NETWORK EFFECTS OF ELECTRIC VEHICLES - CASE FROM NORDIC COUNTRY

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ABSTRACT

Upcoming trend of electric vehicles (EV) may create remarkable reinforcement needs in electricity distribution utilities. In some areas, peak power in the network may even double or triple if charging of EVs is done without intelligence on it. In the paper, case study of network effects of large-scale penetration of EVs in actual distribution company is presented. Both technical and economical perspectives have been taken into account in the analyses. Study presented in the paper is done for relatively large network area, consisting of 11 000 electricity end-users in rural, city and urban area. Case area is located in Fortum Distribution network, locating in southern part of Finland.

INTRODUCTION

The question of the effects of electric vehicles on electric power networks is challenging in many ways. Although there are already numerous analyses on EVs on power distribution networks, many technical and economic questions still remain open. The main research question considering EVs and electricity distribution is to define the network effects of the charging process and what kind of technologies should be developed for fulfill the needs of power balancing, charging profile and grid investments. There is a risk of overlapping of the present peak load and the peak resulting from charging of EVs. This overlapping could lead to a substantial increase in peak loads and thereby reinforcement needs in networks. Finally, it would raise the distribution fee paid by the electricity end-users.

Definition of the network effects requires understanding of the wide-scale use of EVs and long-term development of the distribution infrastructure. At the energy market level, rough calculations show that the amount of energy that EVs need for charging increases the Finnish energy consumption by approximately 9 TWh. This is not a significant increase (+ 10 % to total consumption), and it seems that the distribution network can handle this growth; nevertheless, the medium- and low-voltage networks will pose a challenge to the networks. Even though the increasing trend of EVs is recognised, their market penetration is still unknown. Consequently, this has an effect on the scheduling of the distribution network investments. Secondly, for instance the properties of batteries are developing at a rapid rate. This makes it more difficult to estimate the driving distances, charging rates and speeds for EVs. In Scandinavia and in Finland, low-voltage (LV) charging infrastructure is already available in most of the places because of the car preheating needed in wintertime. This infrastructure is commonly used as a single-phase system, and for vehicle charging, only low power levels can be used. The existing infrastructure can be used up to a certain penetration level with minor changes, but if the demand grows significantly, old parking slots in real estates have to be rebuilt. Even if the infrastructure is ready for EVs, charging will require some kind of smartness so that the consumption peak will not increase or real estates will not have to increase the main fuse size excessively. In most new real estates built in the 21st century, cables are sufficient for EVs, and the infrastructure could be used for charging with only minor changes.

METHODOLOGY FOR THE DEFINITION OF ELECTRIC VEHICLE LOADS

In this study, the EV is considered as a load (grid-to-vehicle). When defining the network effects, information has to be gathered from numerous sources. The National Travel Survey gives information for instance on driving distances as well as how, when and how often cars are used. In Finland, the latest survey was carried out in 2004–05 [1]. According to this survey, the average annual driving distance is 18 200 km/a/car in the case area that makes approx 50 km/car,day.

The energy consumption of a EV depends on various aspects. Factors that affect the consumption include the efficiency of the charging-discharging cycle (including the efficiencies of the charger and the battery), the efficiency of the regenerative braking system, the energy needed for heating and air-conditioning, the coefficient of drag, the rolling resistance, the total mass of the EV and the driving cycle. Fortum has recently measured the consumption of an EV in wintertime in Finland, and obtained average values of 0.20–0.25 kWh/km [2]. In this study, daily energy need (50 km/car) has been 11.5 kWh/car per day.

Besides driving habits and energy consumption of EVs, charging opportunities (including slow charging, fast charging and battery replacement service) in different locations have also an effect on the energy taken from the distribution grid by a fleet of EVs. However, fast charging and battery replacement are not considered in this work, and the maximum charging power is set to 3.6 kW/car. The limit comes from the new preheating system in Finland in wintertime. Today, the system operates on one phase voltage (230 V) and 16 A fuses, and this is the application used in all apartment houses in the study. The capacity of the battery is assumed to be 30 kWh/vehicle.

NETWORK ANALYSIS

In the study, one of the main objectives is to investigate transmission capacities in distribution system in a result of penetration of EVs. Six different 20 kV feeders where chosen for closer investigation (Fig. 1). All the feeders are supplied from the same 110/20 kV primary substation. The feeders have different kinds of loads, such as detached, terraced and apartment houses, offices and service facilities. Several customer types have to be taken into account as the practices in the use of EVs vary. For instance on a city area feeder, where the load is based mainly on office activities, the peak load occurs in the daytime. If the EV charging takes place at the same time, the increase in peak power can be significant. In the residential (household) areas, the time of the day when charging mostly takes place varies more than in the case of an office area feeder.

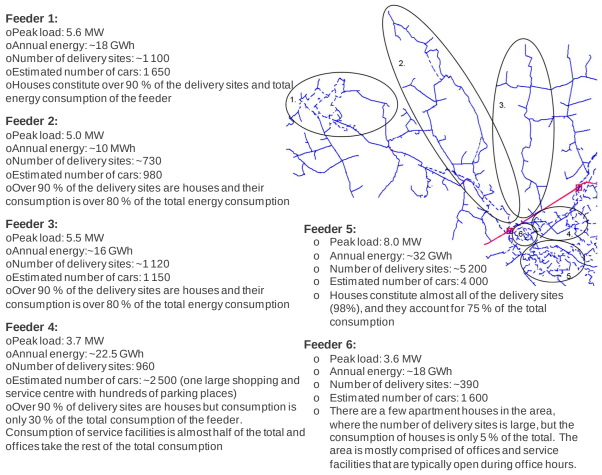

Figure 1. Case feeders and key figures of the network.

The charging time of the EVs depends on where the vehicle is located and how full the batteries are when the charging starts. People commute from home to workplace, after work they may drive on errands, and finally, they drive back home. Moreover, people drive to various free-time activities after work. Hence, we may assume that most of the charging takes place at home and at workplaces, but cars may also be charged for instance at shopping and service centers. Figure 2 illustrates the charging curves used in the study. Figure 3 illustrates weighted daily charging curves for EVs based on number of EVs on the case feeder and charging curves.

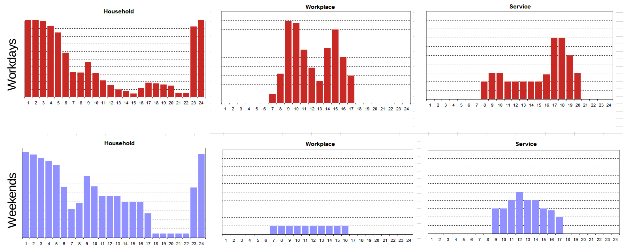

Figure 2. Three charging curves used in the study; households, workplaces and services on workdays (topmost) and weekends (lower).

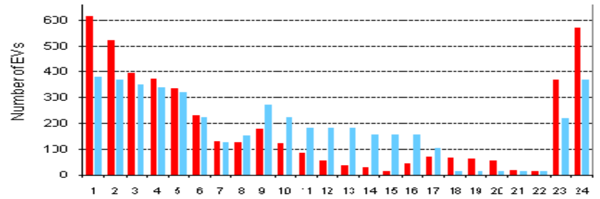

Figure 3. Weighted daily charging curves for EVs based on number of EVs on the case feeder and charging curves presented in Fig. 2.

RESULTS

The results depend strongly on the charging assumptions. The number of EVs and the charging schedule decide how much the peak power can rise from the present situation. Figure 4 depicts the one-year load curve with EVs (the topmost curve). The bottom curve illustrates the powers without EVs. Based on the analyses, the change in the peak load in the case feeder would be from 5.6 MW to 7.6 MW, which means a 2 MW increase. Figure 5 depicts feeder 1 with different penetration levels.

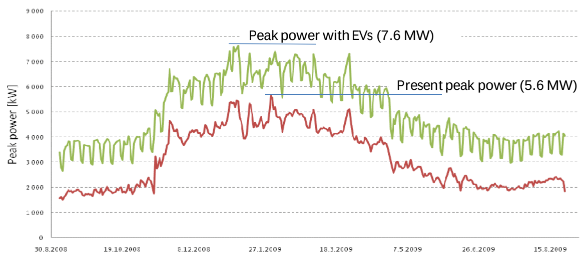

Figure 4. One-year load curve with EVs (topmost) from the feeder 1. The bottom curve illustrates the powers without EVs. The curves include the peak powers of each day; the minimum loads of the days are not presented.

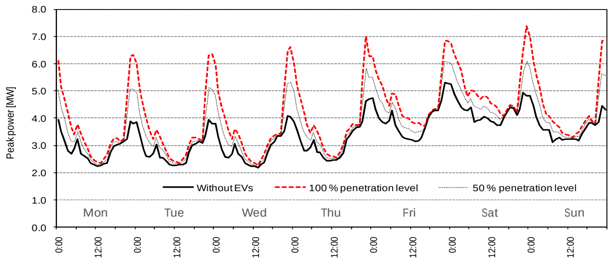

Figure 5. Power flows (base load + charging) in the case feeder for a week. The black curve shows the situation without EVs, the red curve illustrates the situation where all of the vehicles are EVs, and the gray one shows the effect on the network with the penetration level of 50 % of all EVs.

The main reason for peak increase is that the feeder has mainly detached houses with electric heating, and the warm water boilers turn on in the evening. A slight shift in charging would help in reducing the peak load.

Depending on the charging method, the peak load may increase considerably on the distribution network. This means additional investments in larger cross-sections of underground cables and overhead lines, and more transformer capacity. The amount of investments required can be estimated by defining the average marginal cost of the network. It is based on the network replacement value and the maximum load of the year, and it describes how much the network capacity has cost for the distribution company per each peak load kilowatt [3]. In this case, the network value compared with the peak load is 360 €/kW in the low-voltage (LV) networks, 230 €/kW in the medium-voltage (MV) networks and 100 €/kW at the primary substation level (110/20 kV). At the MV and primary substation level, a statistical approach of additional load can be taken because the load is well balanced. In the LV networks, an additional load is difficult to adjust to those time periods when the existing load level is low. On the other hand, there are numerous reasons for the present individual peak loads, such as saunas, electric heating and vehicle electric pre-heating systems, which can be adjusted thereby avoiding the overlapping of peak loads. If the required capacity renovation because of vehicle charging is 2 MW and the average marginal cost on the feeder is 230 €/kW, the estimated need for reinforcement is

$$\begin{aligned} \text{Reinforcement} &= \text{Average marginal cost} \cdot \Delta P \\ &= 230\,€/\text{kW} \cdot 2000\,\text{kW} = 460\,000\,€ \end{aligned} \qquad (1)$$

The additional network investments are paid by the end-customers. Because the replacement value of the case network is 17 M€ (1 M€/a calculated by p = 5% and t = 40 a) and the annual delivered energy on the case feeders is 117 GWh, the network value per delivered energy is 0.86 cent/kWh. The estimated additional annual charging energy required by EVs would be about 44 GWh (12 000 cars, 18 200 km/car,a and 0.2 kWh/km,car). In Table 1, summary of the feeder-specific results are presented.

Table 1. Summary of the feeder-specific results. The present peak power, the peak power with EVs (100 %) and the reinforcement needs.

	F1	F2	F3	F4	F5	F6
Present peak [MW]	5.6	5.0	5.5	3.7	8.0	3.6
Peak with EVs [MW]	7.6	6.0	6.8	5.0	10.6	5.7
Peak increase in MV network	136%	120%	124%	135%	133%	158%
Reinforcement needs [M€]	0.46	0.23	0.30	0.30	0.60	0.49

The total additional load without load control for the case feeders in the MV network will be 10.3 MW. Estimation for reinforcement needs is 2.4 M€. When the reinforcements of the low-voltage networks and 110/20 kV primary substations are taken into account, the total reinforcement investments will be 7 M€. This way, the replacement value of the case network would increase by 41% from the present 17 M€ to 24 M€.

CHARGING OPTIMISATION

Charging of EVs may place significant development requirements on the distribution infrastructure. Because of this, the question of charging control and optimisation becomes relevant. In the study, it was investigated whether it is possible to get all the required energy without increasing the peak power in the network. This is of course more or less a theoretical case, but it provides good perspective on the technical limits of the infrastructure. In Figure 6, the principle of optimised charging is shown. The peak power in a base load in a residential area occurs usually in the evenings when the heat storages are switched on automatically at the same time. It can be seen that in this case it is possible to take all the charging energy needed for cars without increasing the peak power on the feeder on the example day. The increase in smart metering and other smart technology in networks provides an opportunity to control the loads more easily than today. This will be the situation also with EVs.

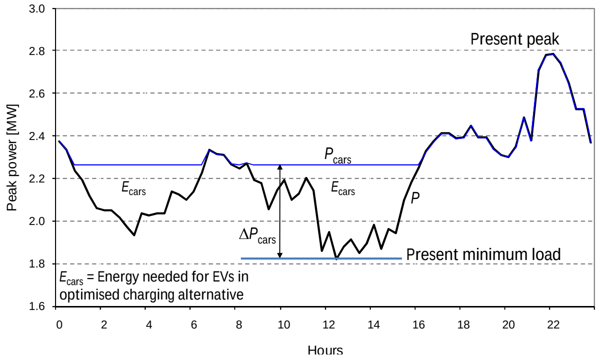

Figure 6. Optimised charging model for a case day. The lower curve represents the existing peak load of the day, while the upper curve represents the load when the charging power is taken into account.

An example of optimisation on Feeder 1 for one week is presented in Figure 7. Based on the analyses in the case network in the optimised charging method, the required energy can be adjusted to hours with a low load level so that the peak power of a certain feeder does not increase at all.

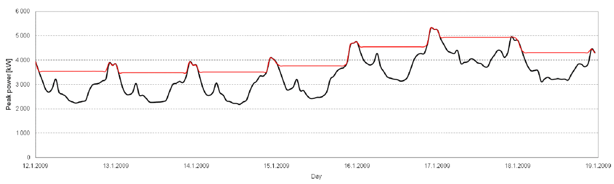

Figure 7. Optimised charging (red curve) for the Feeder 1.

In Table 2, the present peak power, the peak with EVs (100 %) and the peak with charging optimisation are presented.

Table 2. The feeder peak powers before and after optimisation.

Powers [MW]	F1	F2	F3	F4	F5	F6
Present peak	5.6	5.0	5.5	3.7	8.0	3.6
Peak with EVs, no optimization	7.6	6.0	6.8	5.0	10.6	5.7
Peak with EV optimisation	5.6	5.0	5.5	3.7	8.0	3.6

Depending on the charging method and the voltage level analysis of the power increase, a rough estimation of the required investments in a new transformer and transmission capacity in the whole distribution network would be 0–7 M€. The new distribution fee would be 0.63–0.88 cent/kWh after the network reinforcement. This fee range shows that when the peak power of the network increases more than the delivered energy, the distribution fee will increase. If the additional charging load has only a slight effect on the peak power, it is possible to cut the distribution fees.

SUMMARY

The key target of this study has been to demonstrate a methodological approach to evaluate the network effects of EVs in an actual distribution utility. The study has been carried out in cooperation with Lappeenranta University of Technology and Fortum and it is funded by Tekes and the other partners of the ongoing Finnish Smart Grid and Energy Market research program SGEM.

At first, network information was gathered and the number of vehicles in the case area was defined. The case area was chosen so that it reflects the whole network at a certain level. That way, the results of this study can be adopted more widely in the company. After information gathering, load modeling for the case area was carried out. In this phase, feeder-specific information of EVs with appropriate charging profiles was applied both to the research analysis tool and a network information system. In the final phase, the modeling results were estimated from economic perspective; what are the economical consequences of EVs for a distribution utility and for electricity end-users.

The main results are:

- Intelligent control of charging of EVs is strongly recommended in order to avoid a) unnecessary reinforcements and b) an increase in distribution fees paid by the end-customers.
- Without intelligent control of charging, the load growth can be significant, varying from 20 to 50 % in the case.
- Although intelligent control would be possible in some feeder's peaks still remain due to the customer characteristics.
- To understand the network effects of EVs, the present electro technical condition of the distribution network has to be studied first, and careful estimation of the penetration schedule has to be made.
- More efforts have to put for developing charging profiles which consists both normal household consumption load curve and EV charging curve for different purposes (for instance unoptimised and optimised charging and variations of these)

Additional charging powers require expensive reinforcement investments if charging of EVs is not intelligently controlled. First, load control and possible reinforcements are needed in LV networks. Overlapping of different loads (electric heating, sauna, EVs in the same substation) is more probable and significant than in the MV networks. In the MV networks, distortion of loads (timing and volume) is more common, and load overlapping is therefore not such a problem as in LV networks.

When evaluating the results of this study, certain issues have to be taken into account. There is uncertainty especially in the following areas:

- Definition of the total number of cars (and EVs) in the case area (penetration level)
- Definition of the feeder-specific locations for EVs
- Charging profiles (where, when, how much EVs are charged)
- Charging optimisation presented in the study is only a theoretical approach to define the most optimistic case.

The marginal cost method can be used when evaluating large-scale needs for renovation investments. The method cannot be used to define the exact amount of money needed for feeder or secondary substation renovation. At that level, renovation needs have to be estimated by target-specific renovation planning.

In the coming studies, an approach at a secondary substation level will be taken. This work will be based on customer-specific hourly measured AMR data, where implementation of different EVs charging profiles is carried out. The research will provide answers considering overloading challenges in low-voltage networks. Based on these studies, reinforcement needs in LV networks can be defined more reliably. Moreover, an evaluation of the present network information system considering LV network calculation in the case company can be performed.

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