Analysis of a Scenario of Large Scale Adoption of Electrical Vehicles in Nord-Trøndelag

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Abstract

With the Klimaforliket (Agreement on climate policy) signed by the Norwegian government on January 17th 2008, Norway has set a goal to reduce emission caused by transportation with 2.5 – 4 million tons CO2 equivalents compared with the reference for 2020[1]. To reach this goal, a high penetration of electrical vehicles is essential, and new technologies and solutions for the infrastructure must be cleared early in the process. With the aim of triggering and stimulating a discussion in the topic, this paper will present a methodology for the analysis of the impact of large scale adoption of EVs on the electrical grid. A specific portion of a real network will be selected and two charging modalities for the electric vehicles will be investigated.

Keywords: Electric vehicles, charging, distribution network, Smart Grids

1. Introduction

The transport sector is accountable for more than half of the worlds consumption of oil, and a large amount of this is consumed by passenger cars.[2] A large scale adoption of electric vehicles would reduce the greenhouse gas emissions, and also reduce the dependency of oil. Nevertheless, the environment benefit is dependent of the generation mix. The higher percentage of renewable in the generation mix, the more beneficial the integration of EVs is. Renewable resources, such as wind energy, tends to have a stochastic production and will cause surplus energy in certain periods. To have the most efficient usage of the power, a good solution is to implement EVs in the grid. The EVs can also provide ancillary service and support
the network with supply/demand matching and reactive power support[2]. The solution where the vehicle delivers power back to the grid is called Vehicle-to-grid (V2G). Vehicle-to-home (V2H) is the solution where the vehicle delivers power to the owners home. All thought the integration of EVs is an intelligent solution to use the energy surplus, the implementation of a large EV fleet causes a lot of challenges. This paper questions the impact on the distribution grid, where the first bottlenecks are likely to occur. To be able to determine the impact on the distribution grid caused by a increasing number of EVs, a real data analysis of a low voltage network in the middle of Norway will be carried out. The grid is located in Steinkjer, outside Trondheim and is provided by NTE[3]. The analysis will start with chargers located at residences, to then explore how the utility can put forward a system for smarter charging strategies (“dumb” vs “smart” charging). In the first part of the paper, different charging technologies will be discussed. The second part will focus on the consequences a large scale adoption will cause on the selected grid in Steinkjer.

1.1. Ambitions and driving forces

The 17th of January 2008 the Norwegian government signed Klimaforliket (Agreement on climate policy) declaring that the state of Norway will be carbon-neutral no later than 2030. This agreement stated that Norway have to reduce the emission with 15-17 million tons CO₂ equivalents, a reduction of 25% compared with the 2007 reference [1]. It was also stated that the transport sector need to reduce the emission with 2.5 - 4 million tons CO₂ by the year 2020. The transport sector in Norway is accountable for 19% of the emissions. As a part of the obligation given in Klimaforliket a resource group was formed in December 2008 to elaborate a plan for electrification of the transport sector in Norway. The result from this project was presented in Handlingsplan for elektrifisering av veitransport (Plan of action to electrification of the road transportation)[1]. To reach the goal of a 25% reduction in emission, the resource group suggests that the traditional vehicle becomes more efficient as well as an integration of EV and vehicles that run on biofuel. A share of at least 10% electric vehicles is adequate by 2020. It was also stated in the same report that a share of 50% of EVs would cause a reduction of 36% compared to a vehicle-fleet with only efficient traditional gasoline vehicle. An efficient vehicle is calculated with 95 g CO₂ per km. If Norway wants to achieve the ambition of being carbon-neutral, the report propose a large implementation of EVs by 2030[1].

1.2. Electric Vehicle in Norway 2011

As of September 2011, there are according to Grønn Bil 4715 electric vehicles in Norway. The estimated number for November 2011 is 5301[4]. The electric vehicles are mainly located in and around the big cities. Oslo has the largest share with 1223 vehicles. This value is from September 2011. For the same period Bergen had the second largest share with 242 vehicles. In Trondheim the number of vehicles were 228[4]. Grønn bil has also a geographical presentation of where the charging stations in Norway are located on their web page. There are currently 3067 regular and 24 fast charging points in Norway. 4 of these are located in Oslo, 4 is located outside Stavanger, 2 in Bergen and 1 in Trondheim[4]. There are several EV models available at the Norwegian market today. The Norwegian EVs, Think and Buddy are according to the statistics they are the most popular EVs in Norway. 25% of the EV owners in Norway chose Think, while 23% chose Buddy. Mitsubishi is also a popular vehicle, and their EV, i-MIEV, is represented with 17% of the Norwegian market. Both Buddy and Think were produced in Norway, but currently there are no production of EVs in Norway. The production of Think stopped in March 2011. The company was liquidated in May 2011, and the estate was bought by Boris Zingarevish from Russia. Pure mobility, the company that produced Buddy in Økren, was liquidated as of November 1st 2011. Buddy is now owned by Buddy Electric AS that wish to continue production in Norway[5]. For the case study addressed in this paper, Nissan Leaf will be used as the simulation model. Nissan Leaf was selected Car of the Year 2010. According to the sales revenues for November 2011 in Norway, 64% of the models bought in November was Nissan Leaf[4]. Mitsubishi’s i-miev which is also very popular in Norway were considered, but according to Bengt Otterås from BKK Nett AS, future charging system in EVs will as the Nissan Leaf have a charging current close up to the limits for the different charging modes[6]. These modes are explained in section 2.1.
2. Charging Technology

There are many different types of EVs. Essentially, an EV is a vehicle that uses electric motor for propulsion. The term Grid Enabled Vehicle (GEV) represent the vehicles that is directly implemented in the grid. The Plug-in Hybrid Electric Vehicle (PHEV) and the Battery Electric Vehicle (BEV) are included in this term. For the purpose of this paper, the term EV will be used for BEVs when not mentioned otherwise.

2.1. Charging standards

There are several standards for charging electric vehicle. In this paper it is chosen to look at the European standard IEC 61851-1. The charging modes are defined as:[7]

1. Mode 1, (AC) slow charging from a standard household-type socket-outlet not exceeding 16 A and not exceeding 250 VAC single-phase or 480 VAC three-phase, at the supply side, and utilizing the power and protective earth conductors. Mode 1 is the most widely used system today.

2. Mode 2, (AC) slow charging from a standard household-type socket-outlet with an in-cable protection device, not exceeding 32 A and not exceeding 250 VAC single-phase or 480VAC three-phase, utilizing standardized single-phase or three-phase socket-outlets, and utilizing the power and protective earth conductors together with a control pilot function and system of personnel protection against electric shock (RCD) between the EV and the plug or as a part of the in-cable control box. The inline control box shall be located within 0.3 m of the plug or the EVSE or in the plug. Mode 2 requires a control pin, but only on the vehicle side. The supply side does not need a control pin. The control is governed by the control box in the cable.

3. Mode 3, (AC) slow or fast charging using a specific EV socket-outlet and plug with control and protection function permanently installed. Mode 3 connectors require, according to IEC 61851-1, a range of control and signals pins for both sides of the cable. If the there is no vehicle present, the station socket is dead. The pilot pin in the plug on the charger side controls the circuit breaker.

4. Mode 4, (DC) fast charging using an external charger. Mode 4 charging is a solution where the power from the supply is converted in the charging station to DC. Mode 4 allows DC fast charging with currents up to 400 A. As for mode 3, mode 4 connectors require a range of control and signals pins to ensure a safe operation.

Mode 1 is the solution that is widely used today. As for the future, it is expected to use the other modes. Mode 4 defines the fast DC chargers. To be able to replace a large share of the traditional ICE vehicles with EVs, there is necessary to build the infrastructure for it. This include fast chargers at shopping malls, at gas stations and in the streets and at rest stops along the highway. Mode 4 will not be further discussed in this paper. Mode 2 and 3 chargers are the solution that will be the most common modes. The chargers will be stationed at residents, workplace and public sites. The difference between mode 2 and 3 is that mode 3 requires more communication and control in on the vehicle side. One can expect that mode 3 will become the standard solution for resident chargers if the V2H is introduced.

3. Vehicle to Grid (V2G) and Vehicle to Home (V2H)

The terms Vehicle to Grid and Vehicle to Home cover the solution were the battery in the electric vehicle delivers power back to the source. The intention is to save renewable unregulated energy in the battery and feed it back to the grid during peak hours. The introduction of electrical energy storage, such as the EV, could improve the efficiency and reliability in the power supply. The demand on the grid will be smoothed. However, V2G is associated with challenges such as state of charge (SOC) and the availability of the vehicle. How many vehicles are required to stand by as storage? How can we obtain the reliability, and at the same time the EV owners satisfied? Due to the fact that the V2H solution avoid some of the infrastructure and
4. Network Description

For the purpose of this case, a low voltage distribution network was chosen to be simulated. The real data is provided by NTE[3]. This low voltage network is located in Steinkjer, outside Trondheim. The provided system includes a distribution network with primary voltage level of 22 kV transfer down to the low voltage level of 230 V. From the substation there are six outgoing feeders, supplying together the load from 35 residents. There are also 3 residential loads that are supplied directly from the substation. This gives a total load of 38 residents. NTE provided the hourly consumption from one resident in the network in Steinkjer. Due to the demand is highest in the winter, it is beneficial to analyse this case. It is therefore chosen to use the load in December 2010 from the given resident as the simulation data. Yearly consumption for the other residents in the network was also provided by NTE. The hourly real time data from December 2010 for the resident in Steinkjer was used to calculate the daily hourly average demand for the resident. Based on these data, a 24 hour load profile were calculated and designed in PSCAD. Due to some limitation in PSCAD, the residents were lumped together as one load. The cables were connected in parallel, and the line impedances were calculated from data given in Planleggbok for kraftnett, Tekniske data (Guide for power grid, Technical data) provided by SINTEF[9]. To be able to calculate the total consumption a power coefficient was introduced. This coefficient is the relation between the yearly consumption for the given resident and the total yearly consumption. Further it was decided to use the 22nd of December 2010 as the "simulation date". This was done to look at the worst case scenario, and the 22nd had the highest demand. Figure 1a shows the difference between the average demand and the demand on the simulation date. The demand peaks are, as expected, in the afternoon. For the chosen simulation date, the highest peak occurs at 15.00. It was expected that this peak would occur later, like shown on the average where the peak occur around 18.00. It is also expected that the EVs will be connected and charged during this time and cause higher peaks. To be able to simulate these peaks it was determined the average number of EVs connected to the grid during the day. This was made on general assumptions, and is only a calculated value. It is, however, used in other analysis [10] and will correspond to the real situation. These values are shown in figure 1b.

As seen on figure 1b, the electric vehicles are connected from approximate 16.00 until 06.00. However, the recharge time is assumed to be less than the connection time. To determine the recharge time for the EVs, data from Nissan’s EV, Nissan Leaf is used as a basic for the following calculations. The Nissan Leaf has a Li-ion battery with a capacity of 24kWh. The recharge time depends on which level or mode is used. For a charging dock 220/240V and 40A the recharge time is 3.5 hours[11], while a 220/240V and 16 A the recharge time will be 6.5 hours[12]. Due to the fact that mode 2 will be more commercialized in the future, it is then assumed that the recharge time will be approximate 4 hours. This assumption is also used in the Portuguese publication Smart Charging Strategies for Electric Vehicles: Enhancing Grid Performance and Maximizing the Use of Variable Renewable Energy Resources by J. A. Peças Lopes[10]. It is further determined that average value of vehicle per household is equal to 1.5 vehicle, which gives a total of 57 vehicles enclosed in the area of the network. This was based on that the vehicle density in Trondheim is
(a) Average daily load for a resident in December 2010

(b) Percentage of EVs connected to the grid

Fig. 1. Network description

over 500 per 1000 citizen[13]. As mentioned, the Nissan Leaf will represent the EV fleet, this gives the modelled vehicle a rated power of 6 kW. This value is calculated from equation 3.

\[ \text{\( E_{\text{batt}} = 24 \text{ kWh} \)} \]  \hspace{1cm} (1)

\[ \text{\( T_{\text{charge}} = 4 \text{ h} \)} \]  \hspace{1cm} (2)

\[ \text{\( P_{\text{EV}} = \frac{W_{\text{batt}}}{T_{\text{charge}}} = \frac{24}{4} = 6 \text{ kW} \)} \]  \hspace{1cm} (3)

According to the The Institute of Transport Economics (Transportøkonomisk institutt) the average distance a person drives each day in Norway is 43 km [14]. Considering that Nissan Leaf has a driving range at 150 km[12], the average charging frequency could be that the owners charged their vehicle every third night. However, this analysis cover the worst case scenario where all the owners plug their vehicle in the grid at the same day will be analysed in this study due to the insecurity in the owners charging behaviour.

5. Scenarios

According to the Norwegian government’s plan for electrifying the transport sector, it is determined that at least 10% of the passenger cars is chargeable in 2020. It is also stated in the same rapport, that if the share of chargeable passenger cars reached 50% towards 2050, it would cause a reduction of 36% in emission[1]. In consideration to this, the different scenarios were determined. The simulation includes three different
scenarios, which are presented in table 1. This numbers are based on assumption made in section Network Description and consumption provided by NTE[3]. The first scenario is a simulation of the system without EVs, to have it as a base for comparing the scenarios with EVs. The second scenario was made to reflect the governments goal for 2020. A percentage of 10% in this area equal $5.7 \approx 6$ vehicles, resulting in a percentage of 10.53. For the third scenario is was decided to exceed the government’s ambition of 50% by 2050. It was chosen to see what a 60% share of EVs would cause in this LV-gird. The number of EVs in the third scenario was decided to by 36 vehicles, leaving the percentage to be 63.16.

<table>
<thead>
<tr>
<th>Table 1. Scenario Overview</th>
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<tbody>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>N of vehicle</td>
</tr>
<tr>
<td>N of EVs</td>
</tr>
<tr>
<td>Percentage of EVs[%]</td>
</tr>
<tr>
<td>Total demand [MW]</td>
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6. Charging Strategies

As it is previously mentioned, this paper will focus on the impact on the distribution network caused by EVs. Figure 1a and 1b in section 4 illustrate that implementation of EVs in the grid can cause a capacity problem in the afternoon. There is an existing peak in the afternoon and when a large share of EVs is implemented, the peak will increase. That may result in a capacity problem, a situation where the grid is not able to handle the heavy load. For the case study addressed in this work, two different charging strategies for EV charging were analysed:

*Strategy 1 - “Dumb charging”*

In the first approach it is assumed that the electric vehicle owners can connect to the grid whenever they want to, and that the charging will start immediately. In worst case the owners will plug their vehicles at the same time. This situation may occur when the users get home from work, which are typically existing peak hours. In the dumb charging strategy the charging start immediately and last for four hours. This approach is described as a non controlled strategy, leaves the power company to almost guess the production planning.

*Strategy 2 - “Smart charging”*

In the second approach, the smart charging strategy is introduced. It is assumed that there is an active control and manage system that continuously monitor all the elements connected to the grid. Then the charging schedules will be phased in. It is expected that the demand curve will be made more uniform. The vehicle will communicate with the grid when it is connected, and will start to charge when the demand is low. The smart charging strategy requires technology that can measure and communicate. It will also require a commitment from the vehicle owners. This approach will provide a beneficial usage of available resources, and also prevent damaging the grid. The V2H can also be introduced as a part of the smart charge. Due to the continuously monitoring of the elements connected to the grid, the EVs can operate as ancillary services and support the grid. The EVs can both deliver and store electric energy from the battery to the supply in situation with surplus/deficit of energy.
7. Result and Analysis

The hourly demand from the EV was calculated to be 6 kW. Due to the fact that there are no real data of an implementation of EVs, the extra demand caused by the vehicles were added to the load curve in Excel. It was done for both of the different charging strategies and both of the scenarios. As a starting point, the demand from the EVs were added as a function of when the vehicle were connected to the grid with references to figure 1b. For the dumb charging, the vehicle started to charge immediately when connected in the afternoon and charged for four hours. In the smart charging approach, the extra demand was added manually as a function of available vehicle and low demand. That resulted in charging late in the evening and at night. For a proper comparison between the dumb and the smart charging, the load profiles are presented in the same graph, as well as the base demand. A total capacity limit was added as a demand limitation, an indication on how much the system could handle. This limit were calculated to 378,4 kW and was based on the cables thermal limit. The power capacity for each cable were calculated by the nominal voltage and \( I_{th} \), the maximum continuous operating current, found in Planleggsbok for krafnett, Tekniske data from SINTEF [9]. These values were added together to represent the capacity limit for the system.

In scenario 2, six EVs were implemented in the system. Figure 2a show the consequences an implementation of 10% will cause on the load profile. As seen on the figure, the extra demand does not exceed the capacity limit. The highest peak for the dumb charging is 366,01 kW. The figure shows the worst case scenario, when all the EV owners connect their vehicle at 15.00. The curve for the dumb charging and the base is consistent until the vehicles in connected in the afternoon, and then the curves “melt” together after the vehicles is done charging at 19.00. The curve for the smart charging is higher during the nigh when the vehicles is charging, and starts to follow the base demand from 06.00 when the vehicles is disconnected until 20.00 in the evening, when some of the vehicles start to charge. Nevertheless, figure 2a show that the dumb charging strategy will strain the system with extra 36 kW in the existing peak. In the third scenario, 36 vehicles were added. The change in the load profile is shown in figure 2b. The demand for the dumb charging will, as figure 2b presents, follow the base load until 15.00. At this point it is assumed that some of the EVs are connected to the grid. Between 15.00 and 19.00 the dumb charge exceed the capacity limit. The demand for the dumb charging will peak around 17.00 with a load of 454,5 kW, which exceed the capacity with 76,1 kW. The charging will end four hours later, around 22.00. In the smart charging approach the charging is moved, as one can see in figure 2b, to late night and early morning. The load profile in this approach will cause no extra demand during peak hours. The highest peak in in the smart charging approach is the same value as the base demand. The peak of 330,01 kW occur at 15.00. The low demand between 5 and 7 is due to that the vehicles are done charging. In a scenario with a higher EV percentage this period may also be used for charging. Since it is assumed that most of the vehicles is not connected in the grid between 06.00 and 16.00, the low demand will be unchanged in this period.

Scenario 3 was simulated in PSCAD to analyse if the voltage on the load exceeded its limits. As a starting point, the respective limit given from Forskrift for leveringskvalitet that state that the voltage should not exceed \( \pm 10\% \) [15]. The per unit value were measured from the phase voltages in PSCAD. The two different charging approaches were simulated, as well as the base. Figure 3 shows how the voltages decreases as the load increases. The figure shows the voltage between 13.00 and 20.00, when the highest demand occurs. The purple line in the figure is the voltage during the dumb charging. As expected this approach causes a dip in the voltage around 17.00 when the system’s demand peaks. From figure 2b one could see that the smart charging does not cause any extra demand than the residential load during peak hours, therefore there are no extra drop in the voltage either. The curve follows each other up until 19.00 when the base voltage increase more than the smart charge voltage. This reason for the lower voltage in the smart charge, is because the vehicles are starting to charge at that point, causing a higher load. The lowest measured voltages for the different approaches, are presented in table 2. The lowest measured voltage in the dumb charging is measured to 0.984 p.u. - a deviation of 1.6 %. The voltage drop during the dumb charge, were expected to be severe.
(a) Scenario 2 - 10.5% EVs.  
(b) Scenario 3 - 63% EVs.  

Fig. 2. Result - daily demand on substation

Fig. 3. Measured voltage in p.u.

Table 2. Result from scenario 3

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Peak Hour</th>
<th>Voltage (p.u.)</th>
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<tbody>
<tr>
<td>Base (no EVs)</td>
<td>15.00</td>
<td>0.988</td>
</tr>
<tr>
<td>Dumb charging</td>
<td>17.00</td>
<td>0.984</td>
</tr>
<tr>
<td>Smart charging</td>
<td>15.00</td>
<td>0.988</td>
</tr>
</tbody>
</table>

V2H

As a part of the project discussed in this report, a V2H solution was simulated. In this case, the analysis focused on only one EV and the given residential load. The result of this analysis is presented in figure 4. The x-axis on the figure shows the state of charge (SOC), and the hours of the day in shown in parentheses. Between 07.00 and 14.00 the EV is not connected to the supply, and the state of charge is therefore applied as NA (not applicable). It is further assumed that the SOC is 50% when the vehicle is connected to the supply at 15.00. This is based on the average distance a person drives each day in Norway and Nissan Leaf’s driving range, and an assumption that there will be some losses in the battery during the conversion of energy. The purple line indicates the demand in the V2H solution, while the green indicate the base demand. The EV is charged late at night and early in the morning.

In the afternoon, the load from the resident peak and the battery in the vehicle can provide some of the
Fig. 4. Residential demand with Vehicle-to-Home.

demand. This causes less strain on the grid. One can see on figure 4 that this solution makes the load curve more smooth. For the case of the V2H, the peak occur at noon with a load of 10.01 kW. One can expect that the voltage would be smoother, and that the voltage-drop around 15.00 would have been reduced.

8. Discussion

The purpose of the work addressed in this report was to show the strain on the grid by implementing a large share of EVs. The result from the manually simulations shows that the system in not capable to handle a dumb charging approach when the share of EVs are 63%, while the simulations from PSCAD show that the voltage limits is not exceeded. The lowest measured voltage in the dumb charging is measured to 0.984 p.u. This is a voltage drop of 1.6% and therefore does not exceed the limits of ±10%. It was expected that the voltage drop in the dumb charging approach would be larger. The sources of error has not yet been located. The trend of the results does however, show that a smart charge approach will cause less strain on the grid. A large scale adoption of EVs is an intelligent way to reach this goal and addition have a more efficient usage of the available power, and especially in a network with a high share of renewable resources. The result from the analysis shows that the smart charging approach did not causes any extra strain on the demand during the peak hours. A large share adoption of EVs requires beneficial infrastructure. In addition to slow charging from a suitable docking station (mode 2/ mode 3), fast chargers (mode 4) need to be included in the infrastructure. Mode 1, which is the most used charging mode today, will fade out and be replaced. The chargers at residents and workplaces will mainly consist of mode 2 and mode 3 chargers. To be able to introduce the V2H solution, the charging technologies need to be based on mode 3 charging described in IEC 61851-1. Mode 3 requires control and signal pins for both the charger side and the vehicle side. An introduction of V2H and generally smart charging forward a huge opportunity for a third-party to offer add-ons and other business ideas.

9. Further work

The simplifications made in this project make it impossible to look at the different buses in the system. It is expected that the buses far away from the feeder would face large voltage drops. In a further analysis a more detailed simulation should be carried out. A further analysis could also use other areas and time for simulation.
10. Acknowledgement

The authors would like to thank NTE Nett AS for their contribution to the project.

[3] Information and data from the lv-grid from nte, received as an email from Jan A. Foosnaes at the 27th of October.