Impacts of Electric Vehicle Loads on Power Distribution Systems

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***Abstract*-Electric vehicles (EVs) are the most promising alternative to replace a significant amount of gasoline vehicles to provide cleaner, CO_2 free and climate friendly transportation. On integrating more electric vehicles, the electric utilities must analyse the related impacts on the electricity system operation. This paper investigates the effects on the key power distribution system parameters like voltages, line drops, system losses etc. by integrating electric vehicles in the range of 0-50% of the cars with different charging capacities. The dump as well as smart charging modes of electric vehicles is applied in this analysis. A typical Danish primary power distribution system is used as a test case for the studies. From the simulation results, not more than 10% of electric vehicles could be integrated in the test system for the dump charging mode. About 40% of electric vehicle loads could be accommodated in the network with the smart charging mode. The extent of integrating EVs in an area is constrained by the EV charging behavior and the safe operational limits of electricity system parameters.**

I. INTRODUCTION

The transportation sector is one of the major contributors of CO_2, where the passenger cars account for half of the emissions from the transport sector. The introduction of plug-in electric cars is a major step forward in implementing green transportation. The breakthroughs in electric storage technology like that of high efficient lithium-ion batteries have paved the way for the modern battery electric vehicles (BEV). The market share of hybrid and plug-in electric vehicles are expected to reach five million by 2020 [1]. The electric vehicles not only reduce air pollution and green house gas emissions but also reduce petroleum consumption, thus providing increased energy security. Electric vehicles could also support the electricity sector in integrating more renewable energy, especially the wind power by acting as a buffer to the variable electricity produced [2].

In Denmark, it is estimated that 10% of the total passenger-cars could be electric vehicles by 2020 [1], [3], where many projects are initiated to use electric vehicle battery storages to support large wind power integration. The prospects of utilizing electric vehicles in the future ancillary service markets are widely discussed in [4-6]. The car batteries can ideally charge whenever there is a period of excess wind production and low electricity consumption [7]. However, such system level assumptions may not address the coincident peaks of EV charging and conventional loads in distribution system levels. The uncertainty of EV driving patterns, penetration levels and charging of EVs in electric distribution systems could result in new system peaks and negative distribution system impacts. Much attention has also been paid on the impacts of market integration of electric vehicles on the utility distribution load profile [8-10].

The objective of this work is to investigate the impacts of electric vehicle charging on the power distribution network in the Danish island of Bornholm. The key operational parameters of the electrical distribution system like the voltage profile, distribution line loading, transformer loading, peak demand and system losses are analysed for an increased penetration of electric vehicles. The digital simulations are performed on the Bornholm test distribution network using the DIgSILENT Power Factory software. Section II discusses the electric vehicle charging scenarios used in the simulations. A brief description of the test distribution network is detailed in section III. The simulation results are presented in Section IV and concluded in Section V.

II. ELECTRIC VEHICLE CHARGING PROFILE

In this paper, the electric vehicles are assumed to be of three different types. They are categorized based on their rated power charging capacity (Type1 - 2kW, Type2 – 5kW and Type3 – 10kW) [11]. The EV Type1 could be regarded as the charging power needed for a hybrid electric vehicle, where the typical battery storage capacity ranges from few kWh to around 15kWh. The EV Type2 and EV Type3 could be considered as charging requirement for medium and large battery electric vehicles respectively. The integration of the electric vehicles are analysed in steps, and as additional electrical loads integrated to a typical Danish distribution network. Fig. 1 shows the distribution of the three different types of electric vehicles integrated to a geographical area in steps from 0% to 50%, where the total number of cars is equal to 20,000. The 0% represents the reference scenario. The scenario considers the hybrid electric vehicles to constitute a major share of the vehicles during the low penetration of electric vehicles. They are gradually replaced by the battery electric vehicles for a larger percentage of EVs.

Two types of plug-in EV charging are considered in this paper 1) uncontrolled and 2) controlled. Fig. 2 depicts the aggregated EV charge profile used in this paper, where the 100% of battery charging requirement is distributed among the hours of a day. This charging profile is a modified version of what is reported in [12]. The EV charging time is

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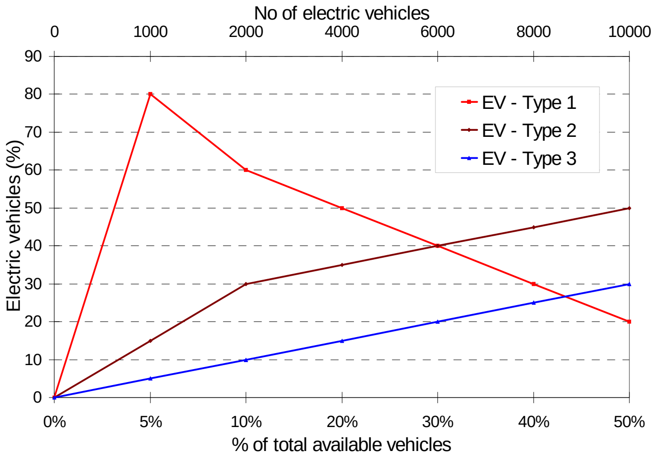

Fig. 1. Electric vehicle integration scenario

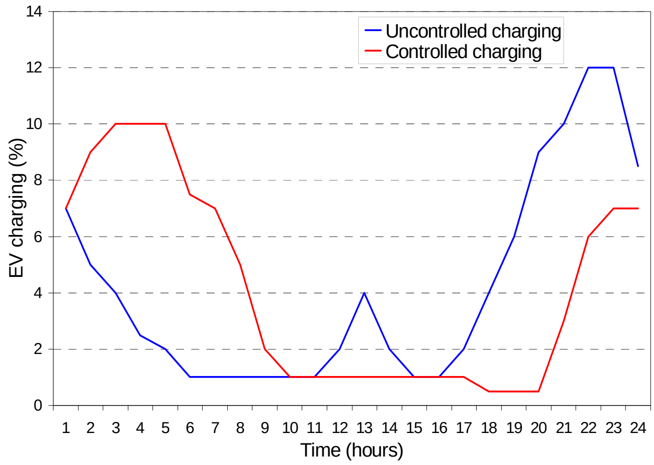

Fig. 2. Charging profile of electric vehicles

considered to be four hours. The uncontrolled charging mode corresponds to a dump charging mode, where the EVs are charged at any time, irrespective of any constraints. The fast charging of EVs (e.g. charging 50% of the battery storage capacity in half an hour) possibly by the taxis and business vehicles during the afternoon hours is also considered under the uncontrolled charging mode. This charging mode represents a scenario where 55% of the battery charging takes place during the off-peak hours (10:00 p.m. to 7:00 a.m.) and the remaining 45% is provided between 7:00 a.m. and 10:00 p.m. The controlled charging is a flexible mode or smart charging, where the battery charging is carried out mostly during hours of low electricity price and low electricity demand (off-peak hours). The EVs have to be equipped with smart metering and communication interfaces to realise this scheme. The charging mode is assumed to ensure minimal plug-in EV loads during the peak demand hours. The controlled charging mode creates a scenario where 75% of the EV battery charging occurs during the off peak period (10:00 p.m. to 7:00 a.m.) and the remaining 25% is provided between 7:00 a.m. and 10:00 p.m.

III. Bornholm Power System

The power system in the Danish island of Bornholm is considered as a test case in this paper. This is a medium voltage (MV) power distribution network. In 2007, the average annual electricity demand supplied by wind power in Bornholm was 32% [13]. As it is a wind dominated distribution system and self contained, it is in focus for a number of future power system research studies, prototype development and testing of new distributed generation technologies [13], [14]. It is a model region for electric cars where projects like "EDISON" plans to demonstrate the use of EVs for supporting large scale wind power [3].

Fig. 3 shows the graphics of the Bornholm 60kV meshed power distribution network modeled in the DIgSILENT Power factory software with the distribution transformers (60/10 kV), generators, wind turbines, shunts and aggregated loads in the 10kV system. The island of Bornholm is connected to the 132kV Swedish network through a submarine cable. The model in Fig. 3 is adopted from the reference article [15], [16] and the other relevant data are taken from similar published articles and reports on Bornholm [13], [17]. The substation names which are abbreviated in Fig. 3 are available in [17]. The actual network data for the 10kV and 0.4 kV feeders are not available for this analysis. So, a simplified radial distribution system, as shown in Fig. 4 with four feeders at 10 kV levels at each of the fifteen 60kV substations, are used in this study. The aggregated system loads and EV loads are distributed across the 10kV voltage levels. Fig. 5 depicts the typical load demand curve in Bornholm. The maximum and minimum demand reported for the year 2007 are 55MW and 13MW respectively.

To analyse the impacts of EV loads on a LV distribution transformer, a 250kVA transformer is considered here in this article. The transformer size is based on the average size of LV distribution transformers in Bornholm with 29 customers per unit [13], [17]. Fig. 6 shows the aggregated load profile of a 250kVA low voltage distribution transformer. This demand profile is scaled from a daily residential curve presented in [18]. The peak demand for the day is 196.35kW at 17:00hrs. The average demand is 68.17kW and the daily load factor is 34.72%.

The plug-in EV loads are added to the system demand (reference scenario) in steps and the impacts of these additional loads on the key operational parameters of the distribution grids are analysed using load flow studies simulated for every hourly data for the typical day. The effect on the system voltage profile per feeder, daily system losses, peak demand period, distribution line losses and transformer (loading and aging factor) operation are investigated for an increased penetration of EV loads. A DPL (DIgSILENT Programming Language) script is developed in the Power factory software for using the charging profile of EVs in the model and also to perform the load flow analysis.

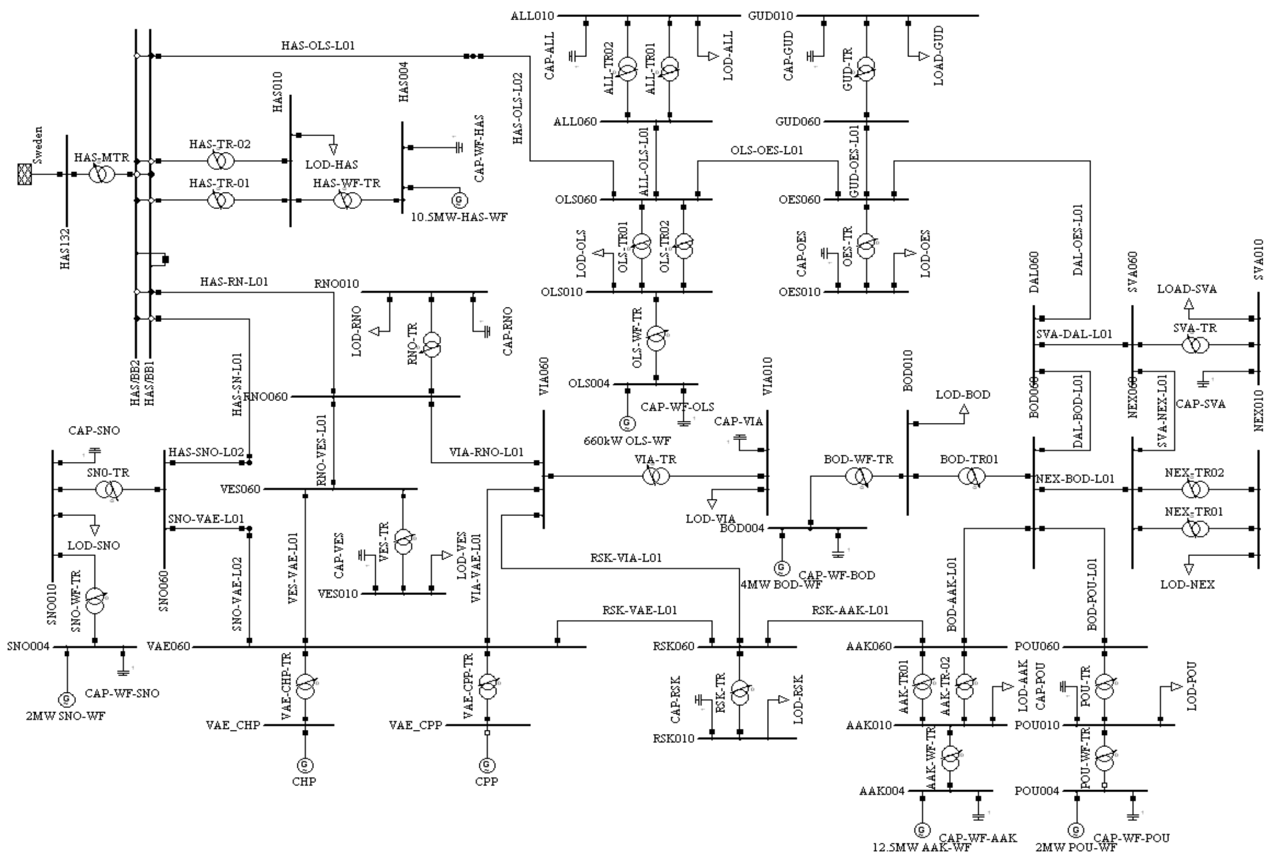

Fig. 3. Bornholm power system network [16], [17]

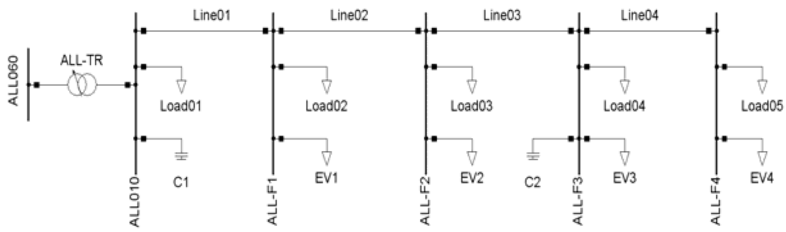

Fig. 4. 10kV radial test distribution feeder

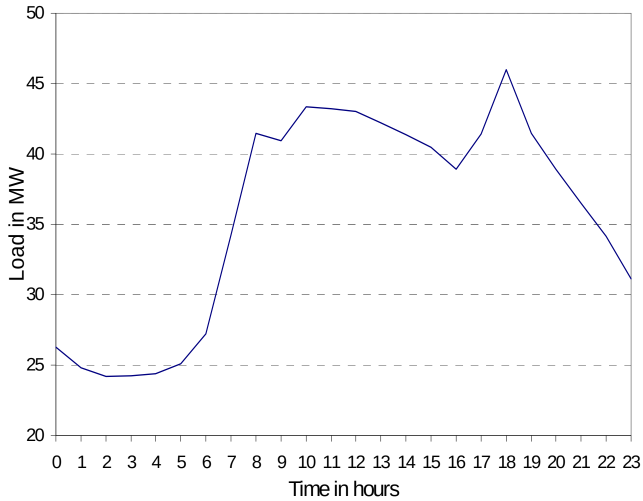

Fig. 5. Typical load consumption curve

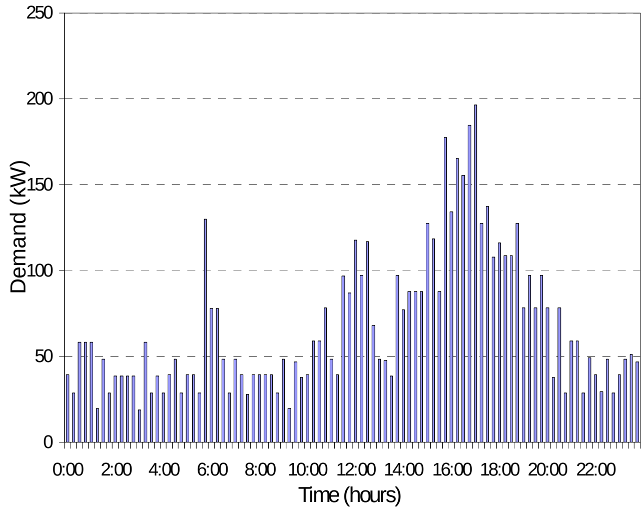

Fig. 6. Demand curve of a 250kVA LV distribution transformer

IV. RESULTS AND DISCUSSIONS

Fig. 7 shows the voltage profiles of three critical feeders in the network for the uncontrolled charging mode of the EVs. From the reference levels, the voltage of the feeders drops below the normal acceptable limits of 0.95p.u [19]. It is observed that the voltages limits are violated for the ALL-F4 feeder even with 10% of EV loads. But for the controlled charging in Fig 8., the voltages of the critical feeders gives better results than for the uncontrolled case as seen in Fig. 7. The voltage falls below the nominal limit only for the feeder ALL-F4, for an EV integration of 40% in the distribution network. The loading profiles of three highly congested distribution lines are shown in Fig. 9 and Fig. 10 for the uncontrolled and controlled charging modes respectively. The loading exceeds the 100% limit for two lines in the uncontrolled mode of charging. The congestion level of the most critical branch is exceeded when the EV load penetration is 40% for the uncontrolled mode.

The line loadings for all the three lines are within the permissible loading range if the EVs are following the controlled charging mode. The distribution system losses and the peak demand distribution for both the controlled and uncontrolled mode are given in Fig. 11. The losses are increased by 40% and 30% for the uncontrolled and controlled charging mode respectively for 50% EV integration. The peak demand in the network for the uncontrolled charging mode is found to be 31% higher than the controlled charging for the 50% EV scenario.

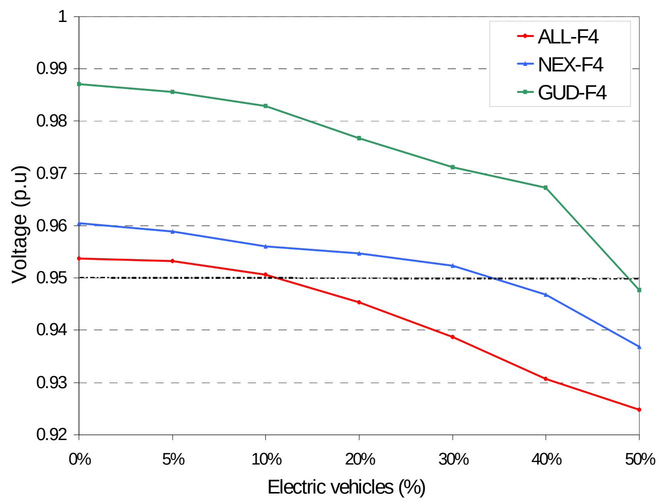

Fig. 7. Voltage profile of three critical feeders for uncontrolled charging

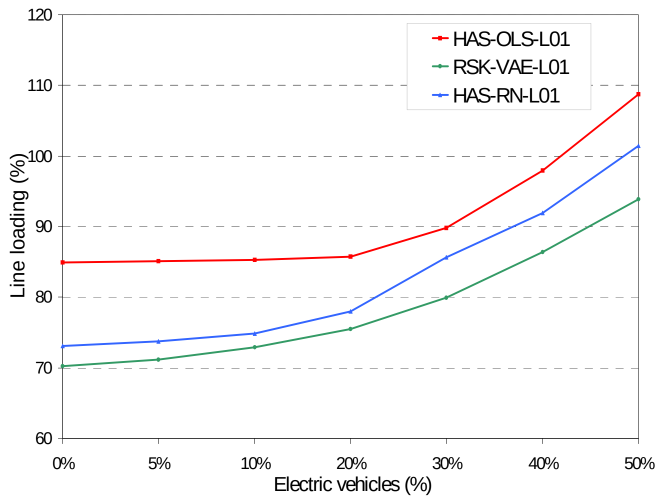

Fig. 9. Loading profile of three highly congested lines for uncontrolled charging

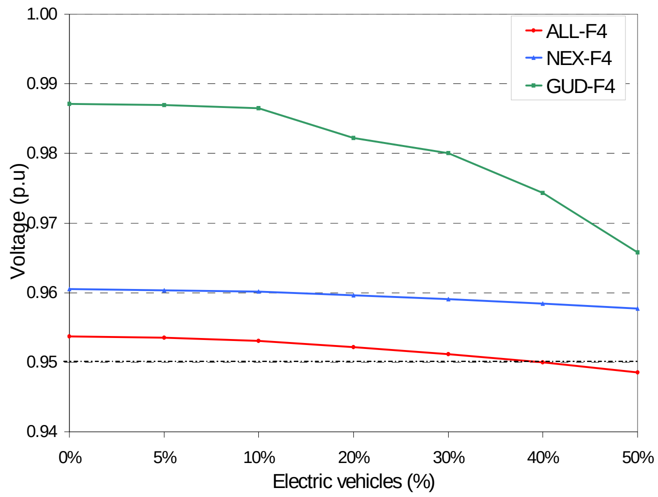

Fig. 8. Voltage profile of three critical feeders for controlled charging

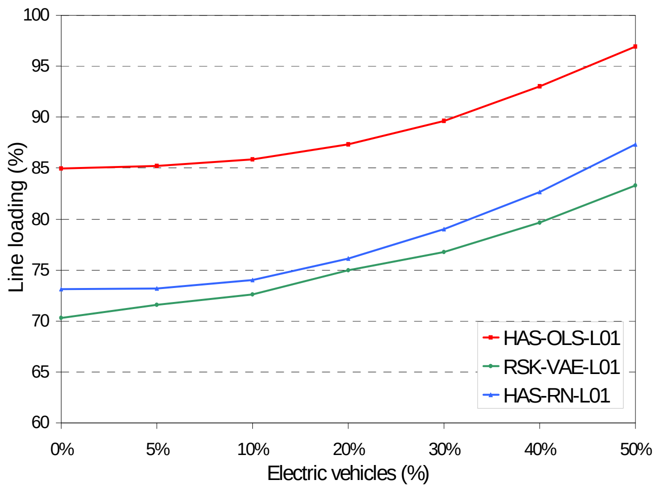

Fig. 10. Loading profile of three highly congested lines for controlled charging

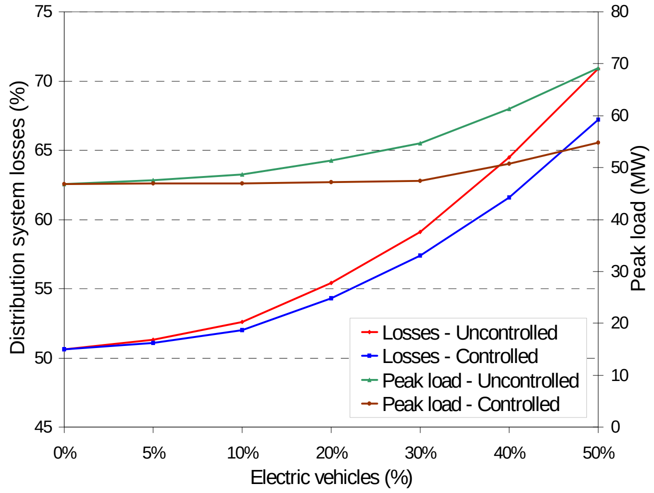

Fig. 11. System losses and peak demand for both uncontrolled and controlled charging modes

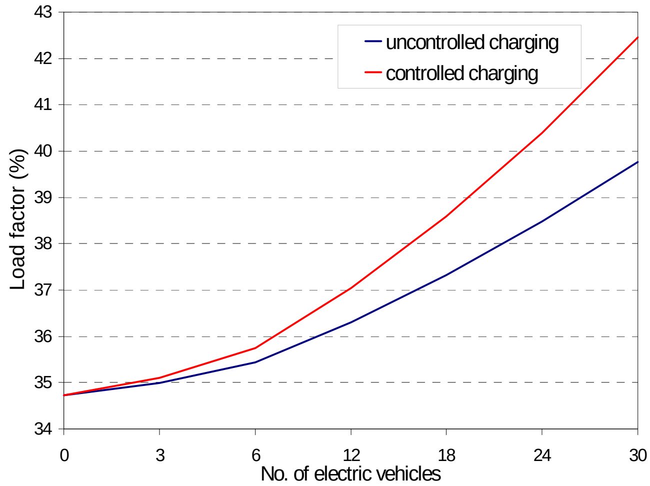

Fig. 12. Load factor of 250kVA LV distribution transformer

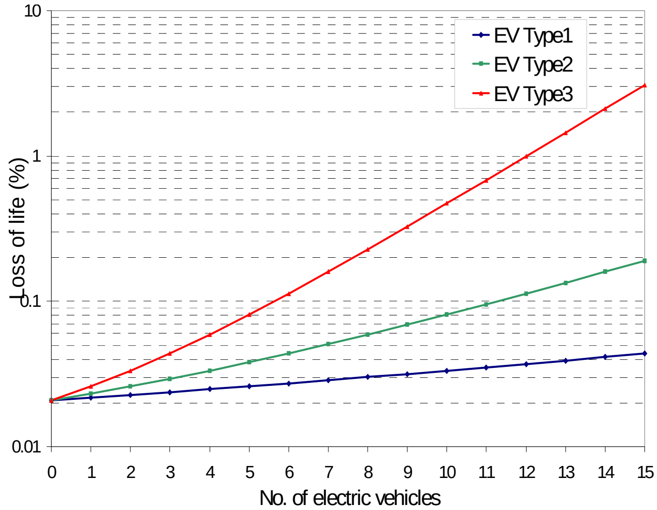

Fig. 13. Daily loss of life of a 250kVA LV distribution transformer from peak loading caused by EV charging

To analyse the daily load factor of a 250kVA LV distribution transformer, the charging profile of Fig. 2 is used. Fig. 12 depicts the load factor in percentage for both controlled and uncontrolled charging for an increasing number of electric vehicles. The controlled charging gives a better demand factor than the uncontrolled charging. The load factor is a measure of load uniformity and efficiency with which the electrical energy is used. For an improved load factor, the demand is held minimum relative to the overall kWh consumption providing a constant rate of electricity use. A better load factor will lower the unit cost of electricity.

The controlled charging mode yield better results than the uncontrolled loading of EVs for the operational parameters observed so far. The EV loads are more distributed across the low system demand periods for the controlled charging mode. This results in a better method of integrating EVs in a distribution network. The voltage drop in the network is more critical than the line loading for the same levels of EV integration as evident from the results. Thus, these network parameters analysed so far acts as limiting factors to higher levels of electric vehicle integration in a distribution network. The network utility has to increase the grid capacity in order to handle the larger peaks, higher losses and congestions resulting from the EV integration in the future. These bottlenecks in the distribution grid could be dealt with intelligent charging of EVs with the help of information technology and smart meters.

The aging of transformer with additional loads from electric vehicles charging during the peak hour is also calculated here (Fig. 13). The method for calculating the % aging of the transformer is based on the IEEE standard C57.91 [20], [21]. The percentage daily loss of insulation life of the 250kVA LV distribution transformer is evaluated by charging the number of vehicles of different types during the peak demand hour at 17:00hrs (Fig. 6). The peak load charging and a large presence of electric car loads connected online could cause overloading, lower operating efficiency and a higher percentage loss of insulation life of the transformer. To reduce these impacts, the demand response strategies could be implemented in households. The daily operation of the household loads like the electric cars, heaters, dryers, coolers etc. could be prioritised based on the consumer comfort and preferences. If the peak load set for a household is reached, the loads could be shed in order of their lowest priority. The transformer demand needs to be monitored continuously to send control signals to a household controller to perform such demand response and load control strategies.

V. Conclusions

This paper investigates the impacts of increasing electric vehicle (EV) loads in a typical Danish primary distribution network. Two modes of charging the electric vehicles are analysed, i) controlled and ii) uncontrolled for an increasing penetration of EVs in the range 0-50%. Only 10% of EV integration is feasible for the uncontrolled charging for the studied test distribution network. The controlled charging is more effective than the uncontrolled charging for integrating more electric vehicles on a moderate level. Electric vehicle (EV) penetration levels depend not only on the battery technologies, market mechanisms or policies but also on the safe operating limits of various electricity network parameters and the charging profile. The levels of EV penetration would not be the same for other distribution circuits. Impacts of EV integration in low voltage secondary distribution and weak networks may yield more conservative results. The utilities must undertake an impact assessment of the penetration levels and charging patterns of the EVs in the distribution grids to implement corrective actions.

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