ELECTRIC VEHICLES CHARGING IN UNBALANCED BELGIAN LOW-VOLTAGE GRIDS: A CASE STUDY

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ABSTRACT

Electric vehicles (EVs) present several environmental advantages: reduced noise pollution, reduced particulate matter emissions and reduced CO_2 emissions in the atmosphere if powered, at least in part, from renewable sources.

The number of EVs being sold in Europe is growing every year. However, it is not fully clear how their use will affect the operation of the electric power system, given the increased energy and power demand to charge EV batteries.

This paper addresses the case of EVs charging in residential low voltage (LV) distribution grids. Different charging strategies are explored, to assess which ones allow a greater number of EVs to be connected without compromising the secure operation of the grid, and without reinforcing the existing infrastructure.

It is furthermore investigated whether the different charging regimes will negatively influence the state of charge of the individual EVs, potentially leading to EVs which are insufficiently charged to perform their trips.

INTRODUCTION

The cumulative sales of EVs in Europe grew from 0 in 2010 to about 500000 units in 2016 [1]. As a result, an increasing number of households own this means of transport. EVs are charged through low voltage (LV) grids and EV owners most commonly live in a single-family house (so typically outside of the city centres).

Therefore, distribution system operators (DSOs) are interested in gaining deeper understanding about the integration of such new loads in their grids, as they try to optimize investments in the reinforcement of the existing infrastructure.

This paper makes use of two test systems from two existing subgrids and a database of domestic power consumption profiles with household consumption. The necessary data was provided by a local DSO[1].

These DSOs are taking active steps towards an active management of distribution grids, making use of devices that allow a more accurate state estimation and/or some communication infrastructure [2].

Nevertheless, this work addresses control solutions that do not rely on communication, which are straightforward to implement in the short-term and avoid breakdown-related and data security issues.

The proposed solutions apply the reduction of the charging power, to limit the occurrence of undervoltages and voltage unbalance issues. The simulation models are developed based on the three-phase four-wire unbalanced power flow equations.

STATE OF THE ART AND SUGGESTED SOLUTIONS

In contrast to PV systems, EVs have the advantage that active power curtailment does not necessarily penalise the owner economically. Given this and the long parking times that characterise personal vehicles, there is a good flexibility margin that can be exploited, e.g. with load shifting [3]: the time an EV starts charging is postponed if the voltage is too low and the battery has still enough time to charge sufficiently before being used again.

In this work, rather than postponing the charge, stress is decreased by reducing the amount of power consumed. This is done with two strategies, and the results are then compared to what would happen if the EVs simply started charging when they arrive home and are plugged in. This is here called "unregulated charging" (Figure 1). The two alternative strategies are "minimum power charging", shown in Figure 2, and "droop control" (Figure 3).

All the aforementioned strategies are implemented on top of four different domestic charging cases as described in standard IEC 61851-1, which defines the maximum current that can be drawn when charging. A maximum power that can be drawn corresponds to each of the current limits. The values are reported in Table 1. Note that the maximum ampere values in the three-phase case refer to each of the phases.

Case	max. current per phase	max. power
Case 1	16 A single-phase	3.3 kW
Case 2	32 A single-phase	6.6 kW
Case 3	16 A three-phase	9.9 kW
Case 4	32 A three-phase	19.8 kW

Table 1: current and power values for EV charging

1 This work was prepared in collaboration with Eandis and Infrax and performed under the project ADriaN. The authors would like to extend their appreciation to Bruno Macharis and Joris Lemmens.

Unregulated charging

The gray line in Figure 1 corresponds to the power consumed over time. It is illustrated as function of the rated power, which relates to the values in Table 1. When the EV is parked but not fully charged, the charging power equals the rated power, while it is zero when the EV battery is completely charged or being driven.
The green line corresponds to the energy content of the battery, which is the integral of the power over the charging time. The slope is constant in this case and only becomes flat when the maximum state of charge (SOC) is reached. The state of charge is the ratio of the current energy content and the battery rated capacity (kWh).

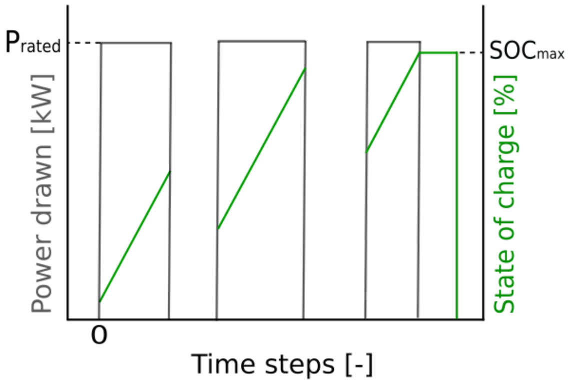

Figure 1: power and SOC in unregulated charging

Minimum power charging

This strategy is sometimes known as peak-shaving in the literature [4] and requires the driver to communicate to the charging controller how long the EV is going to be parked before leaving again and how many kilometers will be required during the next trip. With these two parameters, the charging controller will set the power drawn to the minimum required by the EV to be sufficiently charged to perform the upcoming journey.

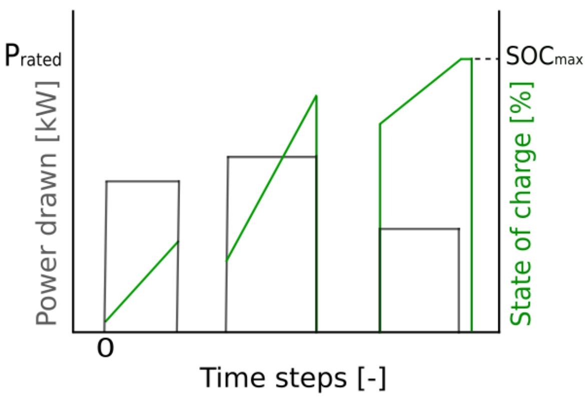

Figure 2: minimum power charging

Droop control

Droop control is also broadly discussed in the literature [4] and consists of measuring the voltage at the charger connection point, and reducing the charging power when the voltage magnitude observed is too low, following a predetermined function.
In this work, two different kinds of droop control are examined. One includes a deadband (DB) (left curve in Figure 4) and one does not (right curve in Figure 4) .

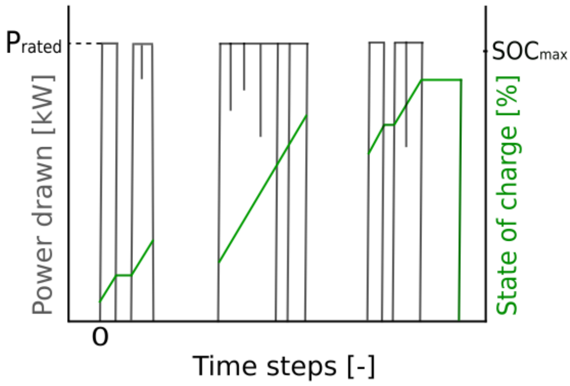

Figure 3: power and SOC in droop control

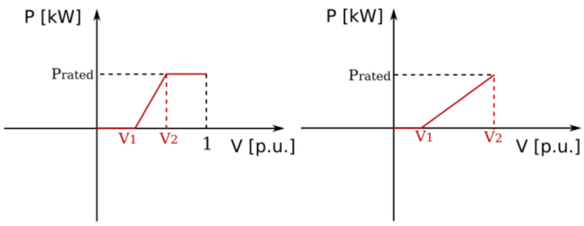

Figure 4: droop curve implementations

Definition of congestion problems

The following criteria are used to assess the impact of charging on the grid.
1) Occurrence of undervoltage (UV): when the voltage magnitude at a bus is less than 0.92 [p.u.] of the rated voltage.
2) Occurrence of overcurrent (OC): when the current is above 90 % of the cable rated ampacity.
3) Occurrence of excessive voltage unbalance (UB): when the ratio between the negative and positive sequence voltages exceeds 2 %.

DATA AND SIMULATION SET-UP

The data pertaining to the grid includes the distances between each house and the MV/LV transformer, the cross-section and length of main feeder and connection cables. The household consumption profiles are 15-minute resolution power measurements, and are

extracted for the chosen one-week simulation horizon.
The EV specifications are taken from products that are already present on the market, while the fleet mobility is based on the Third Flemish mobility study [5]. On weekdays, both the departure time and the traveled distances are assigned to each EV according to a normal distribution.
During weekend days, traveled distances are also assigned according to a normal distribution, while the departure times are randomly spread between 10 AM and 6 PM. Homecoming times are respectively 9 and 6 hours after the departure on weekdays and at weekends.
Table 2 illustrates the main features of EVs and mobility behaviour.
In order to show the effect of EV charging on the particular grid systems, the following procedure is followed. The simulations start from 0 EVs and progressively add individual EVs until every household is assigned an EV, so all penetration levels are explored. EVs are placed randomly in the grid, connecting to the grid either as a single phase (same phase as the house) or a three phase connection. Twenty different spatial configurations are taken into account, as the distance between the EV charging point and the transformer is an important factor.
Given the radial nature of the distribution grids, a backward-forward sweep algorithm is used to solve the three-phase unbalanced power flow equations.

EVs power factor	1
Specific EV consumption	190 Wh/km
Battery capacity	75 kWh
EVs not being used, weekdays	0 %
EVs not being used, weekends	15 %
Average departure, weekdays	7 AM
Departures standard deviation	30 min.
Home-work average distance	32.2 km
Home-work standard deviation	6.67 km
Weekends average distance	39 km
Weekends standard deviation	8.33 km

Table 2: EVs specifications and mobility behaviour

RESULTS

It is observed that undervoltages are typically the limiting factor to EV integration, occurring more frequently than the other congestion criteria, which are mostly negligible. The only case in which this condition does not hold is unregulated charging at 32 A, single-phase: as shown in *Figure 6*, the number of UB events is high.
Also, that of UVs is on average between 5 and 7 times higher with respect to 16 A single-phase, as shown in *Figure 5*. The difference is remarkable especially when a limited amount of EVs is connected.
The values reported on the Y-axis are the total number of congestions occurring at all buses, averaged over the twenty configurations ("seeds"). Only results pertaining to one of the two grids are shown as those of the other grid are similar.
Minimum power charging allows a reduction of UV issues between 69 % and 87 % (see Figure 7) in the single-phase case and it makes the number of UB events negligible. Adopting droop without DB actually allows to further reduce the occurrence of congestions.

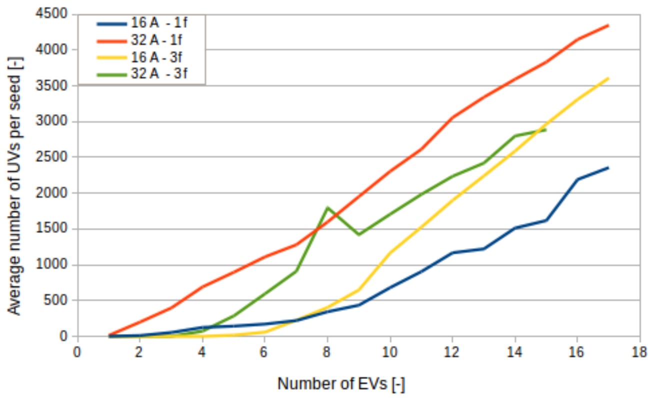

Figure 5: UVs with unregulated charging

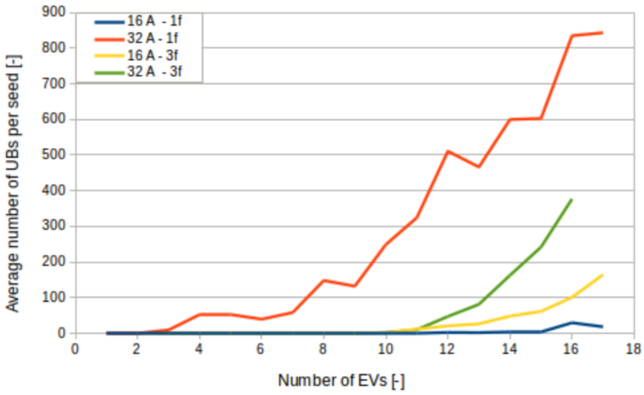

Figure 6: UBs with unregulated charging

Anyway, this strategy proved to be less effective than droop control, which allows to avoid almost all UVs and UB events (both less than 5 per configuration), and this regardless of the use of the DB.
Droop control without DB further reduces the number of UVs. Employing the new strategies is clearly advanteagous with respect to the coping capability of the grid. However, the power drawn varies all the time, due to the control loop. Furthermore, another disadvantage emerged: the number of EVs which were not sufficiently charged during the loading cycle increased with this strategy, as shown in Figure 8 and Table 3.
In particular, *Figure 8* displays the average number of EVs that at least once in a week are not charged enough to perform one of their trips. Results for less than 7 EVs are not shown in the 16 A single-phase case, because the vast majority of configurations allow to avoid SOC

problems at all.

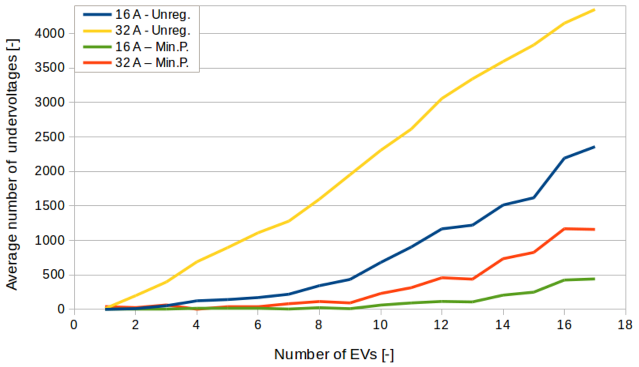

Figure 7: UVs reduction with min.power charging

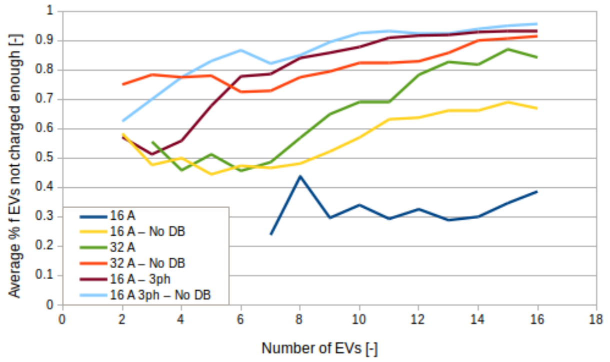

Figure 8: percentage of EVs with SOC-related issues

16 A single-phase	57 %
32 A single-phase	24 %
16 A three-phase	9 %

Table 3: additional share of EVs with SOC issues with DB

It is observed that, in general, where higher amounts of power are involved, the higher is the percentage of EVs that present SOC-related problems. This is because they are also prone to more curtailment. Even more so in the case of the droop without deadband, where the power drawn is never the rated one.
Both minimum power and unregulated charging, on the other hand, allow the EVs to be charged enough in all cases.
Before performing the simulations, the configurations that were expected to perform worse were those with a larger amount of EVs connected far from the MV/LV transformer, as remote nodes inherently have lower voltage magnitudes due to the impedance of the feeder.
However, the simulations have shown that the worst spatial configurations turn out to be those that present a less even distribution of single-phase charging EVs over the three phases.

CONCLUSIONS

UVs occur faster and more frequently than other types of congestion in the LV grid, making them the limiting factor to EV integration.
Arguably, 16 A single-phase charging is the best option for domestic charging: although it results in a slow charging, it is still proven to be sufficient to charge the EVs to full capacity in the unregulated case. Even with droop control it is still the best perfoming, battery charge-wise, as it results in a more limited grid impact, it is also less subjected to curtailment.
On the other hand, 32 A single-phase charging should be avoided where possible, as the amount of congestions it causes are significant. The results pertaining to this case also suggest that phase unbalance significantly contributes to raising the number of undervoltage problems as well.
It should also be kept in mind that the assumptions made are rather conservative: the EVs are here assumed to charge only at home, while in reality, fast-charging public infrastructure is also present, as well as opportunities to charge at the workplace. Furthermore, a non-negligible share of EVs are also at home during the day, while in the developed scenarios EVs charge only during the evening, coinciding with domestic power consumption peak, and during the night.
To make the grid model more complete and realistic, PV injection to the grid should be considered, as well as the presence of batteries and heat pumps that can respectively help manage the power flows and increase the domestic loads.
Finally, minimum power charging was not tested on the three-phase charging cases and could be explored in future work.

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