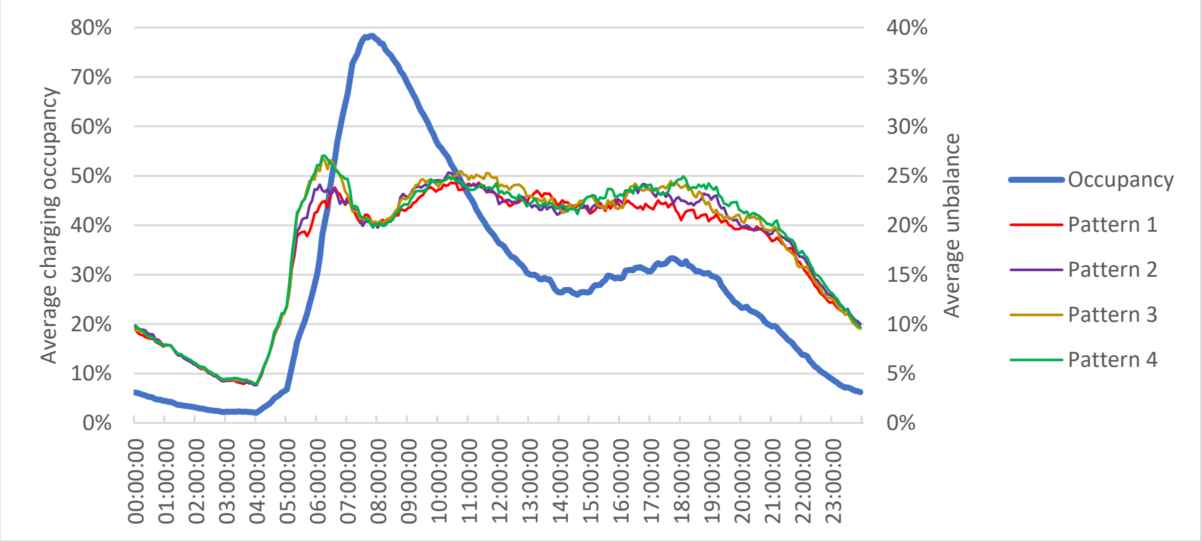

Figure 8. Replication simulation: Average charging occupancy and average unbalance in four phase connection patterns by time of day, 253 working days.

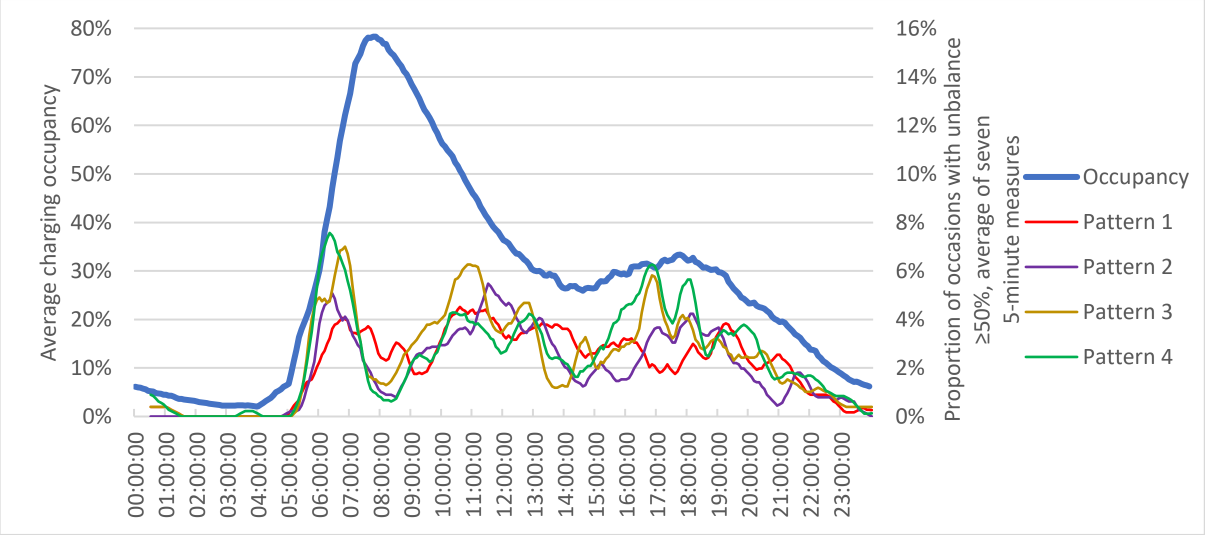

Figure 9. Replication simulation: Average charging occupancy and proportion of severe (≥50%) unbalance in four phase connection patterns by time of day, 253 working days.

The results of the replication simulation are shown in Fig. 8 and 9. It is clear that the simulation largely approximated the real-life data, both with respect of average load, average unbalance, and proportion of severe unbalance across times of day. In the simulation data, the average unbalance was marginally higher, and the difference in proportions of severe unbalance among connection marginally more clearly in favor of Patterns 1 and 2 as opposed to Patterns 3 and 4. This may be an effect of the simulation replicating the average result across all working days, while in the real-life data; there was variation among days in charging timing, making the results less clear-cut.

3.3 Simulation of hypothesized large charging site

For the hypothesized 96-point facility, we modeled a site with 48 points on each side of a street, with city as well as harbor access on the same end. We used the same input for connection times, charge times, and frequency of parking without connecting as in the replication simulation. For the model to fill up the parking in a resembling way as the real-life data, we assumed 8 times more frequent arrivals than in the replication simulation. We investigated four point-to-phase connection patterns: (a) 123123…, (b) 112233…, (c) 111122223333…, and (d) the first third of points nearest to city to Phase 1, the next third to Phase 2, and the last third to Phase 3. We chose the following preference rules to generate point choices for the hypothesized site in a Rasch-measure-based probability model:

Static rules

1. Avoid points further from the city (increasing linearly from 0.0 for the point nearest city, on each side of the street, to 4.0 for points furthest from city).
2. Avoid points on the left side of street when coming from city (1.0).

Dynamic rules

3. Prefer the first free point nearest to city (-3.2).
4. Prefer the point nearest to city with both adjoining points free (-2.0).
5. Avoid any point with both adjoining points occupied (2.4).

We generated one single set of simulated data for 253 working days for this model.

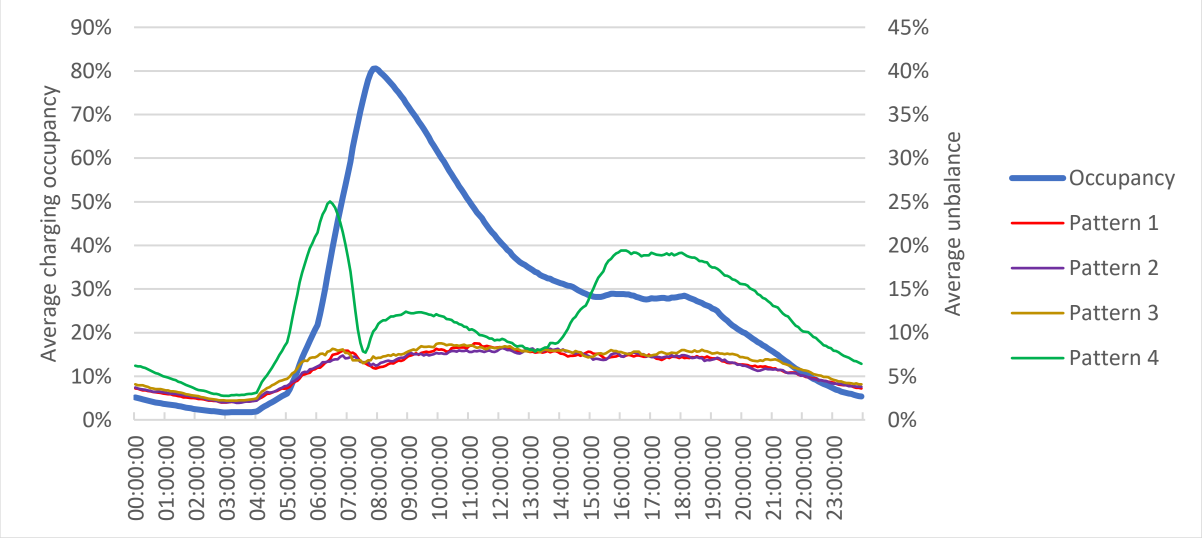

Figure 10. Simulated 96-point site: Average charging occupancy and average unbalance in four phase connection patterns by time of day, 253 working days.

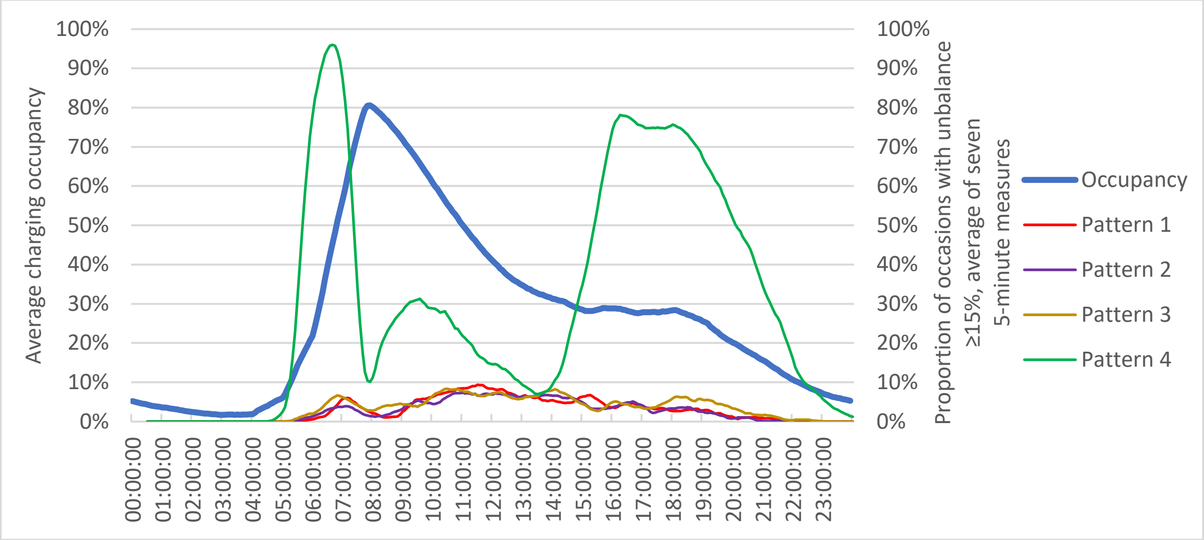

Figure 11. Simulated 96-point site: Average charging occupancy and proportion of severe (≥15%) unbalance in four phase connection patterns by time of day, 253 working days.

The results of the simulation of the hypothesized 96-point site are shown in Fig. 10 and 11. We defined severe unbalance as 15% or more for this size of site. As can be seen in the graphs, the pattern of average and severe unbalance across times of day largely followed the findings from the real-life and replication data set for patterns 1, 2, and 3. However, for pattern 4 (the one with 16 points in a row connected to each phase) the average as well as severe unbalance was very unfavorable to an extreme degree. Because we had modeled strong preferences of city-near points, and Pattern 4 was maximally sensitive to such a bias, the Pattern 4 results suggest the maximum extent to which unwise selection of point-to-phase connection pattern can create unbalance in a large site.

4 Discussion

Our random-generated results illustrated how unbalance decreases with the number of charging points in a facility, when choice of point is random. However, as our real-life findings show, choices are not random, not even in a small facility of only 12 points. Different connection pattern of points to phases therefore have different potential for an increased load balance. In our real-life small-facility findings, the worst connection pattern resulted in a slightly higher proportion of times with severe unbalance; however, in our simulated 96-point facility, the worst connection pattern resulted in a huge unbalance relative to the best patterns, both in terms of average and proportion of severe unbalance.

Our findings of timing of high load and unbalance in the real-life data may possibly be representative of many similar charging facilities (i.e., city charging facilities that fill up quickly in the morning and empty gradually over the day). At popular facilities for office hour charging, it is thus reasonable to assume that the load may peak at the time when the facility has filled up in the morning, and that the following decline may start soon and be rather strong initially. In addition, unbalance situations will have a short duration in the morning hours as EVs arrive, whereas the unbalance created by individual end of charge times may last much longer in the afternoon. This, again, would be dependent on the allowed parking time at a facility.

Our findings highlight the importance of point-to-phase connection patterns for avoiding unbalance. Different patterns may balance out or exaggerate the non-randomness caused by drivers' preferences for points. To some extent, preferences may apply uniformly (e.g., drivers may prefer points close to where they want to walk after parking). However, our real-life findings strongly suggest that preferences are not only static, but also depend on the pattern of parked EVs at the time of choosing a charging point: for example, in our data set, drivers preferred points with both adjoining points free, and avoided points with both adjoining places occupied. Our findings suggests that connection patterns that cycle phases over points or pairs of points (e.g., 1, 2, 3, 1… or 1, 1, 2, 2, 3, 3, 1…) seemed to balance out point attractiveness rather well under the conditions we studied. Patterns that assigned a larger contiguous group of points to one phase created a greater potential for unbalance.

4.1 Strengths

This study was, to our knowledge, the first to investigate intra-facility unbalance as an effect of parking behavior and times of connection/charging. We had access to a full year of real-life data from a representative and popular city charging facility, which made the detailed real-life data analyses possible. Norway is one of the regions worldwide where EV use to date has been most widely adopted; thus, charging behavior may be representative of a future common situation in many other regions.

4.2 Limitations

The real-life data set we investigated came from a small facility, which may limit the generalizability to larger facilities. Our large-facility findings came from data simulation, which relies on the underlying assumptions and parameters built into the model.

The real-life data set did not contain information about the real load. As an EV can pull less current than what the charging point is configured for, such resulting unbalances will be challenging to predict.

One particular limitation of our study was the unavailability of actual times of end of charge in the real-life data set. This was due to a limitation in the communication protocol used, Open Charge Point Protocol (OCPP Version 1.5) [3], in which a timestamp for when an EV has reached its end of charge is not available. In our real-life and simulation results, we assigned end-of-charge times based on an assumed distribution of charging times. To the extent that we have misestimated this distribution, we have also misestimated the timing of unbalance that results when EVs stop charging (i.e., in the afternoon hours). However, while the timing may differ from the real, the magnitude of unbalance would in average not deviate much from what is shown in Fig. 6.

Our considerations of load unbalance were based on the European 3-phase power network, with 230V phase-to-neutral. While our findings are thus not directly applicable to other electrical supply systems, analogous considerations apply in any system; thus, unbalance in the number of EVs connected to phases creates load unbalance that may cause voltage unbalance in all kinds of systems, although the specific circumstances that create unbalance differ among network systems. Future research should look at real-life EV charging data from large facilities.

4.3 Practical consideration

4.3.1 Facility design

Ideally, a charging facility should be regarded as a separate load, as it by itself should ensure the highest possible degree of load symmetry, where the facility's calculated magnitude of random load unbalance could be evaluated together with conditions of other loads connected to the same supply.

Facility design should involve selecting a point-to-phase connection pattern that balances out driver's preferences for points, that is, distributes attractive and unattractive points equally over phases. A pattern that cycle phases over points or pairs of points (e.g., 1, 2, 3, 1… or 1, 1, 2, 2, 3, 3, 1…) may do a good job of balancing out point attractiveness in facilities that resemble the ones we studied. Point attractiveness seems to depend on many static as well as dynamic conditions. Observation of actual parking patterns on the site (e.g., of fossil-fuel cars on a site before conversion to EV charging) or simulation based on realistic assumptions may further guide the selection of point-to-phase connection pattern. Cautious planning of phase distribution for new charging facilities might ensure a lowered risk for load unbalance. In facilities where random parking is allowed, physical obstacles like poles, pillars, walls, corners are elements that may be associated with unattractiveness, and therefore, charging points close to such, should be distributed across the phases.

4.3.2 Automated protection technologies

One obvious question that arises, is what measure is best to apply when an unbalance situation occurs. Control technologies provide the ability to ensure avoidance of any severe unbalance load situation caused by an unfortunate pattern of charging EVs at any given point in time. Applying technology with control functions that monitors the overall charging situation and either reduces the charging rate of the phase with the heaviest load, or alternatively actively selects or changes connections to the most suitable phase (least loaded) for the actual charging point. The latter technology has the advantage of being able to counter an already existing unbalance in the supply feeding point, but is much more costly.

The fact that many grid owners/utility companies allow for single-phase loads up to 20A and even 32A in stronger networks implies an acceptance of some unbalance created locally, hopefully that the average sum of it will even out. Within the Ampere-range from the international charging standard (IEC 61851-1), a facility may still provide charging for up to five vehicles connected in parallel to the same phase, where each, in such a configuration, is assigned the lowest possible charging current of 6A. (5 x 6A = 30A). In a facility, up to fifteen 1-phase charging points (5 per phase), where all charging currents are controlled by a common power management system, may not worsen the unbalance situation more than the magnitude of only one 1-phase EV, charging at 30A without a power management system. However, the power management may not be able improve the unbalance before more EVs will connect, or before charging ends of those already connected.

The awareness of voltage unbalances within residential parts of the distribution network will most likely arise in parallel with higher EV market shares, in which it will create demands for cost efficient ways to avoid unbalance situations. From our findings, a control function that reduces the charging rate at an occurrence would seem sufficient into smaller facilities, where currents are lower, and as severe unbalance seem likely to happen relatively rarely in larger facilities where the attractiveness has been balanced with a carefully planned point-to-phase distribution.

Acknowledgements

We thank the City of Oslo for providing the real life data set, from their charging facilities.

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