Electric vehicle grid integration analysis in low voltage networks – A case study

E. Vega-Fuentes[1], F. Déniz[2] and A. Vega-Martínez[1]

[1] Institute for Applied Microelectronics
Department of Electronic Engineering and Automatics
University of Las Palmas de Gran Canaria
Campus of Tafira, 35017 Las Palmas de G. C. (Spain)
phone:+34 928 451248, fax:+34 928 457319, e-mail: **eduardo.vega@ulpgc.es**, **aurelio.vega@ulpgc.es**

[2] University Institute of Intelligent Systems and Numeric Applications in Engineering
Department of Electric Engineering
University of Las Palmas de Gran Canaria
Campus of Tafira, 35017 Las Palmas de G. C. (Spain)
phone:+34 928 451974, fax:+34 928 457319, e-mail: **fabian.deniz@ulpgc.es**

Abstract. Technical progress in electric vehicles (EVs) has enhanced their competitiveness in the transport sector. Social and environmental awareness regarding greenhouse gases reduction and fossil fuels dependency forecast an increase of EVs adoption.

It is important to understand the impact that EV will have on distribution networks. With high EV penetration, massive or uncontrolled charging may result in significant technical problems on the low voltage (LV) electricity networks such as voltage drops and thermal problems on wires and transformers.

In this paper a methodology is described to find out the hosting capacity for EVs in a given network, without any charging control and without any risk of causing negative effects to the grid. The IEEE European low voltage test feeder has been used as case study and simulations were performed using the tool OpenDSS. The nodes where voltage problems will come up were identified and the distribution network weaknesses were detected.

Key words

Distribution network, electric vehicles, EV penetration, low voltage networks, OpenDSS.

1. Introduction

Technical progress in electric vehicles (EV) has enhanced their competitiveness in the transport sector. Moreover, the environmental and social awareness regarding greenhouse gases reduction and fossil fuels dependency forecast an increase of EVs adoption [1].

It is important to understand the impact that EV will have on distribution networks. With high EV penetration, massive or uncontrolled charging may result in significant technical problems on the low voltage (LV) electricity networks, such as voltage drops and thermal problems on wires and transformers [2, 3]. This will undoubtedly stress the electricity network.

Increasing the EV charging capacity, certain line segments in distribution network will reach the rated capacity. Voltage profile of certain nodes will probably become lower than the acceptable range. Possible mitigation methods include: improving the power factor of EV charging station; installing energy storage inside charging stations; coordination to redirect the power flow from a local distribution generation; and coordinated charging control with network loading conditions [4]. When there is no charging coordination, the vehicles are charged instantaneously since they are plugged in or after a fixed start delay. The impact of EV charging to the LV distribution network in terms of voltage violation, voltage unbalance, feeders' thermal limit and transformer thermal limit were evaluated in [5]. The results of different simulated scenarios showed that the higher penetration level of EV charging will lead to a higher voltage drop and unbalance if uncontrolled EV charging is applied. Moreover, the uncontrolled EV charging causes the feeder and transformer to reach their thermal limits with much lower EV penetration compared to controlled EV charging.

In [6] a charging control strategy is used over the IEEE 13 nodes radial distribution network. Again, it reduce network losses and voltage drops compared to an uncontrolled charging scheme. In [7] a dynamic programming technique is implemented to coordinate plug-in hybrid electric vehicles charging using historical data of the load profiles. As result power losses and voltage deviations are lower by flattening out peak power.

The analysis performed in [8] reveals that LV networks are not an obstacle for introduction of EVs, since the negative effects are not prevalent in scenarios of low penetration. In regulated charging mode at slow charging stations, LV networks can support charging of a large number of EVs. Slow charging stations should however be distributed evenly between the phases, in order not to increase voltage asymmetry.

A better performance can be reached through vehicle to grid (V2G) schemes, where the cars return electricity to the grid. This way not only the voltage deviation is reduced but load demand profile is flattened [9].

In this paper, the integration of EV in the IEEE European low voltage test feeder is studied. This network is widely described in Section 2. As every 55 loads vary during the day, voltage, and current profiles are checked before connecting any EV. The methodology of this work is described in Section 3. Results are presented in Section 4. Finally, conclussions along with a discussion of the findings are presented in Section 5.

2. LV Network description

The analysis presented in this paper is carried out on IEEE European low voltage test feeder [10]. It provides a benchmark for LV feeders studies including mid- to long-term dynamic behaviour. The main features are:

- 416 V (phase-to-phase) voltage level with a base frequency of 50 Hz.
- Loadshapes with a one-minute time resolution over 24 hours for 55 single phase loads.

The feeder is connected to the medium voltage system through a 800 kVA delta-wye transformer (11/0.416 kV) at substation. The one-line diagram of the test feeder is shown in Fig. 1.

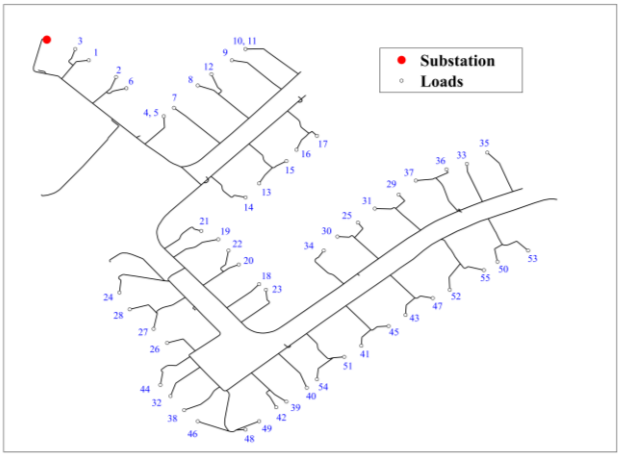

Fig. 1. Test feeder one-line diagram.

Fig. 2 shows the loadshapes (power vs. time) for the 55 loads.

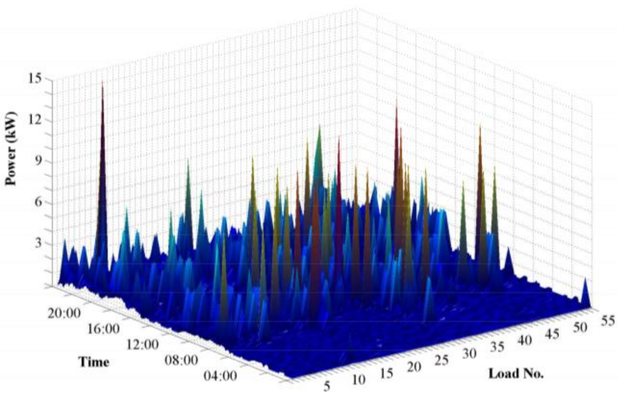

Fig. 2. Distribution network loadshapes.

The first constraint considered with the feeder model refers to voltage. The test feeder defines 1.05 pu voltage at transformer primary, this generates overvoltages values for every load (attending to spanish regulation, voltage at service points must be 230 V ± 7%). For simulation purposes, it has been supposed that the transformer is configured with tap 0.95. With this regulation, voltage range at service points keeps within limits. This is showed in Fig. 3 where mean values during the day are marked with a blue dot. The voltage raises to 1.0569 pu at loads 52 and 55 at 10:20 h and the minimum voltage is 0.9661 pu. It is found at load 35 at 09:28 h.

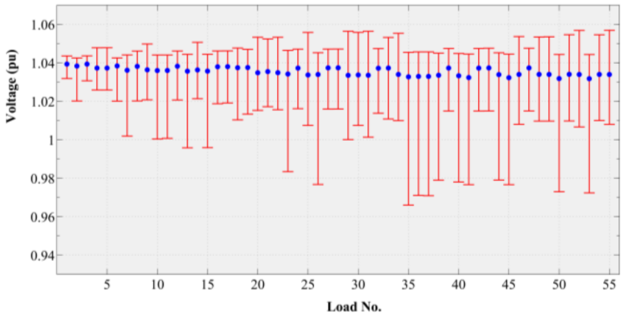

Fig. 3. Voltage range at service points w/o EV.

The amperes profile along the feeder from substation to the farthest node where load 35 is connected, is represented in Fig. 4. No thermal limit is exceeded.

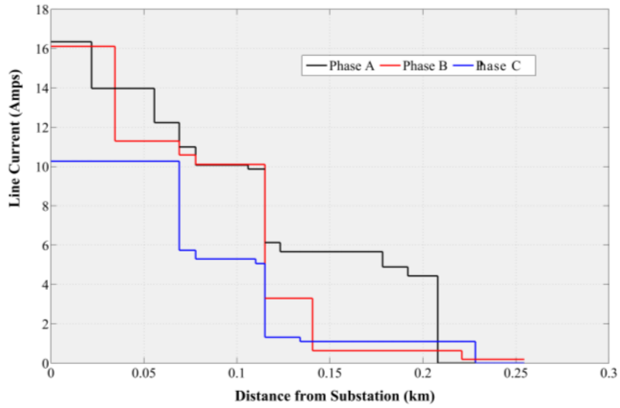

Fig. 4. Feeder Amp profile at the farthest node.

3. Methodology

The network under study and all the scenarios were modelled and simulated with OpenDSS, the EPRI open source tool, via Matlab [11, 12].

Regarding charging, it was supposed that all vehicules are charged at home. In a time slot that starts at 7 pm and finishes at 23 pm, but randomly selected. Fast charging is not considered because of the power required (50 kW). Only the charging modes 1 to 3 from Table I have been considered.

Consumers may only use a charging mode with a power consumption below 80% of their actual maximum load. When there are more than one valid modes, it is randomly selected in each iteration.

TABLE I. – EV charging times

Mode	Power (kW)	Charging time (h)
1.a	2.3	10.5
1.b	3.7	8
2	4.6	5.5
3	6.6	4
4	50	0.5

With the conditions defined in previous section, we started connecting just 1 EV in 1 dwelling. And checked the behaviour in all dwellings. Then 2 EVs in every possible pair of dwellings and so on until undervoltages or overcurrents were detected. Next step was assess the number of cases for that level of EV integration that crossed the limits and estimate the probability. We kept increasing the EV penetration and calculating probabilities until a 100% undervoltage or overcurrent presence probability was reached.

As the number of possible combinations increases exponentially with the number of EVs to integrate (for instance, there are 26,235 different combinations to connect 3 EVs in 55 nodes and 341,060 for 4 EVs) only 100 combinations for each level of integration were simulated.

4. Results

The simulations performed produced no issues regarding amperes through any of the lines.

Voltage was a whole other matter. Fig. 4 shows the probability of undervoltage in at least one node related to number of EVs connected. The number of consumption points with undervoltage in the worst case is expressed in Table II which presents all the points with voltage under 0.93 pu in the worst scenario for each EV penetration.

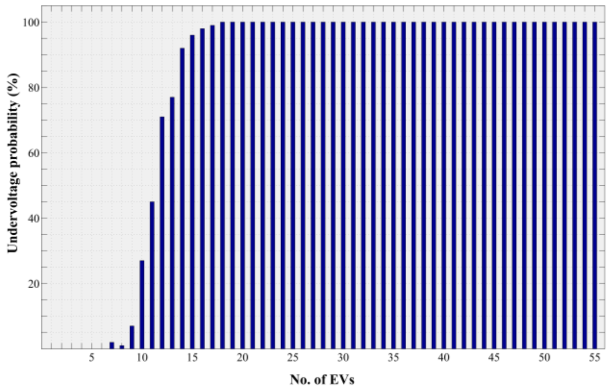

Fig. 4. Voltage violations (%) vs. No. of EVs.

The first violations occurred when there were 7 EVs, (2% probability). For this penetration level, the worst case produced undervoltages at 4 consumption points (where loads 25, 29, 30 and 31 are connected). With 11 EVs the voltage violation probability reached to 45% (12 nodes with undervoltages in the worst case). With 18 vehicles or more the voltage violation probability in at least one node was 100%.

TABLE II. – Worst cases points with undervoltages

No. of EVs	No. of Nodes	Loads
0-6	-	-
7	4	25, 29, 30, 31
8	2	52, 55
9	7	46, 48, 49, 51, 52, 54, 55
10	7	46, 48, 49, 51, 52, 54, 55
11	12	25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
12	14	20, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
13	14	20, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
14	15	20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
15	14	20, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
16	15	20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
17	16	14, 20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
18	15	20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
19	16	14, 20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
20-28	17	9, 14, 20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55
29-55	19	4, 5, 9, 14, 20, 21, 22, 25, 29, 30, 31, 34, 46, 48, 49, 51, 52, 54, 55

Fig. 5 shows the voltage profile along the feeder at 9 pm in the worst scenario when there were 18 EVs to be charged. Only Phase A, represented in black, went below the lower limit, and not at its farthest node.

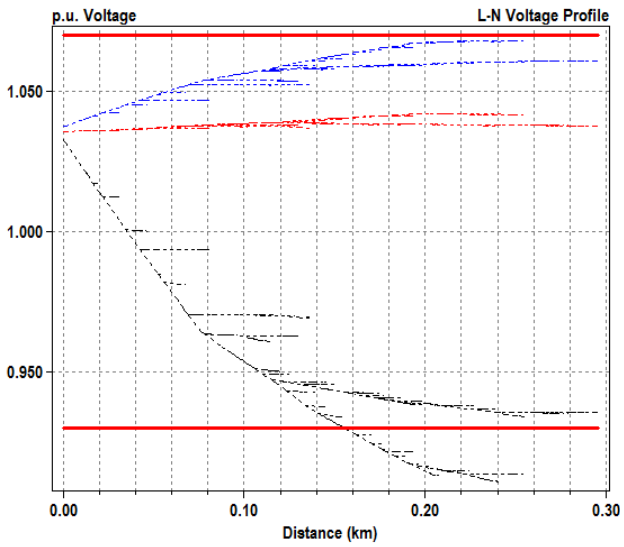

Fig. 5. Voltage profile at 9 pm with 18 EVs.

The voltage range at every service point with 18 EVs can be seen in Fig. 6. The mean values during the day are marked with a blue dot. The solid blue line represents the low voltage limit (0.93 pu). The minimum voltage was 0.8809 pu. It was found at load 52 at 22:50 h. The 15 loads which suffered under-voltages are easily identified.

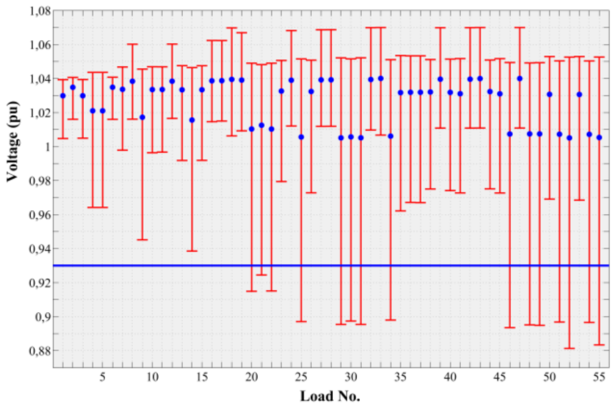

Fig. 6. Voltage range at service points with 18 EVs.

5. Conclusions

All distribution networks present different characteristics regarding length, wires ampacity, power served, features and number of loads, demand curves, phase balance, etc. So the hosting capacity for EVs varies from one to another and it is not a constant for different times of the day.

In this paper, a methodology has been described to find out how many EVs can be hosted in a given network without any charging control and without any risk of causing negative effects to the grid. This number is 6 EVs (10.91% of the dwellings) for the IEEE European low voltage test feeder.

With 11 EVs (20.00% of the dwellings) there is a 45% probability of finding undervoltages in some points. With this EV penetration level the worst scenario produces undervoltages in 12 nodes.

The precise number of EVs beyond which the probability of undervoltages presence is 100% was defined too. 18 EVs (32.72% of the dwellings) for the case studied.

The nodes where voltage problems will come up with the arise of EVs were identified (showed in Table II for the assessed network). They were related to a specific phase (phase A) and an unbalance was detected (Fig. 5).

The results obtained will be helpful as a basis for further studies in the search of an improved electric vehicle hosting capacity. Phase balancing methods, voltage boosting through capacitor banks, use of storage devices such as batteries inside charging stations and coordination to redirect the power flow from a local distribution generation will be assessed.

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