ELECTRIC VEHICLES INTEGRATION WITHIN LOW VOLTAGE ELECTRICITY NETWORKS & POSSIBILITIES FOR DISTRIBUTION ENERGY LOSS REDUCTION

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ABSTRACT: With the prospect of an increasing number of electric vehicles (EVs) on the road, domestic charging will be the most obvious way to recharge the vehicles' batteries. However, this can have adverse impacts to low voltage (LV) distribution grids such as high current demand, increased 3-phase load unbalance and subsequently higher energy losses. In order to investigate to what extent existing infrastructures can support a gradual introduction of EVs at the residential level and what are the possibilities for distribution energy loss reduction, a complete model of a LV grid was developed. By simulating the interaction of EV users with electricity distribution networks, an insight was created into the energy saving potential but also into the possible barriers that might arise in the short term future. Simulation results show that if the charging process of the EVs' batteries is left uncontrolled, the introduction of EVs will have a negative impact on distribution systems in terms of overloaded circuits and increased energy loss. Nevertheless, the concept of electric transportation can provide the means to optimise the use of the distribution grid's capacity and to minimize energy loss. By controlling the charging process of the vehicles' batteries, the potential energy savings can be significant. Furthermore, EV technology can play an important role in releasing the distribution system's capacity and improving system reliability.

I. INTRODUCTION

The generation and use of energy sets a wide range of pressures on the environment and public health. The unsettling findings of recent scientific research, about the impact of anthropogenic activities to the environment, indicate that the great societal and technological challenge of this century will be to avert the worst effects of climate change, global pollution and overconsumption of non-renewable resources. In the E.U., energy related greenhouse gas emissions account for 80% of the total emissions, with the largest emitting sector being electricity and heat generation, followed by transport (EEA, 2008). Although transportation is an essential element of our society, it is also a significant source of toxic emissions. Conventional Internal Combustion Engine (ICE) vehicles have been in existence for over a century. With the increase of the world population, the demand for passenger cars has increased dramatically in the past years and this trend of increase will only intensify with the catching up of the developing countries (Chan C.C., 2007).

II. ELECTRIC VEHICLES IN SYNERGY WITH THE GRID

The automotive industry is aware of the need to develop new propulsion technologies with less environmental impact and one of the most important current developments in the industry is the electrification of the power-train. EVs are promoted for their environmental performances, especially when the electrical energy for charging purposes is provided from renewable energy conversions. Latest advances on battery technology and power electronics enhance significantly the appeal of EVs in the commercial car market and most of the major car manufacturers have already announced the launch of EVs in the market by 2012 (Handa K. et al., 2007), (Bernhart W. et al., 2009). EVs are expected to achieve a high share of passenger cars in the future and one of the characteristics than can accelerate this development is their ability to serve the electrical grid when parked (Kempton et al., 2004). Current developments in the energy sector indicate that major transformations of the power network will take place over the following decades. The future power systems will incorporate advanced load and generation control techniques, demand response mechanisms and high penetration of distributed generation and renewable energy sources. In this context, electrical energy storage systems will play an important role and its combination with the transportation sector may provide significant benefits for all parties involved.

A. Background

For utilities and grid operators, the delivery of power for charging the batteries of EVs provides substantial opportunities and challenges. Charging during off-peak hours can create new revenue streams by capitalizing on under-utilized equipment. On the contrary, the demand for charging power from end users can result in additional current demand burdens in the local or higher network level and bring equipment to failure. The Dutch distribution network operator Enexis B.V. is planning to introduce the Mobile Smart Grid (MSG) concept which entails an integrated system of hardware and software that allows the interaction between EVs, distribution grids and power generation units (MSG, 2009). Utility company Essent, together with Enexis B.V. have commissioned a fleet of electric powered VW Golf, which is used for exercising on the MSG concept. In the years 2010-2012, a number of pilot projects, aimed at bringing together communities, end users, corporations and government, will roll out in the Netherlands.

B. Problem definition

With the prospect of an increasing number of electric vehicles in the short term future, domestic charging will be the most obvious way to recharge the vehicles' batteries, due to lack of public charging infrastructures. However, this can have adverse impacts to LV grids such as additional current demand burdens and increased 3-phase load unbalance. Unbalance is a common occurrence in 3-phase distribution systems but it can be harmful to the operation of the network. Furthermore, measurements show that real power loss increases due to unbalanced loads (Ochoa et al., 2005). Load unbalance can be minimised by monitoring the loads between the three phases and adjusting the charging power rate at each phase. This will result in increased utilisation of grid assets, reduced 3-phase unbalance and consequently reduced electrical energy losses. System losses represent a considerable cost for network operators and its evaluation and reduction has been recognized as of interest by researchers.

C. Case study

The scope of this work is to investigate to what extent existing infrastructures can support the gradual introduction of EVs at the residential level in the short term future. As a case study was taken a typical medium size LV distribution grid operated by Enexis B.V. in the Netherlands. The distribution transformer, with a nominal capacity of 400kVA, was connected to a number of 290 households. By utilising actual power measurements from smart metering devices and simulating the interaction of consumers and EV technology with the electricity distribution network, the aim is to outline the opportunities but also the possible challenges that might arise to LV grids after the introduction of EVs. By calculating the annual energy losses and running scenarios for 'uncontrolled' and 'controlled' charging of the EVs' batteries, the maximum energy saving potentials can be quantified for the scenario where EVs are coupled with power systems through advanced power management systems.

D. Scenarios and projections

Four different scenarios were defined in order to investigate the power loading of the LV distribution grid and the energy losses after the introduction of electric vehicles. In these scenarios, it was assumed that 25%, 50%, 75% and 100% of the total number of households in the investigated area possess an electric vehicle. The four scenarios utilised in the model are presented below:

- ***The baseline scenario*** *(Scenario 1)* represents the case prior to the introduction of electric vehicles and will be utilised as reference in order to calculate the energy saving potentials after the mass market introduction of electric vehicles. Since only residential loads are considered in this scenario, the actual grid losses are calculated.
- ***The uncontrolled charging scenario*** *(Scenario 2)*, assumes that EV users plug-in the chargers to their vehicles' batteries when they return at home. The charging process starts with no delay and no control is applied.
- ***The optimised charging towards symmetric load scenario*** *(Scenario 3)*, represents the equalised case where all the three phases are perfectly balanced in terms of active power loading, while the reactive power demand from the households is the same as in the baseline scenario.
- ***The optimised charging with load levelling scenario*** *(Scenario 4)*, represents the case where the energy content that fulfils the energy needs of both household loads and EVs is evenly distributed between the 3-phases of the system and also at the same power level during the day (load levelling). The power load is assumed ideally levelled, regardless the availability of plugged-in electric vehicles as a function of time in the investigated area.

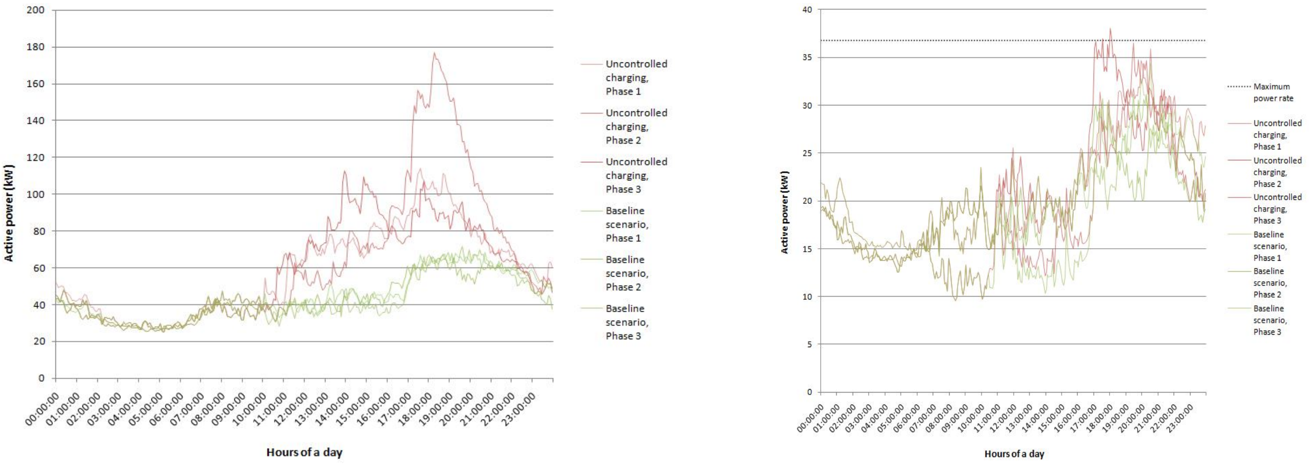
III. MODELLING THE SYSTEM

The model refers to a representation of the system at some point in the future, after the introduction of EVs. Nine user groups were defined, based on different mobility motives, and the population of simulated EV users was allocated among these groups. Time schedules were constructed for all simulated drivers, based on data from the mobility research of the Netherlands (MON, 2008), and assuming that EV users will demand the same level of driving convenience compared to conventional ICE vehicles. These time schedules show how the amount of EVs available for charging varies as a function of space and time. Time schedules and charging energy demand requirements were utilised in the model of the charging process and the output was weekly charging power profiles for all simulated drivers. The charging process was modelled for single-phase charging, according to the CC/CV principle and assuming a unity power factor. The charging connection points were allocated evenly between the three phases and among the distribution feeders and branches, in relation with the connected number of households. The maximum AC charging current was assumed equal to 15 A_{rms}. The VW Golf EV of Enexis, with a battery capacity of 37 kWh, was used as reference. The vehicle's average energy use of 174 Wh/km was calculated based on measurements from an on-board energy meter. The load-flow model of the unbalanced distribution network was developed in Gaia software (P2P, 2009), and included actual time series data of average power demand figures with five minutes intervals. The integrated model was driven by superimposing charging power profiles to actual measurements from residential loads. The calculations with the model resulted annual energy loss figures and load profiles for the investigated grid for all different scenarios and projections. These results are presented and discussed in the following section.

IV. RESULTS

A. Load profiles for uncontrolled charging

In figure 1a, the transformer's daily active power loading for each phase has been plotted, for the baseline scenario (green coloration lines) and the scenario of uncontrolled charging (red coloration lines) assuming that each household possesses an EV. What can be seen is that the peak demand for charging power coincides with the peak power demand from households' loads. Most of the power for charging purposes is provided before the conclusion of the day, and this is mainly due to the relative short distances driven and the related low demand for energy, as well as due to the fact that most of the users initiate the charging process when they return at home. In addition, figure 1a, illustrates how the three phase load unbalance increases, compared to the baseline scenario, due to different time schedules and requirements of EV users. The load unbalance occurs mainly during the second half of the day because most of the drivers return at home after 18:00 hours and this is the time period that most of the demand for charging power occurs.



(a) *(b)*

Figure 1. Daily load profiles; a) Transformer's 3-phase active power loading for the scenario of uncontrolled charging and assuming that each household possesses an electric vehicle, b) Distribution feeder's active power loading for the scenario of uncontrolled charging and assuming that 25% of the households possess an electric vehicle.

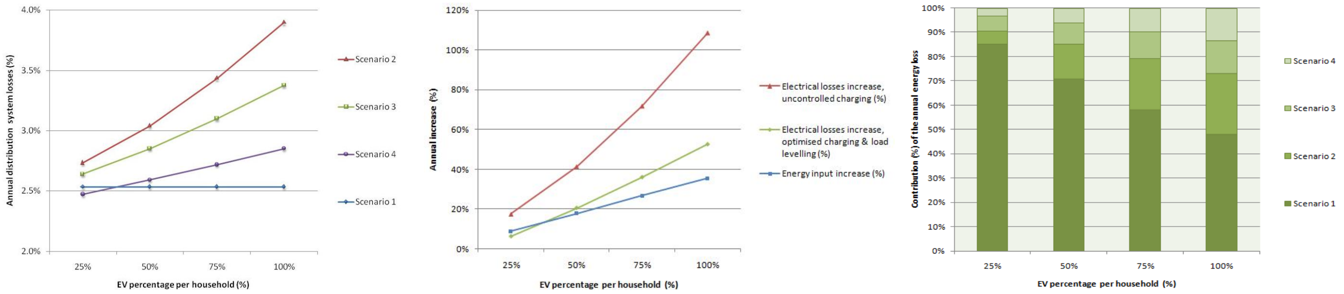
Moving one step further, it is also interesting to investigate if the feeders are able to transfer the additional power for charging purposes. For the case of one of the system's most loaded feeders (connected to a number of 123 households), the maximum allowable power that can be drawn from each phase is approximately 36.8 kW, limited by the feeder's safety fuses. In figure 1b, the daily active power load for each phase of the investigated feeder has been plotted for the baseline scenario (green coloration lines) and the scenario of uncontrolled charging (red coloration lines), assuming that one every four households possess an EV. The dashed line represents the maximum allowable power rate per phase. As it can be seen, even for a relative small portion (25%) of the total households possessing an EV, the load of one phase of the feeder exceeds the maximum allowable rate of 36.8 kW, a few minutes after 18:00 hours. In a real system, this situation would probably result the electrical fuse to blow and would lead to a subsequent outage, affecting at least all the customers connected to this phase (Provoost F., 2009). Even though there is a significant amount of available capacity for transferring electrical energy through this feeder, it is the combined and coincided demand for power from end-users during peak demand hours that create this problem. If no charging control is applied, the feeder will have to be reinforced in order to cope with the extra load during peak demand hours.

B. Electrical Energy Loss

Annual electrical energy losses in the investigated grid were calculated as a percentage of the total energy input for each scenario. Figure 2a illustrates how the annual distribution energy loss increases with an increasing number of EVs, and for each scenario. The index 'EV percentage per household' refers to the percentage of households that possesses an EV. The number of households' connections in the investigated distribution grid is 290. For a 25% share of the households possessing an EV, this results of approximately 74 EVs owned by people living in the related area.

In figure 2b, the annual increase of electrical energy input and loss is illustrated for the scenario of uncontrolled charging (Scenario 2) and optimised charging with load levelling (Scenario 4), as a percentage of the annual energy input and loss in the baseline scenario. Figure 2b, illustrates that for a linear increase of the system's energy input, due to a gradual introduction of EVs, system loss increases disproportionally. For the case where each household possesses an EV, the energy loss is more than double for the scenario of uncontrolled charging, while the increase in the energy input accounts for only 35.5%. Assuming an optimised charging technique (Scenario 4), the annual increase in energy loss would be limited to 52%. The disproportional increase between the annual energy input and loss, during the scenario of uncontrolled charging, is mainly due to the fact that the demand for charging power coincides with the peak power demand hours of the day and contributes to increased 3-phase load unbalance.

In figure 2c, the normalised contribution (%) of each scenario to the total energy loss and potential loss reduction for the investigated distribution grid is illustrated. The contribution of each scenario is presented as a percentage of the total energy loss. As it can be seen, the potential energy savings by balancing the load between the three phases (Scenario 3) are close to the potential savings by applying load levelling (Scenario 4). A combination of both techniques can provide the means for substantial energy loss reduction. On average, for a number of 25%, 50%, 75% and 100% of the total households possessing an EV, the potential loss reduction in the investigated grid, accounts for 10%, 15%, 21% and 27% respectively, compared to the scenario of uncontrolled charging.



(a) *(b)* *(c)*

Figure 2. Energy loss in the investigated grid; a) Annual distribution network energy loss (%) for all different scenarios, b) Average annual increase of electrical energy input and loss for the scenarios of uncontrolled and optimised charging with load levelling, c) Contribution (%) of each scenario to the total energy loss and potential loss reduction

V. CONCLUSIONS

In order to investigate to what extent existing infrastructures can support a gradual market penetration of electric vehicles and the possibilities for distribution energy loss reduction, a complete model of a low voltage grid was developed. By simulating the interaction of electric vehicles' users with electricity distribution networks and looking into different scenarios, an insight was created into the energy saving potentials but also the possible barriers that might arise in the short term future at the residential level. Simulation results show that if the charging process of the vehicles' batteries is left uncontrolled and unmonitored, then the gradual introduction of electric vehicles will have a negative impact on electricity distribution systems in terms of overloaded circuits and increased energy loss. This finding indicates the need for developing charging control mechanisms and business models prior to the introduction of electric vehicles. Distribution networks are relatively extended and electric vehicle technology can play an important role in releasing the system's capacity and improving system reliability. An effective control mechanism would result in a higher utilisation ratio of assets while preventing feeders and transformers from being overloaded. Furthermore, by controlling the charging process of the vehicles' batteries, the potential energy savings can be significant. However, not all losses are controllable and not every loss reduction is economically justifiable. In reality there is a clear trade off between investment costs and network losses. In many European countries, energy regulation incentivizes network operators to prevent losses from increasing, but not to reduce them (ERGEG, 2008). Besides this, in order to achieve the objectives of controlling the process and charging during off-peak hours, customers' needs and preferences should be taken into account.

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