EVALUATION OF THE IMPACT OF PLUG-IN ELECTRIC VEHICLES IN GREEK DISTRIBUTION NETWORK

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ABSTRACT

In this paper the impacts of a large deployment of electric vehicles (EVs) on selected distribution grids of the Hellenic Distribution Network are assessed. Mainly technical restrictions are taken into account, such as voltage limits, branches' congestion levels or losses' evaluation. EVs are considered as simple loads that charge from the grid. The analysis takes into account driving profiles of EV owners, type of vehicle (battery capacity, energy consumption), travelling distance, road conditions etc and approximates the hourly allocation of the energy requirements under various EV charging strategies. A steady state analysis toolbox is used to estimate the critical number of EVs that can be integrated in a distribution line.

INTRODUCTION

The future massive integration of Electric Vehicles (EV) in electricity grids is very likely to pose several challenges to power systems' operation and planning. The rapid development in the area of charging infrastructure technologies (i.e. fast charging, inductive charging etc) and standardization contributed to the increase of the electrified vehicle market share. The additional charging power requirements of EVs are expected to significantly modify the network demand profile affecting the operation of the whole electricity network.

Looking at EV as a simple load, it represents a large amount of consumed power, which can easily approach half the power consumed in a typical domestic household at peak load. Thus, major congestion problems may appear in already heavily loaded grids and voltage profile problems mainly in radial networks, particularly if the peak load periods coincide with EV charging periods, as presented in [1]. Hence, if no load management strategies are defined, significant technical problems will occur and their drawbacks might even be larger than the economic/environmental benefits arising from electric vehicles usage. These management strategies can be adopted in two ways: a) by developing a dynamic price signal approach such that EVs will charge predominantly during low energy price moments or b) by developing a technical management system such that charging can be distributed during valley hour periods and at times when there is large renewable power generation.

The impact of plug-in vehicles in distributed networks has been studied in several papers [2] - [7]. This paper performs a steady state analysis of distribution lines in the Hellenic Distribution Network with different levels of EVs penetration in order to find the critical number of EVs that can be connected to a distribution line, i.e. the maximum number of EVs that can be connected to a distribution line, without the violation of certain constraints. The above studies are performed for a rural and an urban distribution line. The energy amount that fulfills EV charging needs is estimated by considering vehicle and charging specifications (EV class, average EV class consumption and charging power level), as well as EV owner's behavior (time of plug-in and departure, daily travel distances). Different charging strategies are investigated and a comparison is made between them.

FRAMEWORK OF THE PROPOSED METHODOLOGY

Fig. 1 illustrates the framework of the proposed methodology. It comprises 3 main parts, the first is the estimation of energy requirements of EVs, the second is the formulation of a load demand time series , depending on the charging strategy adopted, while the third is the steady state analysis of the grid for an annual period on an hourly basis.

The EV fleet under study is first classified into several categories based on the European Commissions' official "Mobility & Transport: Vehicle Categories" document [8]. In this paper, only the classes that are expected to dominate EV sales (L7e, M1, N1, N2) have been considered [9]. It is assumed that L7e=1%, M1=88%, N1=10%, N2=1% as a percentage of the total fleet [9].

The maximum charging rate of each EV depends on the charging infrastructure. Based on IEC 61851-1, three different charging levels have been considered in this paper namely **Level-1** (3-10kW), **Level-2** (10-20kW) and **Level-3** (40kW and more). It is assumed that each EV can be charged at any power level with a certain probability depending on its class [9]. The probability is zero in extreme combinations, for example in case N2 vehicle is charged at power level 1 due to the unrealistic duration of the charging process.

The arrival and departure times are stochastic parameters defining the total period during which an EV remains plugged-in and available for charging. EVs must be fully charged before their departure time. Due to the stochastic nature of EV mobility, their traffic behavioral parameters are approached by normal distribution functions [9].

The energy charging requirements of each EV are defined by the daily travel distance (km) and the battery consumption (kWh/km). The first parameter is stochastic describing the distance covered by an EV between two successive charging cycles. The battery consumption depends on various factors such as weather conditions, road traffic, EV specifications etc. In case there are no available historical data for these factors, average values can be considered for each EV class.

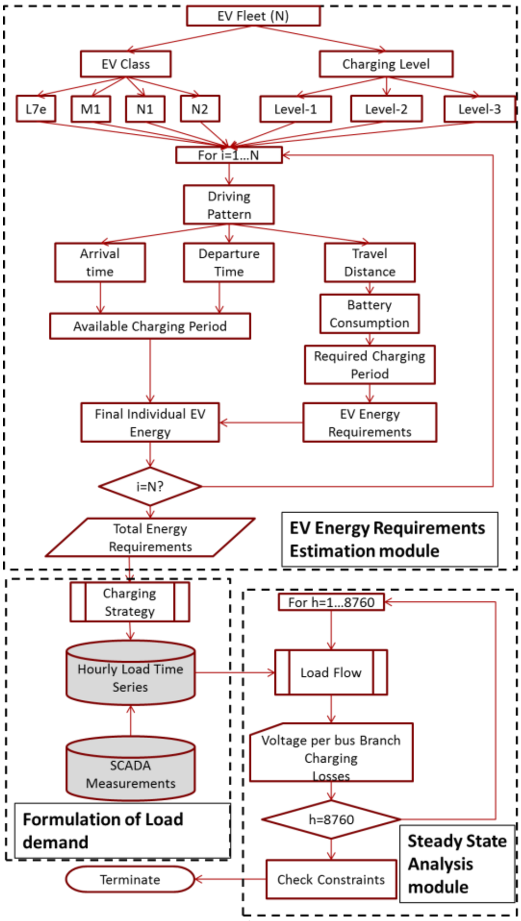

Fig. 1. Framework of the proposed methodology.

The "required charging period" parameter expresses the number of timeslots required for the complete charge of an EV according to its forecasted energy requirements. Timeslots can be defined in hourly base or less depending on the desired accuracy of the forecasted demand.

Charging Strategies

The output of the EV Energy Requirements Estimation module is a matrix providing information about the availability and the required charging timeslots of each individual EV. This matrix is combined with the charging strategy adopted, in order to provide the system load curve. Three charging strategies are examined in this paper , Dumb charging, Valley Filling Charging and Peak Curtailment Charging, as described below :

Strategy A : Dumb Charging:

This is the unplanned "plug and play" connection of electric vehicles into the grid, typically after the last trip of the day or when a charging point is available

Strategy B: Valley Fill Charging:

In this type of charging it is assumed that the EV owners charge their cars during the hours of the day when the load demand forms a "valley". Typically, EV mobility during off-peak hours is limited and this allows effective charging management.

Strategy C: Peak Curtailment Charging

The concept of peak curtailment charging in this case, is to arrange the energy demand of the EVs during the time periods when the feeder loading at its departure exceeds a pre-defined ceiling. In this simulation, the ceiling was assumed equal to the annual max load of the feeder At each hour (t) total load demand is compared to a power ceiling. In case the total load demand is below this ceiling then EVs are permitted to charge. The maximum allowable charging of EVs is in this case equal to

$$P_{EV}(t) = \min\{P_{EV\_tot}(t), P_{EV\_d}(t) + P_{EV\_res}(t-1)\} \qquad (1)$$

Where $P_{EV\_tot}(t)$ is demand of all the EV when charged simultaneously and $P_{EV\_d}(t)$ is the real demand of EVs at time t (as it would be in dumb charging).The residual is updated according to the equation

$$P_{EV\_res}(t) = P_{EV\_res}(t-1) + P_{EV\_d}(t) - P_{EV}(t) \qquad (2)$$

In case the total load of the line exceeds the pre-defined ceiling, the charging of EVs is blocked.

The EVs charging constraints imposed in our simulation are:

- For the 95% of days over the year, all EVs are fully charged during the required time slot
- For the rest 5% of the days, EVs are charged at least to a level of 90% of their nominal battery capacity.

Steady State Analysis

The time series produced in the previous step is used as an input to the steady state analysis module. For each hour of the year the charging of EVs is determined according to the charging policy adopted. Then a load flow analysis is performed and results such as voltage level of buses and branch loadings are recorded. The process is terminated after the hourly load flow of one year.

After the load flow analysis is terminated, the set of constraints are evaluated. The constraints taken into consideration 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 equation (3)

$$V_{dev} = 100 \cdot \frac{V_{\max} - V_{\min}}{2 \cdot V_{nom}} \% \qquad (3)$$

The above procedure is applied for each distribution grid under study under various scenarios of EV installed capacity. The goal is to identify the critical number of EVs that can be integrated to each grid under study.

APPLICATION 1: RURAL DISTRIBUTION LINE

Rural Distribution Line

The rural distribution line under study is a line of Lagadas HV/MV substation (referred to as Line R24) and is illustrated in Fig. 2 and Fig. 3. This line was chosen because it is a particularly long distribution line of Greece with total length 45 km and covers an area with increased PV penetration (73 PV plants with 1,5 MW installed capacity). Its voltage level is 20kV and it consists of 340 MV/LV substations. The peak load during the year is around 7 MW and it is observed in January and July while the minimum load is 2.5 MW, observed in April.

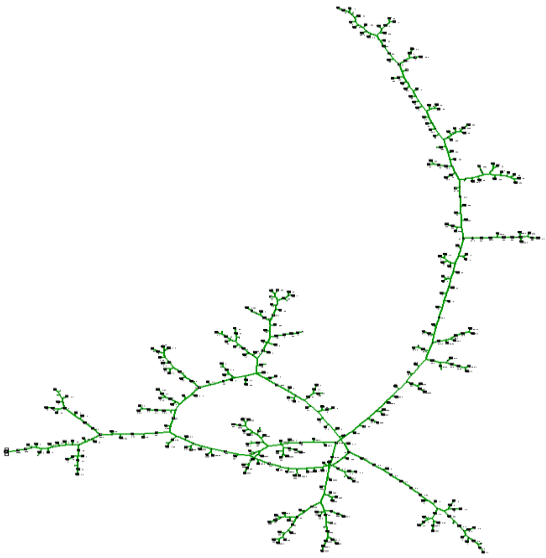

Fig. 1 Rural distribution grid diagram

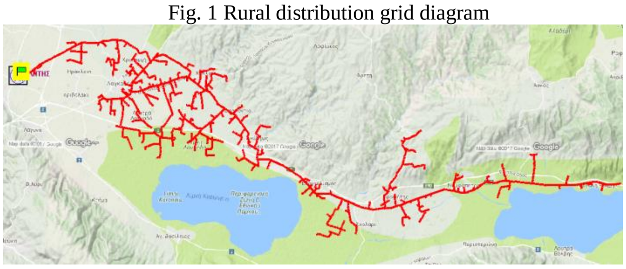

Fig. 2 Rural distribution grid geographic diagram

Results

In order to identify the critical number of EVs that can be connected to the line, the following cases are considered:

- **Case 1 : no EVs**
- **Case 2: 100 EVs**
- **Case 3: 200 EVs**
- **Case 4: 500 EVs**
- **Case 5:1000 EVs**

The combination of the above cases with the three charging strategies constitutes a number of 12 scenarios which are analyzed using the steady state analysis framework described in above. Fig. 3 illustrates the load duration curves for case 5 for the 3 charging strategies compared with the load duration curve of the line without EVs.

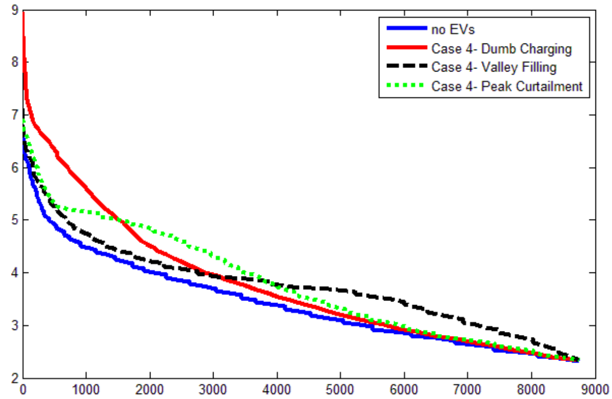

Fig. 3 Load Duration Curve for different Charging Strategies

It is observed that dumb charging shifts upwards the load duration curve especially for high and medium load levels, while valley filling charging shifts the curve for all load levels. Peak curtailment on the other hand decreases the duration of peak loading (above 6 MW) and increases the duration of high load levels (between 5 and 6MW)

Fig. 4 illustrates the maximum and minimum voltage levels per node for the charging strategies under study, considering Case 5.

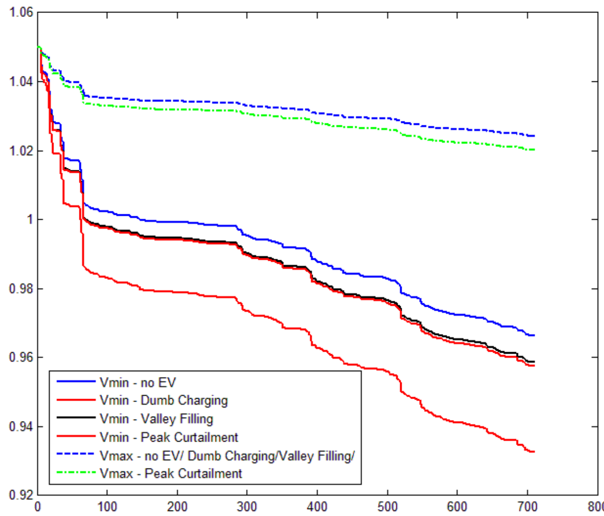

Fig. 4 Voltage Profiles

It is observed that all buses are within voltage limits; however the voltage deviation exceeds the constraint of 3% in several cases. Table 1 presents the number of buses that violate the voltage deviation criterion per case and per charging strategy. It is observed that only peak curtailment charging alleviates voltage deviations.

Table 1 Number of Buses with Voltage Deviation > 3%

	Charging Strategy		
	Dumb Charging	Valley Filling	Peak Curtailment
Case 1	0	0	0
Case 2	0	0	0
Case 3	56	0	0
Case 4	193	0	0
Case 5	369	70	0

Fig. 5 illustrates the feeder's loading as % of its nominal capacity, while Fig. 6 depicts the % feeder active losses for all the cases and the charging strategies under study.

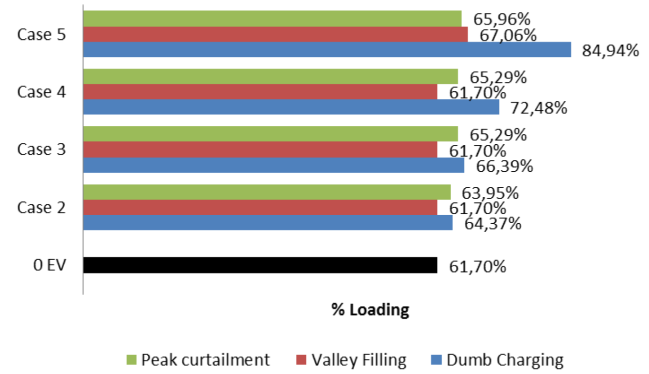

Fig. 5 Feeder Loading % of capacity

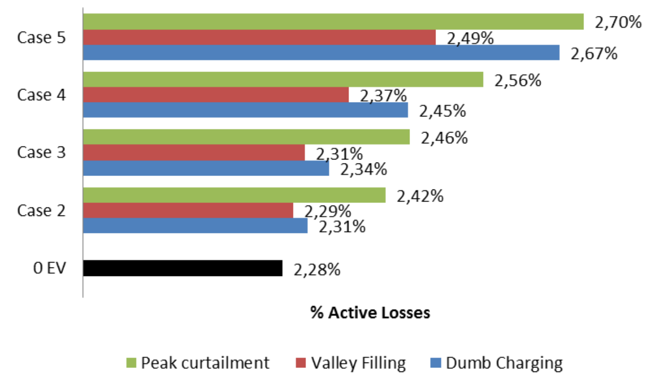

Fig. 6 % Active Energy Losses for rural grid

The critical number of EVs that can be connected to the line is highly dependent on the charging policy. The constraint that is violated due to the EVs connection is the voltage deviation constraint. Voltage mean, min and max values of buses remain into the limits for all cases under study. Branches are not overloaded in this case. Thus under dumb charging policy only 100 EV can be connected to the feeder without violating the constraints, while under Valley Filling charging up to 500 EVs can be connected and with Peak Curtailment more than 1000 EV.

APPLICATION 2: URBAN DISTRIBUTION LINE

Urban distribution line

The urban distribution line under study is a feeder of the Greek town Thessaloniki (Fig. 7). The line examined is an underground feeder with total length around 8 km, comprising 31 MV/LV substations. The peak load is 8MW while the minimum load is 1.5MW. It is estimated that the feeder supplies 2700 households The total number of vehicles of permanent residents in the urban area examined is estimated to be 4000 (with 1.5 vehicles owned per household [10]).

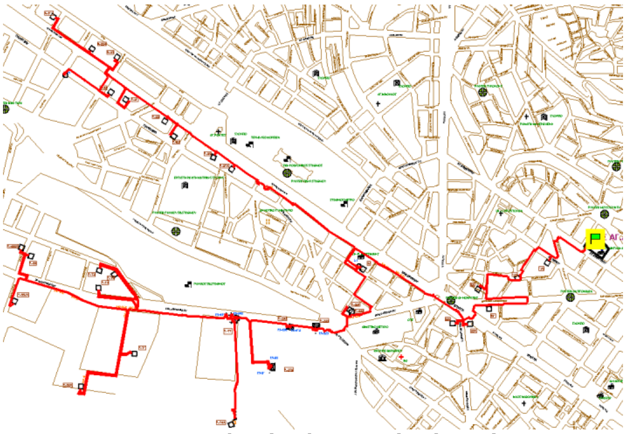

Fig. 7 Urban distribution grid under study

Since this line is located at the center of the city it is expected that it will serve charging needs of visitors who park their EVs in parking stations in the area. It is assumed that during the day (from 9 to 18) around 8000 cars may stop by the area. The penetration level of EV among visitors car is assumed to be equal to that of resident cars. A part of visitors (40%) would require charging their cars within an average time slot of 2 hours.

Results

In order to identify the critical number of EVs that can be connected to the line, the following cases are considered:

- **Case 1 : no EVs**
- **Case 2: 500 EVs**
- **Case 3: 1000**
- **Case 4:1500**
- **Case 5:2000**

Load flow analysis indicates that impact of EV penetration with regard to voltage profile of the feeder is almost insignificant, mainly due to its short length.
Fig. 8 depicts the % feeder active losses for all the cases and the charging strategies under study. It is observed that charging strategy adopted contributes significantly to

the active power losses of the feeder. Valley Filling is the most preferable strategy with regard to the minimization of active power losses.

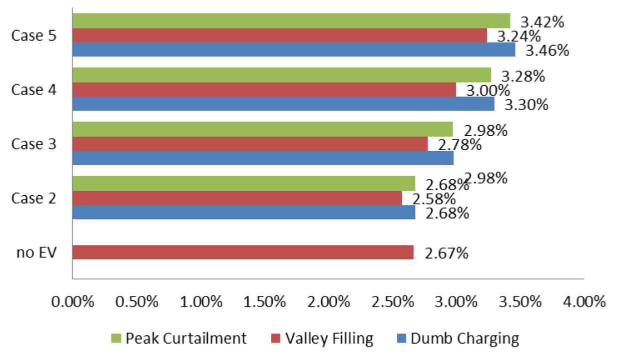

Fig. 8 % Active Energy Losses of urban feeder

Fig. 9 illustrates the maximum loading of the feeder compared to its thermal capacity. It is observed that thermal limits are violated for case 5 only peak curtailment strategy manages to satisfy thermal limit constraint of the feeder. The critical number of EVs that can be connected to the line is highly dependent on the charging policy. The constraint that is violated due to the EVs connection is branch overloading constraint. Voltage mean, min and max values of buses remain into the limits for all cases under study. A 50% penetration of EVs can be achieved by adopting a smart charging strategy. For higher levels of penetration, reinforcement of the line would be necessary, unless alternatives, such as dispersed generation deployment, are adopted.

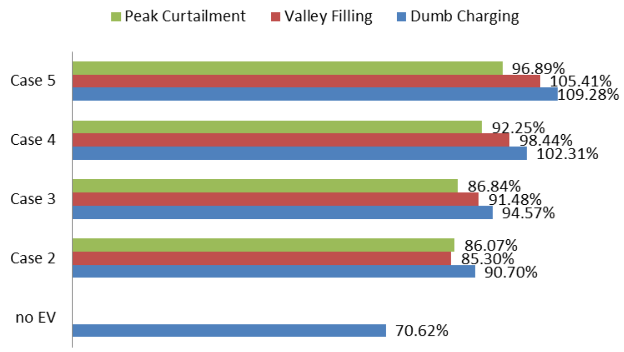

Fig. 9 Branch Loading of urban feeder

CONCLUSIONS

In this paper the impacts that a large deployment of EVs will provoke to selected distribution grids are evaluated. The additional EV charging demand is identified according to the travelling needs of EV owners which depend on local characteristics such as driving profile of EV owner, type of vehicle (battery capacity, energy consumption), travelling distance, road conditions etc. The aforementioned factors were studied for the cases of a rural and an urban distribution line of the Hellenic distribution network and the hourly allocation of the energy requirements was estimated under various EV charging strategies. The steady state analysis identified the critical number of EVs that can be integrated. It is observed that EV charging creates voltage deviation constraint violation in rural lines and overloading in the urban line. Appropriate charging strategy can alleviate the above problems and enable higher levels of EVs penetration. Active power losses are also significantly increased under dumb charging and high EV penetration. Smart charging strategies (i.e. Valley Filling and Peak Curtailments) can contribute to the minimization of power losses.

REFERENCES

[1] G.A. Putrus, P. Suwanapingkarl, D. Johnston, E.C. Bentley, M. Narayana “Impact of electric vehicles on power distribution networks”, IEEE Vehicle Power and Propulsion Conference, pp. 827-831, Vancouver, Canada, Sept. 2009.

[2] Putrus G.A., Suwanapingkarl P., Johnston D., Bentley E.C., Narayana M., “Impact of Electric Vehicles on Power Distribution Networks”, Northumbria University, 2009.

[3] S. Papathanassiou, “A technical evaluation framework for the connection of DG to the distribution network”, Electric Power Systems Research 77 p.p.24-34, 2007.

[4] J. Tomic and W. Kempton, “Using fleets of electric-drive vehicles for grid support,” J. Power Sources, vol. 168, no. 2, pp. 459–468, Jun. 1, 2007.

[5] S.W. Hadley, “Evaluating the Impact of Plug-in Hybrid Electric Vehicles on Regional Electricity Supplies”, iREP Symposium: Bulk Power System Dynamics and Control, 2007.

[6] K. J. Dyke, N. Schofield, M Barnes, “The Impact of Transport Electrification on Electrical Networks”, IEEE Transactions on Industrial Electronics, vol. 57, issue 12, Feb. 2010.

[7] E. L. Karfopoulos, E. M. Voumvoulakis, and N. Hatziargyriou. "Steady-state and dynamic impact analysis of the large scale integration of plug-in EV to the operation of the autonomous power system of Crete Island." *MedPower 2014*. IET, 2014.http://ec.europa.eu/transport/road_safety/vehicles/categories_en.htm.

[8] http://ec.europa.eu/transport/road_safety/vehicles/categories_en.htm

[9] N. Hatziargyriou, E. L. Karfopoulos, K. Tsatsakis, “The impact of EV charging on the System Demand”, Chapter 3 of book entitled “Electric Vehicle Integration into Modern Power Networks”, Spinger, ISBN 978-1-4614-0134-6, 2012

[10] UNECE, “Trends in Europe and North America: The Statistical Yearbook of the Economic Commission for Europe 2005”