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Abstract: Norway has implemented economic incentives over several years to encourage a transition from conventional vehicles to electric vehicles (EVs), and now has the largest share of EVs per capita in the world. In this study, the authors explore the impacts of increasing EV penetration levels in a Norwegian distribution grid, by using real power measurements obtained from household smart meters in load flow analyses. The implications of installing a fast charger in the grid have been assessed, and an optimal location for it is proposed, aiming at minimising both grid losses and voltage deviations. Moreover, the potential for reactive power injection to reduce the voltage deviations caused by fast chargers has been investigated. Results show that the EV hosting capacity of the grid is good for a majority of the end-users, but the weakest power cable in the system will be overloaded at a 20% EV penetration level. The network tolerated an EV penetration of 50% with regard to the voltage levels at all end-users. Injecting reactive power at the location of an installed fast charger proved to significantly reduce the largest voltage deviations otherwise imposed by the charger.

1 Introduction

When driven on electricity with a low carbon footprint, most electric vehicles (EVs) cause less greenhouse gas emissions over the course of their life cycle than similar cars with internal combustion engine [1]. Viewed as an effective measure to reduce the climate impact of the transport sector, governments around the world have initiated policies to encourage consumers to drive electric. Norway's economic incentives have been particularly effective, and Norway has today the largest share of EVs per capita in the world [2].

The electrical energy required to fuel an increasingly more electrified transport sector in Norway is expected to constitute a tolerable addition to the existing consumption. The Norwegian Water Resource and Energy Directorate (NVE) estimated that Norway might host 1.5 million EVs by 2030, which will require 4 TWh of electricity annually [3]. This is less than the estimated 6.5 TWh of new annual wind power capacity currently under construction in Norway by the end of 2017, and another 17.1 TWh of expected annual production has been granted approval to be constructed, mainly in the form of wind power [4]. The power levels required to charge this fleet may, however, constitute a significant strain on the existing power grid, as the necessary power levels can be higher than the rated power capacities of the lines and transformers in the power grid. NVE calculated in 2016 that an average power increase of 5 kW consumption in all households will overload >30% of the distribution grid transformers in Norway [3]. It is, therefore, a reason to believe that a large number of EVs charging simultaneously with similar power levels may cause overloading of grid components.

Public fast chargers are being built to strengthen the range and attractiveness of electric transportation. The potentially high amounts of power they can draw will pose an additional challenge to the grid, and a well-considered placement of the fast charging point will be valuable. If the voltage level drops too far, the charger may be able to mitigate this by offering a voltage-stabilising service by injecting reactive power [5].

In this study, we investigated the state of the current grid based on the smart meter measurements. Its EV hosting capacity was then assessed by modelling various EV penetration levels, and the implications of installing a fast charger at various locations are also looked into. Finally, the potential for reactive power injection at the

fast charger's location as a means to reduce expected voltage drops in the system was assessed. All analyses were conducted using the load flow package MATPOWER in the MATLAB software.

The paper is organised as follows: Section 2 details underlying theory, with an emphasis on information that is distinct for Norway. Section 3 describes the data set being used, and how further information has been derived from the original data. Section 4 contains the methodology and model description, and Section 5 presents the results. The results are discussed in Section 6, and conclusions are given in Section 7.

2 EV penetration in Norwegian distribution grids

By the end of 2017, the EV market share in the private car sector in Norway had risen to 20% and it was registered more than 135,000 EVs in the country. More than 65,000 plug-in hybrid cars come in addition to these [6, 7]. With a total passenger car fleet of 2,662,910 vehicles at the end of 2017, the share of full-electric EVs approximates to 5.4% of all passenger cars in the country [8].

2.1 Isolée Terre (IT) and Terra Neutral (TN) grids in Norway

There are two main types of distribution voltage systems in Norway: IT (French) and TN grids. Power for a common 230 V single-phase load is drawn from an IT grid by connecting it between two 230 V phases, while the TN grid provides the same voltage by connecting the load between one of its 400 V phases and a neutral line, resulting in 230 V as seen from the load. More than 70% of the Norwegian distribution grid is built as an IT-grid [9]. As IT-grids usually only allows single phase power consumption, the maximal available power is effectively limited to 7.3 kW in most cases, due to the nominal voltage of 230 V and a maximally allowed current through one phase of 32 A.

2.2 EV-charging changes the consumption profile

The power drawn to charge an EV may effectively double or triple a given household's power use during the time of charging. Fig. 1 shows an excerpt of 8 days of hourly smart meter measurements of two households. The power series with the largest peak values stems from an end-user who is confirmed to charge an EV with a 7.3 kW charger. The other series belongs to an end-user with a

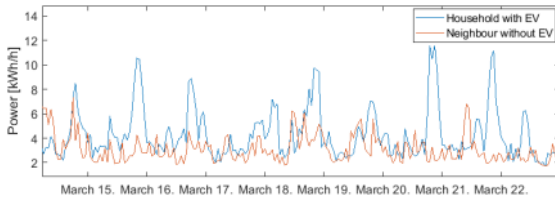


Fig. 1 : Comparison between a household known to charge an EV regularly, and its neighbour without an EV. Each date on the x-axis begins at midnight

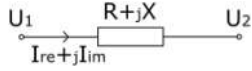


Fig. 2 : Sample impedance

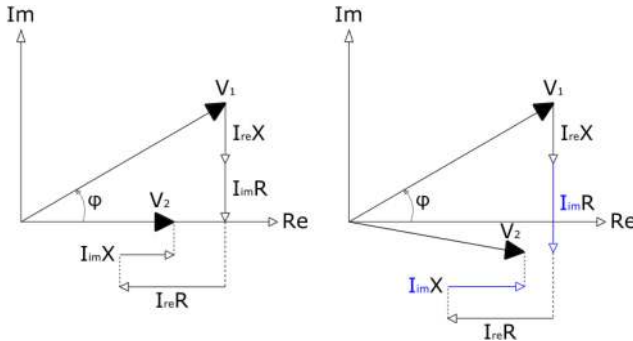


Fig. 3 : Illustrating the difference in voltage magnitude due to an increase in the reactive current component

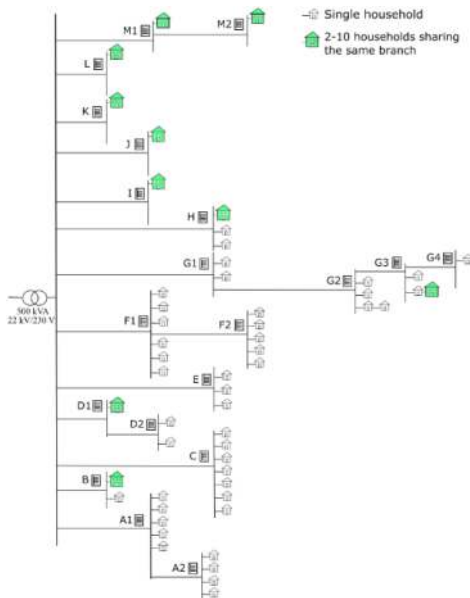


Fig. 4 : Studied grid with its 54 consumers connected to the distribution transformer via 20 feeder cables A1–M2

comparable base load profile, but without EV-charging. The five largest peaks all happen between 18:00 and 21:00.

2.3 Reactive power control in distribution networks

Reactive power flow in a network can be manipulated to an extent in order to stabilise the voltage level. This is explained in the following paragraphs, with the help of Fig. 2 and (1)–(3):

U_1 is the voltage at the beginning of the line, U_2 is the voltage at the end of the line, U_{drop} is the voltage drop over the impedance, and R and X are the active and reactive component of the load impedance. The difference in voltage in U_2 compared to U_1 can be outlined as follows:

$$U_2 = U_1 - U_{\text{drop}}, \quad (1)$$

$$U_2 = U_1 - (R + jX)(I_{\text{re}} + jI_{\text{im}}), \quad (2)$$

$$U_2 = U_1 - j(I_{\text{im}}R + I_{\text{re}}X) - I_{\text{re}}R + I_{\text{im}}X. \quad (3)$$

With a lagging power factor of 0.98, giving us an angle of 11.5° , Q amounts to 20% of S . If the angle is leading, the absolute value of Q remains the same while the sign will be negative instead of positive. Reactive power is now injected to the system by the load, instead of delivered to the load from the system. This increase in Q will also increase I_{im} , which as seen in (3) will reduce the voltage drop due to the resulting voltage V_2 having a larger absolute value. This is illustrated in Fig. 3. The deliberate injection of Q to help stabilise voltage is called reactive power control and was in this study tested as a way to help increase the grid voltage stability. A side effect is larger transmission losses due to the increased total currents in the system. The effectiveness of reactive power control is highly dependent on the line impedances in the distribution network, both in terms of absolute values and the R/X ratio [10].

3 Data set

A single line diagram depicting the studied IT-grid can be seen in Fig. 4. It consists of the following main parts:

- A 500 kVA distribution transformer.
- 20 distribution feeder lines, A1-M2, branching out from the transformer.
- 54 end-user buses and their respective cables.

In reality, there are 95 end-users present in the system, but some of them live in various forms of shared housing such as row houses or apartment blocks, thus sharing the same connection line. These larger nodes have been aggregated into single loads, and are marked with a larger, coloured symbol in the single line diagram. After this aggregation, the total number of end-users is 54.

The following data set was provided by the distribution system operator (DSO):

- Hourly active power flow measurements for all end-users in the system for the year of 2012, which is considered as a ‘zero EV’ base case.
- All interconnections in the system and the types of cables being used.
- Smart meter measurements for a neighbourhood in 2016, in which one household regularly charges an EV.

The following information was derived from this data:

- Hourly reactive power flow based on the DSO's assumed power factor of 0.98.
- MVA ratings for all cables.
- The single line diagram is shown in Fig. 4.
- An empirical EV charging profile for a whole year.

It was assumed zero EV to be present in the grid when the data was collected in 2012. This is supported by the fact that the municipality as a whole had only 13 registered EVs dispersed over its 38,075 inhabitants that year [11, 12].

The external power grid was modelled as an infinite bus connected to the main feeder, acting as the generator in the system. The impedances and MVA rating of the transformer were assigned to a virtual cable connected in series between the transformer and the main feeder. This infinite bus acted as a slack bus with a constant voltage of 1 p.u. All end-users in the system were modelled as load buses. Finally, the bus bars connecting the transformer's feeder lines to the end-user branches were implemented in the model as load buses with zero active and reactive power consumption. The mentioned bus bars are denoted with letters A1–M2 in the single line diagram in Fig. 4.

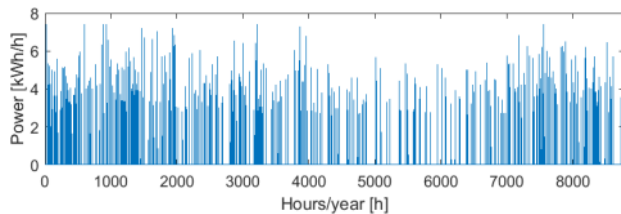


Fig. 5 : Proposed EV charging profile

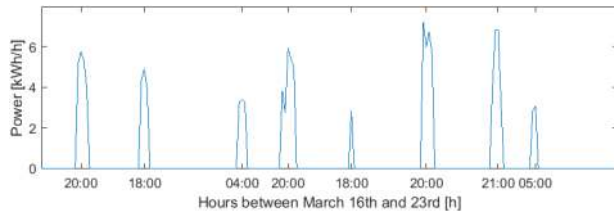


Fig. 6 : Excerpt of eight consecutive days from the charging profile depicted in Fig. 5, with the power spikes marked with their respective time of day

Before modelling the network, an EV charging pattern had to be acquired. As it was desired to run load flow analyses for every hour of the year and due to this study aiming at using actual measured EV charging patterns instead of an assumed charging pattern, it was desirable to acquire one or more data sets of measured residential EV charging profiles spanning the same length. Since this was not to be found, an EV charging profile has been derived from the smart meter readings from a household confirmed to regularly own and charge an EV with a 7.3 kW charger, by attempting to subtract the base household consumption from the total readings. This was done by constructing a sample household base load profile and subtracting this from the consumption profile seen in the household known to charge an EV.

NVE assumes an average consumption of 2667 kWh per EV per year in Norway [3]. In this study, it is assumed that an EV adds an extra 3000 kWh to the household consumption, which gives an average daily consumption of 8.22 kWh/day. A comparative base load has therefore been constructed by making an average load profile from the surrounding neighbours, which is 3000 kWh smaller than the EV-owning household is.

After subtracting the constructed average base load from the EV-owning household, small oscillations around the x-axis could be seen. This was interpreted as residual noise left over from the subtraction. To remove it, all values <2.7 kW were set to zero. This eliminated the noise left over from the subtraction with minimal effect on the total area, as approximately half of the values were below zero. Finally, all peaks >7.3 kW were clipped down to 7.3 kW, as this power level is considered the maximal household charging rate in a Norwegian IT-grid. Remaining values higher than this level is therefore considered residuals left over from the base household consumption. The resulting charging profile is shown in Fig. 5, and an excerpt of this graph is shown in Fig. 6, displaying eight days of energy consumption.

The area below the curve of the charging profile equals 3024 kWh. This is close to the expected yearly energy consumption for an EV, and it is therefore assumed that the consumption shown in the graph mainly stems from EV charging.

4 Methodology and model description

8784 individual load flow solutions were conducted – one for each hour of the (leap) year. By doing this, the grid could be remodelled as it was in its actual state in 2012, based on the load flow results. This provided a basis of comparison when the theoretical EV charging profiles were subsequently added on top of the actual measured values. The load flow results were found by using MATPOWER [13]. Due to the nature of load flow analyses, the power consumption in the system was assumed to be balanced.

4.1 Assigning EV owners to the system

Ten different EV penetrations from 10 to 100% with an incremental increase of 10% between each case were modelled. The peak voltage deviation and peak load ratio levels at all 20 feeder connections will be presented, along with a summary of any end-users experiencing a violation of the 10% voltage deviation limit or overloading with respect to the nominal power rating. A voltage deviation of 10% is considered as the lower limit for distribution systems according to the European Standard EN 50160.

The EV charging profile was added on top of the existing household consumption at various buses in order to model different EV-penetration levels. 100% EV penetration was in this study defined as equal to one EV per household. The buses containing aggregations of multiple household consumption profiles were set to take in an equivalent number of EV loads.

To construct the different EV penetration cases in a systematic order, the charging profiles were added in accordance with a delegation array that keeps track of where the load profiles should be added in all cases. In the 10% EV penetration case, the first ten locations in the delegation array were assigned their respective EV charging load. For 20% EV penetration, the first 19 locations in the delegation array were assigned their respective load etc. This ensured a cumulative development from one EV penetration percentage to another. The delegation array was made using a MATLABs random number generator *randperm*.

It is desirable to avoid adding identical EV charging patterns to all the end-users, as that would not happen in a realistic scenario. For each new end-user being assigned an EV charging load in addition to its base household consumption, the charging profile was, therefore, shifted forward in time before adding it to the respective end-user. To preserve a natural daily use pattern, the profile was only shifted a single hour back and forth in relation to its original pattern, before it was shifted 24 h forward in time for the next end-user.

4.2 Adding a fast charger to the model

To investigate the possible interaction between a fast charger and existing EV-loads, the system model developed for the 30% EV penetration was to be used as the base model. The fast charger was modelled as a constant 22 kVA load. This provides a consistent worst-case scenario for the fast charger part of this paper's data analysis.

The fast charger was modelled in three different ways:

- Adding the fast charger load to the existing system without changing any other variables.
- Assuming the fast charger replaces the five EV loads closest to its location.
- Repeating the last case while also examining the effects of 15 different power factors at each location.

4.3 Including reactive power control

While keeping the assumption that nearby EV-loads are substituted by the fast charger, each potential charger location is now also tested for 15 different power factors in order to see the potential effects on the voltage levels at its location. The power factor was varied from 0.98 lagging to 0.74 leading, with an increment of 0.02 between each. 0.98 is assumed by the local DSO to be the actual power factor observed in their grid today. A power factor of 0.74 corresponds to a -42.3° angle between the voltage and current phasors. The resulting reactive power injection will, in that case, be approximately equal to the active power consumption and is therefore considered the minimally acceptable power factor. Since the apparent power is held constant, a power factor of 0.74 will represent an active power consumption of 16.3 kW and reactive power consumption of -14.8 kVAR.

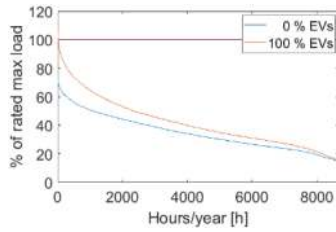


Fig. 7 : Duration curve for the transformer loading for the base case model and for an EV penetration of 100%

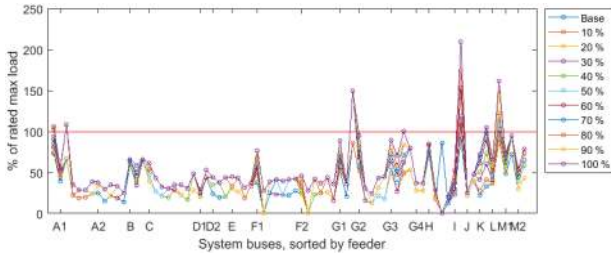


Fig. 8 : Largest loading reached for all cables in the system for all ten EV penetration cases, expressed in per cent of nominal capacity

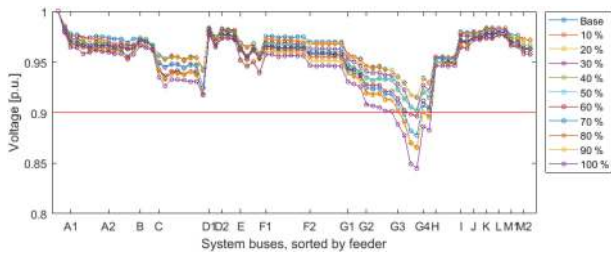


Fig. 9 : Largest voltage deviations in p.u. reached for all cables in the system for all ten EV penetration cases

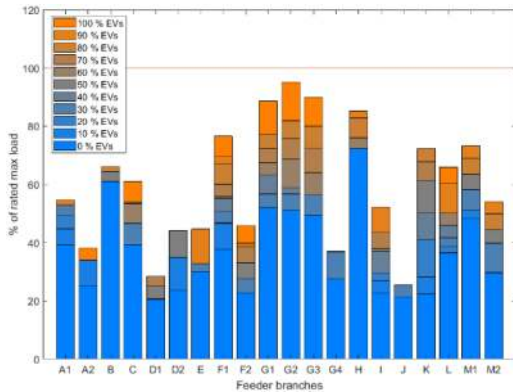


Fig. 10 : Largest loading reached for the 20 feeder cables in the system for all ten EV penetration cases

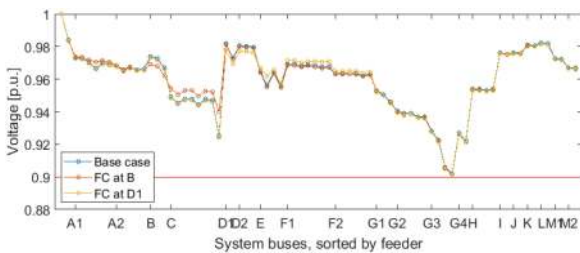


Fig. 11 : Resulting worst voltage deviations throughout the year from placing a fast charger at location 'B' and 'D1'

4.4 Finding an optimal fast charger location

Once all necessary data on how a base EV penetration and a fast charger placement at the potential locations would affect the voltage stability and power flows throughout the system was

found, we weighed these voltage deviation levels and total power loss in the system against each other with a weighed-loss-voltage-factor (WLVF) as shown in (4). By doing this, a location for the fast charger that minimises the overall voltage drops and system power losses can be chosen

$$WLVF_i = w_1 * V_{dev_i} + w_2 * P_{loss_i}, \quad (4)$$

$$w_1 + w_2 = 1. \quad (5)$$

P_{loss} is the per cent-wise increase in total system power losses when the feeder connection (FC) is placed at location i , compared to the base case. V_{dev} is the average voltage deviation observed at all 20 FCs when an FC is placed at location i , in comparison with the base case. The WLVF can then be computed with the weighing factors w_1 and w_2 varying between 1.0 and 0.0 in order to determine a suitable location.

5 Results and discussion

5.1 Unmodified base case and EV hosting capacity

A duration curve of the transformer loading throughout the year is shown in Fig. 7, displaying both the 0 and 100% EV-penetration case. There were no violations of the voltage or loading limits for any cables in the grid for the unmodified base case, and 12 h of overloaded hours for the 100% case.

5.2 EV hosting capacity

10 EV use cases were modelled – one for each cumulative 10% EV penetration. Fig. 8 displays the most extreme hour for the whole year with regard to power consumption for each case, expressed in terms of the respective power cables' nominal rating for all buses in the system. Fig. 9 displays the same results, with regard to the largest voltage level deviation at each bus connection instead of the cable loading. The end-users are sorted by the feeder connection buses to which they are connected, denoted with the letter codes on the x-axis.

An estimated EV penetration of 50% was possible before the first voltage deviation incident occurred, while the weakest distribution lines experienced overloading at an EV penetration of 20%. Fig. 10 depicts the same results as Fig. 8, but only for the feeder cables branching out from the transformer and not the cables connecting the end-users to them. It emphasises that neither of the 20 feeder cables was overloaded at any time during any of the ten EV penetration cases – only the smaller cables connecting the end-users to the feeder connections were. This indicates that in a case where the same EV charging loads had been wired directly to the feeders, the system as a whole could have managed the extra loading.

The distribution transformer experienced 12 h of overloading above its nominal power capacity during the 100% EV-penetration case, but these hours occurred during the coldest two days of the year. The cold temperature cools the transformer, and NVE assumes Norwegian distribution transformers to tolerate up to 120% of their nominal loading capacity during these conditions [3].

5.3 Fast charger implementation

Fig. 11 displays the worst voltage deviation for all buses in the system with the fast charger placed at the two locations where it caused the least and largest amount of voltage deviations in the system. The improvement is due to the assumption of the nearest 5 EVs to charge at the fast charger's location instead of at their respective household, thus offsetting the weaker end-user cables.

5.4 Reactive power compensation

By calculating the WLVF from (4) for all 20 investigated fast charger locations, 'G4' returned the worst results. Fig. 12 displays the voltage deviations in the system for three cases: the 30% EV-penetration case as the base case, a fast charger located at 'G4'

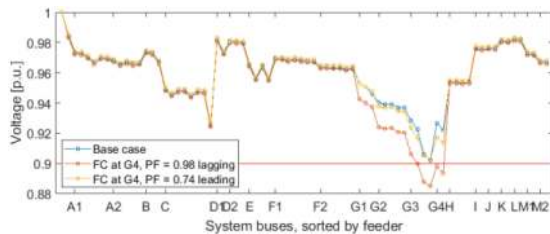


Fig. 12 : Locating the fast charger at G4 gave the largest voltage deviations in the network (red line), but could be negated by injecting reactive power (yellow line)

with a power factor of 0.98 lagging, and the same case but with the charger having a power factor of 0.74 leading, thus effectively injecting reactive power. In the base case and the case with power factor (PF) = 0.74, the voltage levels in the system remained within bounds, while it was 0.03 p.u. below the base case when the power factor was 0.98.

Due to the fast charger being connected directly to the feeder line G4 and the assumption of it replacing the five nearest EV-loads, there were no additional violations of the nominal permitted loading. Although still the least beneficial location for such a load, Fig. 12 indicates that reactive power injection can help support the voltage in weaker parts of the grid when necessary. For instance, new EV loads may be connected to an already stressed location, given they were equipped with the ability to inject reactive power when needed.

5.5 Limitations of the study and sources of error

All EV charging profiles used in this study stems from a measurement series of a single household for a single year. This measurement included the base load of the household, which had to be subtracted. One or more directly measured EV charging profiles over the course of a year would be superior to the one derived in this study, as no residual household consumption measurements would interfere the dataset, and no real charging data would have been lost as part of the subtraction process. Additionally, a larger sample could reduce the impact of potential outliers in the individual data set.

As described in Section 4.1, the simultaneity factor, which gave the maximum rate at which the EV-loads drew their semi-daily charging peak of 7.3 kW at the exact same time, was significantly altered by shifting the load profile back and forth between each assignment to a new household. This reduced the simultaneity factor from 100 to 33%. In a report in which NVE explored different EV-behaviour scenarios, a simultaneity factor of 70% was used as a worst-case scenario [3], while the 2017 survey by the Norwegian EV Association estimated a max simultaneity factor of 22% among its respondents [7].

6 Conclusion

This study explored the effects of increasing EV penetration levels in a Norwegian distribution grid, relying on real power measurements obtained from household smart meters and realistic load flow analyses with increasing EV penetration levels. The

impact of a new fast charger in the grid has been assessed, and the optimal location for it has been proposed, minimising losses and voltage deviations. Finally, the potential for reactive power injection to reduce the voltage deviations caused by it has been investigated and discussed.

The EV hosting capacity was large, as all but six end-users stayed above the minimum voltage limit and below the nominal cable power rating at all hours of the year for the 100% EV-penetration case. The main transformer was overloaded for a 12 h at that point, but only during the time of year where it is expected to tolerate the load due to the low outside temperature. When restricting EV penetration to comply with the limitations of all end-users in the system, the distribution grid can tolerate a 50% EV penetration regarding voltage, and 20% EV penetration with regard to the rated power of the weakest cable.

Implementing a fast charger in the grid with a standard power factor of 0.98 lagging caused significant voltage deviations at several locations, the worst of which reached an extra voltage deviation close to 0.03 p.u. By assuming that the nearest 5 EV charging loads were replaced by the fast charger, the largest voltage deviations in the network were significantly reduced. Injecting reactive power at the location of the fast charger, therefore, gave significant results. A power factor of 0.74 leading made it possible to implement the fast charger in the weakest part of the grid without violating the minimum voltage level requirement of 0.9 p.u. By utilising the voltage stabilising properties of injecting reactive power, larger loads such as a fast charger or a large EV household charger might be installed in weaker parts of a power grid than would otherwise be possible.

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