IMPACT OF ELECTRIC AND PLUG-IN HYBRID VEHICLES ON GRID INFRASTRUCTURE - RESULTS FROM THE MERGE PROJECT


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SUMMARY

This paper highlights findings of the European Commission funded project called MERGE (Mobile Energy Resources in Grids of Electricity). MERGE is a collaborative research project that includes utilities, regulators, commercial organisations and universities with interests in the power generation, automotive, electronic commerce and hybrid and electric vehicle sectors across the entire European Union (EU). This major two-year research initiative began in January 2010. The MERGE project mission is to evaluate the impacts that electric vehicles (EV) will have on the European Union (EU) electric power systems with regards to planning, operation and market functioning. The focus is placed on EV and SmartGrid/MicroGrid simultaneous deployment, together with renewable energy increase, leading to CO2 emission reduction through the identification of enabling technologies and advanced control approaches.

In this paper indicative results from the impact of the additional EV load will have in the daily and yearly system load diagrams and in the operation of the transmission and distribution networks of five European countries (Greece, UK, Spain, Portugal, and Germany) in 2020 are presented. General conclusions are drawn.

KEYWORDS

Electric Vehicles, Transmission and Distribution Networks, Power System steady state analysis

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1. INTRODUCTION

Substituting conventional vehicles with vehicles powered wholly or partially by batteries would create a noteworthy contribution for the urban air quality enhancement, which can be further promoted by exploring the dispersed storage provided by these vehicles to, simultaneously, increase wind generation deployment and reduce fossil fuels needs. Nevertheless, the energy requirements that fulfill EV charging needs will increase electricity demand and provoke several changes to the load diagrams, which will promote substantial changes in the energy cost, generation schedules and, consequently, in the volume of CO2 emissions of the European electric power systems.

The profile of the energy requirements that fulfill EV needs is highly dependent on the traffic pattern of EV owners, namely travelling distances, time of plug-in, available charging period etc. A detailed analysis on drivers’ traffic pattern for different European countries (Greece, UK, Spain, Portugal, and Germany) can be found in [1]. Based on this analysis, a detailed study of the EV charging demand is presented in Section 2 considering different charging scenarios (dumb, dual-tariff and smart). Three EV penetration scenarios (realistic, aggressive and very aggressive) have been defined in [2], for the five European countries in order to examine the impact of the additional EV load in the daily and yearly system load diagrams. The time horizon of these studies is the 2020.

Currently, in most European countries the share of EVs is limited and thus the additional EV charging demand is negligible. However, a future mass EV deployment may result in a significant increase of the system demand. This can raise challenging issues for the network operators concerning the adequacy of the grid capacity. Thus, further studies need to be performed aiming to evaluate the impacts that large deployment of EVs will provoke in the distribution networks, namely Low Voltage (LV) and Medium Voltage (MV) grids, taking into account technical restrictions like voltage limits, branches’ congestion levels and losses evaluation. In Sections 3 and 4, the Greek and Spanish distribution networks [3] are analysed in steady state using the analysis tools developed in [4]. One of the innovative tools applied in MERGE studies is described in Section 5.

The conclusions derived from the extended analysis made within the MERGE project are presented in Section 6 along with recommendations concerning the efficiency of the studied charging strategies for the scalable stages of EV deployment.

2 IMPACT OF EV CHARGING ON THE SYSTEM DEMAND DIAGRAMS

The integration of EVs into power systems will be confronted by the system operator as an additional system demand especially at the initial stage of EV deployment. The amount of this additional EV demand depends mainly on the EV penetration level and their mobility. The scope of this section is to identify the EV charging energy requirements and their impact on the daily and yearly system demand diagram considering the stochastic EV owner’s driving profile. For this purpose, a probabilistic simulation tool has been developed which enables the energy analysis of the EV charging demand by defining a set of deterministic (EV penetration level, EV classification, charging strategy, charging rates) and probabilistic parameters (plug-in time, travelled distance, battery capacity). Five different European countries, namely Greece, Germany UK, Portugal and Spain, have been studied considering the respective traffic pattern and EV penetration level of each country.

2.1 SIMULATION TOOL
Fig. 1 presents the simulation tool which models the additional EV energy requirements considering all the parameters and variables defining an EV charging. Different charging strategies (dumb, multi-tariff, and smart) can be simulated and the output results will be utilised for assessing their impact from EV present in the short term horizon. The inputs of this model are described below:

**EV penetration Scenarios**

Three sales scenarios were identified [1]:

- **Scenario 1**: The most likely to occur in reality
- **Scenario 2**: More optimistic than is expected in reality
- **Scenario 3**: A very aggressive EV uptake scenario

**Classification of EV**

EVs can be classified into two general categories depending on the type of engine:

- the plug-in hybrid EV (PHEV) and
- the pure battery EV (BEV)

BEV can be further subdivided into several categories according to their technical characteristics as:

- **7e**: small city purpose vehicles
- **M1**: 4-seater passenger vehicles
- **N1**: carriage of goods with a maximum laden mass of less than 3,500 kg
- **N2**: maximum laden mass of 3,500 kg to 12,000 kg for commercial purposes

**Daily Travelling distance**

This parameter describes the daily distance covered by an EV between two successive charging cycles and thus the corresponding amount of charging energy. An average energy consumption over travelled distance (kWh/km) can be implemented for the purpose of EV analysis.

**Availability of charging**

- **Charging after last trip (home charging)**: Since the electrification of transportation remains at an initial stage, the number of charging points will be limited. Thus, most of the EV owner will not have the ability to charge their EV anywhere but mainly in their home private charging post.

- **Charging when a (public or private) charging point is available**: In this scenario, an EV owner has also the ability to charge his EV away from home, for example in a...
workplace. This requires a mass installation of charging points in various private or public areas. Since it is not possible to define the exact number of EV that will be charged at home (workplace) different charging patterns should be adopted, depending on the percentage of home/work charging.

- **Charging when the battery state of charge is lower than a desired level**: The average travelling distance of an EV is more than 100km according to the current technologies. When the daily travelling distance is limited, for example in urban areas which may be less than 30km, then there is a possibility that the owner will not plug in his EV daily but only when he estimates that it is necessary. In this scenario, it is assumed that an EV owner will charge his EV only when the battery state of charge is lower than a threshold, which is 40%.

**Charging Station Technologies**

It determines the maximum allowable power exchange between EV and power grid which depends on the line power capacity. The power level of charging affects also the duration of the charging cycle. At the end of each charging cycle the battery must be fully charged (SOC=100%). There are different charging levels (normal, fast and dc). The selection of the charging level for a specific EV is probabilistic and depends on its type.

The losses when converting the AC grid power to DC for charging the EV batteries and vice versa due to the operation of power electronic equipments are considered equal to 10-15% of total energy demand.

**Charging Strategy**

Different charging schemes should be analysed in order to reach safe conclusions when assessing the impacts of EV penetration in power systems. These are *Erreur ! Source du renvoi introuvable.*

- **Dumb Charging**: The plug and play connection of Electric Vehicles into the grid. This happens after last trip of each day or when a charging point is available and there is no need for mobility

- **Multiple Tariff Charging**: It's a market way of controlling energy demand. There are different tariffs in order to promote energy demand in off-peak hours.

- **Smart Charging**: In the present analysis, a “fill valley” concept has been adopted as smart charging scenario. EV charging load should be delivered in off-peak hours where demand is limited due to low human activities. Moreover, the EV mobility in these off-peak hours is limited and this serves their charging management.

The simulation model of Fig.1 has been implemented for different European countries. Indicative results are presented in Fig. 2 for Germany. This analysis is based on the forecast scenarios 2020 of European Union [5] indicating a total increase of 7.3% on base load. Fig. 2(a) presents the system peak load increase considering “dumb charging” and “home charging”. The daily system peak demand increases analogously to the EV penetration scenarios (0.73%, 1.46% and 3.03%). The system demand increase during high-load hours due to EV dumb charging is also illustrated in Fig. 2(b) where the modified German annual system load curve is presented.
German energy market is characterized by many energy providers who follow different low-pricing periods for their customers. For simulation purposes, the low energy pricing period is considered between 22:00 and 06:00 which is adopted by the majority of German providers. Dual-tariff charging strategy seems a natural step in the first phases of EV uptake where the EV penetration level is low (Fig. 2(c)). As the EV share increases, the impact on the system demand becomes more intense. In the aggressive scenario, the synchronised EV charging results in a new peak demand which is larger than the system’s daily one. Smart charging strategy presented in Fig. 2(d) reduces approximately four times the peak EV demand compared to that of dumb charging and allocates it smoothly during night valley-hours.

3. TRANSMISSION NETWORKS

The hourly based steady state analysis which has been performed to assess the impact that large scale EV integration will provoke in the EU transmission networks is presented in Fig. 3. The maximum penetration level of intermittent power sources (such as wind power) is limited by the technical minimum of the units. In the unit commitment module, a maintenance schedule for units is integrated based on the current maintenance practice and is modified to include future installations. The required spinning reserves are determined so that the following constraints are valid: i) greater than the 15% of total load, ii) greater than wind power production and iii) greater than the maximum generation of compatible units.
The steady state analysis toolbox is utilized to investigate the grid impact of high EV penetration level in the Hellenic Transmission System considering different charging strategies. The additional EV load is determined by the simulation tool of Fig. 1 considering the stochastic properties of EV mobility for this country. The results recorded through this analysis include voltage levels in high voltage buses, power flows in the transmission lines of the system as well as power losses of the transmission system.

In the worst case EV charging scenario of dumb charging, the system peak load increase due to EV demand which is approximately 2%. Such load increase does not affect significantly the voltage profile of the studied transmission network. The upper and lower bounds of bus voltages are not violated independently of the adopted charging strategy. Fig. 4 presents the power losses of the studied transmission network for the three charging strategies. The differences among the studied strategies are not considerable; however it can be concluded that the power losses are minimized in smart charging strategy.

Fig. illustrates a histogram of increase/decrease of maximum loading of lines under the scenario of high EV penetration with dumb charging and smart charging, compared to the non EV scenario. In case of dumb charging, the increase of the maximum loading of the transmission line is less than 10 MW for the vast majority of the transmission lines. There is a small number of lines with a slight decrease in their maximum loading when dumb charging policy is adopted. These lines belong mainly to the area of the power system with a generation surplus, which is reduced by EV charging. On the contrary, in case of smart charging, the maximum increase of the line loading is 45.5 MW which is significantly lower compared to the 748 MW in the dumb charging scenario. This happens because smart charging takes place during the base load hours, thus, there is no need for additional imported
power. In smart charging scenario, the increase of the maximum loading of the transmission line is less than 2 MW for the vast majority of the transmission lines.

![Dumb Charging](image1) ![Smart Charging](image2)

Fig. 5 Histogram of Increase/decrease of Maximum Loading of Lines in MW
(Comparison with the non EV Scenario)

4. DISTRIBUTION NETWORKS

Since EVs are expected to be plugged-in in the distribution systems, namely in Low Voltage (LV) and Medium Voltage (MV) grids, these type of networks are the ones where the EV charging impacts will be strongly noticed. Congestion problems are expected in already heavily loaded grids, while in radial networks voltage limits violations are likely to appear more frequently. The changes in the energy losses is also a matter of great concern, since the increase in the energy demand owed to EV charging will probably make their value rise considerably. Nevertheless, the referred impacts will always depend on the EV penetration level and of the EV charging strategies adopted.

In order to evaluate the grid impact of high EV deployment, several EU MV networks have been analysed within the MERGE project. The parameters evaluated in this analysis are:

- **Branches thermal limits**: It is required that loading of lines and transformers of the distribution line are below their thermal limits.
- **Maximum Voltage limitation**: Voltages in all buses of the distribution line must be below the level of 110% of its nominal value.
- **Minimum Voltage limitation**: Voltages in all buses of the distribution line must not be below the minimum level of 90% its nominal value.
- **Mean Voltage**: The mean value of voltage during the simulated period of one year must stay within the limits [0.95 1.05] of the nominal value.
- **Voltage Deviation**: in all buses must be below 3%. Voltage deviation is defined in the following equation (1)

\[
V_{dev} = 100 \cdot \frac{V_{\text{max}} - V_{\text{min}}}{2 \cdot V_{\text{nom}}} \%
\]

Indicatively, the results obtained for a set of real Spanish MV networks are included, covering a wide area where rural and urban environments were enclosed, as well as different types of consumers: industrial, commercial and residential. The tool used is the PSS/E software adapted to incorporate several EV models, allowing accurately estimate the EV charging impacts in the studied networks, along a week period, when different charging strategies are adopted. Moreover, this tool also allows identifying the maximum number of
EV that can be safely integrated in a given network under a given charging strategy. Voltage profiles, lines loading, energy losses variations, as well as changes in load diagrams and the additional requirements to fulfill EV needs have been object of analysis in the simulations performed.

In all case studies, it was assumed the existence of one fast charging station per network. Fast charging stations have a considerable impact in branches’ congestion levels and in the voltage profiles. For this reason, the network bus to which the fast charging station was assumed to be connected, in each case study, was selected among the network buses with the highest voltage values.

Fig. 6 depicts the impact of high EV integration level in the load profile of the studied urban network for one week. The different charging strategies have also been considered. In the scenario without EV, this network has a peak load of 128.5 MW, which is incremented to 135.6 MW using the dumb charging, to 133.9 MW using dual-tariff scheme and to 132.1 MW using the smart charging. The latter can be considered an outstanding achievement, since the peak load only increased 3.6 MW with an EV integration of 57%, representing ca. 12047 EVs. It is interesting to notice that the EV charging, for dumb and dual-tariff charging, provokes changes in the hour at which the networks’ peak load occurs.

The maximum allowable EV integration percentages for the different distribution networks are depicted in Fig. . The percentages are relative to the total number of conventional vehicles enclosed in the geographical area covered by this network, which was 21135, 109641 21749, 34155 vehicles for urban, rural, residential and touristic networks respectively. Branches’ overloading was the factor that limited the EV integration in all the charging approaches analysed. In the particular cases of the dumb charging and multiple tariffs, the overloaded branches were located in the same feeder where the fast charging station was assumed to be installed. Hence, the large amount of power absorbed by the fast charging station was probably the main factor that contributed for the branches overloading.
Fig. 7 Maximum EV integration percentage in different MV distribution networks

Fig. 8 depicts for each of the networks analysed, the voltage values obtained in the worst bus of the respective network, when the maximum allowable EV integration is reached. The values presented are referred to the hour at which the worst voltage conditions in the networks are verified, which can be different from the hour of the peak load. As it can be observed, with the exception of the Rural network, the EV extra demand provokes almost insignificant decreases in the voltage values with relation to the initial value (with no EV present in the grids). It is important to recall that in MV networks the R/X ratio is low, contrarily to LV networks, what makes the impacts of the active power consumed by EV less relevant regarding voltage drops. In addition, as the majority of the MV networks studied are from urban areas, they are more prone to congestion problems than under voltage issues. Although the voltage values regarding the use of different charging strategies are presented in the same figure, for each network, it should be stressed that they are referred to different scenarios of EV integration. Thus, the only possible fact that can be concluded from the figures presented is that the smart charging provides better results, as it is the charging strategy that allows safely integrating a larger number of EV in all the case studies evaluated.
Differently to what was verified for the voltage profiles, branches’ congestion levels were the most critical aspect in the generality of studied networks, with especially emphasis in the networks with urban characteristics. Looking at Fig. 9, where it is depicted the rating percentage of the most congested branch during the hour at which the worst branch overloading is verified, the effects of the EV charging can be observed for the three charging strategies. The maximum rating limit allowed was assumed to be 100%. The results show that the branches’ load levels considerably worsen with the growth of the number of EVs, in all the networks. In fact, the branch loading deteriorates further EV integration in the Urban, Residential and Touristic networks. The Rural network suffers from both low voltage problems and overloading issues.

Smart charging outperforms compared to other charging strategies enabling safely integration of larger fleet of EVs. Assuming a fixed EV deployment, the worst rating percentage obtained in smart charging would be significantly lower than that of dumb and the dual-tariff charging. Dumb charging strategy accounts for the worst results in the Urban and Rural networks. The worst results of the dual-tariff obtained in the Residential and Touristic networks. The location of the fast charging station is, in fact, a very important variable in what regards branches’ overloading, as the large amount of power absorbed by these facilities might overload the branches upstream. For this reason, it is advisable that the installation of a fast charging station should always be preceded by a detailed impact study.

Fig. presents the weekly energy losses of the networks analysed. Each chart presents the absolute value of the losses (bars), referred to the left vertical axis, and their value relative to the overall energy consumption (circles), referred to the right vertical axis. As it is expected, the supply of the additional EV demand increases the system losses in all charging scenarios. However, smart charging compared to the other scenarios yields some benefits in the majority of the cases studied, namely in the Urban and Residential networks. The adoption of dual tariff strategy could also lead to some positive results compared to dumb charging (Urban, Residential and Touristic area). Exception is the Rural network which can be justified by the fact that the valley hours, occurring in the late afternoon, do not coincide with the period when the majority of dual-tariff adherents charge their EVs. Generally, the charging method
that yields the worst results is the dumb charging ensuing the highest peak loads and the higher increases in the energy losses.
5. Spatial-Temporal Model for EV Impact Analysis

A Spatial-Temporal model (STM) was developed to address the correlation between population movement and the EV charging load, in order to facilitate the impact analysis of the large scale deployment of plug-in EVs on an urban electric power system.

The main components of the STM are:

- **EV characteristics**: The charging load drawn by an EV depends on battery type, battery capacity, maximum travel range, travel distance within a day and the time charging starts. The EV database created by the MERGE project provides such information obtained for all EVs intended for the European market. Based on the deterministic information provided in that database, appropriate probability density functions were identified and used by a Monte Carlo simulation method to estimate the EV charging load.

- **Origin-Destination (OD) analysis**: OD analysis [6] was used in the STM to model the EV transportation throughout a day to reduce the uncertainties caused by EV mobility.

- **Monte Carlo simulation**: Monte Carlo simulation was used as the core algorithm of the STM. It used repeated random sampling to estimation the EV charging load based on the EV characteristics and the OD analysis; It was also used to analyse the EV impact on electric power systems in a statistical way.

- **Sequential power flow**: Sequential power flow was used to analyse the performance of electric power systems with plug-in EVs for a period of time.

5.1 Case Study

The EHV6 model developed in the UK Generic Distribution Systems [7] was used to investigate the impact of EVs on UK urban networks. The UK peak electricity demand was 68 GW and the total amount of cars in the UK was 28.4 million (2010 data) [8]. In the EHV6 system, the peak load is 300 MW [7], which is 0.44% of the UK peak electricity demand. In the case study, the total vehicle number was also assumed to be 0.44% of the UK national data, i.e. there are 125000 cars considered. Three EV penetrations were investigated: 0%, 25% and 50% of the total vehicles replaced by EVs. Results from dumb charging and smart charging are compared. Test results are shown in Figure 11.

(a) Total power demand

(b) Voltage failure rate with 25% EV penetration and “dumb” charging
Figure 11 (a) shows that the STM provided a much lower system peak demand compared with a “worst case” situation where all EVs were connected to the network at the same time. Figure 11 (b) shows the statistical information of the nodal voltage failure, (c) and (d) shows the nodal voltage magnitude with two different charging strategies. All three figures provided the spatial temporal distribution information which can be used to enhance the system in order to accommodate more EVs.

Thus, the STM is able to address the correlation between population movement and the charging load of plug-in EV, therefore to reduce the uncertainties caused by the EV mobility. The STM provides both average and probabilistic information of a number of system indexes, such as system demand, nodal voltage, branch loading and power losses. It is able to facilitate the identification of the most critical network components that are subjected to upgrade and therefore facilitates network reinforcement.

6. CONCLUSIONS

The steady state analysis of the transmission systems has shown they will not confront significant impacts due to the additional EV load even in the case of highest Ev deployment. More specifically, the following general conclusions can be drawn for the EU transmission networks:

a. Dumb Charging leads to an increase in loading of transmission lines. In case there is not enough loading margin, EV penetration in large scale may require the reinforcement of certain components of the transmission system.

b. Smart Charging does not lead to overloading of the transmission lines of the system.

c. Voltage constraints are satisfied for all the buses of the transmission system, regardless the type of charging and even for high EV penetration.

d. Power System losses are minimized in smart charging and maximized in dumb charging.

The distribution system analysis indicated that the operation of these networks is affected more that the transmission networks. The magnitude of the EV impacts is influenced by several factors namely the EV integration level, the EV owners’ behaviour, mobility patterns, the networks’ load profiles and technical characteristics, the number and location of fast charging stations in the grid and the EV charging modes. These factors have been carefully analysed being possible to reach the following conclusions for the EU distribution networks:
a. The analysed distribution systems can handle up to a certain number of EVs without the need of premature reinforcements. However, it was verified that the maximum number of EV that can be safely integrated in the networks depends on the charging schemes adopted by the EV owners. From the three charging strategies analysed, smart charging enables the highest EV deployment without violating the networks’ technical restrictions.

b. Dumb charging revealed to be the most problematic charging strategy. Allowing EV owners to freely charge their EVs will provoke a considerable increase in the system peak load, with negative consequences regarding voltage profiles, branches overloading, and energy losses. This happens because the EV home arrival and plug-in for charging are synchronised with the periods when the households’ consumption is higher.

c. Dual tariff can be a good charging strategy for some networks, provided that pronounced valley periods exist in the daily load diagrams and that they occur more or less during the same daily periods. However, it should be underlined that the sharp increase of the EV load verified in the beginning of the low energy price period, due to simultaneous charging of a large number of dual-tariff adherents, might provoke several technical problems in some networks, namely those operating in more strained conditions. Dual-tariff can be an efficient strategy in the initial stage of EV uptake.

d. Smart charging enables a better exploitation of the resources available at each moment, preventing the occurrence of voltage problems and branches’ overloading. The smart charging also proved to be very effective in reducing the energy losses. Nevertheless, smart charging concept requires advanced control architectures and smart metering infrastructures.

e. Urban networks have short lines and are more prone to face branch/transformer overloading problems faster than voltage drop issues. Contrary to urban networks, rural networks have usually long radial lines, which provoke considerable voltage drops. Thus, low voltage problems are expected in this type of networks, namely in the buses farthest from the feeding points.

f. The location of the fast charging stations should be carefully analysed, as they might provoke severe voltage violations or branches overloading, due to the large amount of power that they consume (ca. 40 kW). In fact, the studies performed have demonstrated that the congestion problems identified in two of the studied networks, namely in Urban Old and Touristic Area networks, were likely provoked by the power consumed in fast charging stations.

BIBLIOGRAPHY


