OPTIMIZATION OF LOW VOLTAGE DISTRIBUTION NETWORKS IN A STRONG EMBEDDED MICROGENERATION AND ELECTRIC VEHICLE PENETRATION CONTEXT

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ABSTRACT

The growing search for electric vehicles and decentralized micro production units is forcing electric power companies to adjust their grid exploitation strategies to the new paradigm, with less predictable load profiles. Both of these tendencies have direct impact on the power grid network, where the dynamic between offer/demand must be predicted and balanced. This paper addresses the issue by conducting a study of consumption tariffs that attract the electric vehicle charging to periods with lower network utility and major photovoltaic (PV) production. First, a contextualization of the subject is presented, followed by the development of strategies created to control Plug-in Electric Vehicle's (PEV) load connections through tariffs. Finally, a set of case studies is presented, in order to simulate and compare the PEV's penetration and PV production effect on a real grid model. The results support the suggested optimization strategy, showing a significant reduction of current and voltage perturbations and system losses.

Keywords - Low voltage network's exploration, optimization, electric vehicle, photovoltaic microgeneration, consumption tariffs.

INTRODUCTION

Nowadays it's difficult to imagine our quotidian lives without the using of electric energy. The energy sector assumes a fundamental part of every government's vision. Plug-in electric vehicles (PEVs) are growing in popularity as zero emission technologies, alternatives to the conventional fuel-based automobiles **[1]**. Depleting natural oil and fossil fuel reserves, rising petrol costs, and increasing governmental regulations to adopt more sustainable technologies, have driven to the development of plug-in electric vehicles and photovoltaic generation **[2]**.

An important component of electric mobility consists on the electric vehicle integration form on the grid. Using load control strategies, it's possible to attract the PEV's charging to periods with more energy available on the grid. In a PEV's penetration scenario, charging management allows the reduction of load's peaks through accommodating PEVs charge on high renewable production periods, improving the energy consumption equilibrium. This paper exposes the results from the study of a LV electric grid, in different scenarios of high load's variability resulting from PEV's quick and slow charging and a growing PV production. The main objective is to identify optimal solutions for the network exploitation in these scenarios, improving system losses, reducing voltage and current's perturbations and trying to dynamically predict consumer behavior in order to balance the system.

Problem Identification and Proposed Solution

Electric vehicles and Distributed Energy Resources penetration and operation may have a direct impact on the network assets, as overloads, voltage fluctuation and power losses. As showed in Figure 1 and 2, Plug-in Electric Vehicles (PEVs) power demand is often higher during the peak period (corresponding to the time when PEV users arrive home after work), whereas photovoltaics (PV) production peak occurs in periods of grid's low demand, leading to an excess of energy flowing upward the grid. The proposed optimization is based on a customer Demand Side Management (DSM)

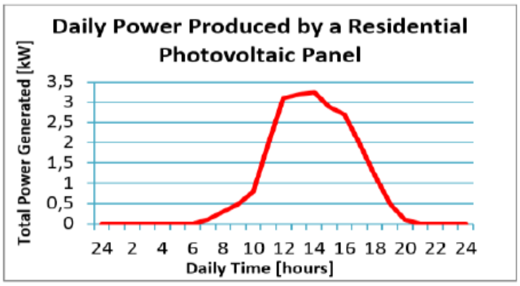


Figure 1. Daily Power Production Curve of an 3,68 kW PV Panel on 10 of May 2015. Region of Coimbra (data from *EDP Distribuição*).

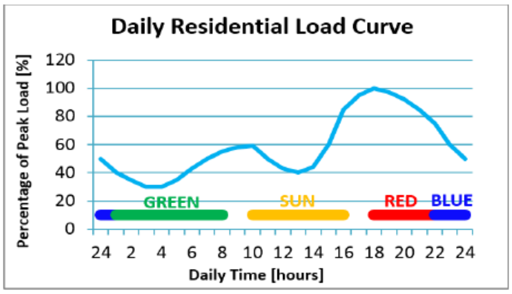


Figure 2. Daily Residential Load Curve and PEV's exclusive tariffs proposed.

strategy that “redirects” the unpredicted load connections (PEV) to periods with lower energy demand, through the creation of new consumption tariffs exclusive for PEVs **[3]**. The design of PEV's exclusive charging tariffs (GREEN, BLUE, RED and SUN) aim to be economically attractive compared to regular consumption tariffs, especially during periods of lower energy demand. This solution monetize the grid capacity during all day, attracting the energy consumption to PV’s production peak period (low demand hours).

RED Tariff (18h00-22h00) –The kWh’s price for this tariff should be very high, when compared with the other proposed tariffs. The kWh’s price should be equal to the regular market price.

BLUE Tariff (22h00-01h00) – Attending to the fact that the BLUE tariff is available in a partially off-peak schedule, the kWh’s price should be higher than GREEN Tariff but lower than RED Tariff.

GREEN Tariff (01h00-09h00) – For this period the kWh’s price should be the lower tanks BLUE and RED tariffs.

SUN Tariff (10h00-17h00) - Created to encourage PEV charging during higher solar intensity period of the day. For this period the kWh’s price should be the lowest from all of the proposed tariffs, because there will be, simultaneously, more energy available (resulting from PV production) and a lower costumer demand.

MODEL AND SIMULATION

DPlan - Distribution Planning was used in order to experiment several grid exploitation hypothesis. DPlan is an analysis and optimization software for electricity distribution systems that assists the user’s decision making concerning energy systems operation and emergency planning. DPlan is mathematically modelled by power flow equations, system losses equations, and current and voltage limits.

For each simulation there were collected from *DPlan* the following data:

- Grid’s edge voltage variations;
- Transformation Point input current variations;
- Total system losses.

CASE STUDIES

The idealized optimization strategies presented before were simulated based on the real grid’s characteristics data. It was considered a 42 node’s grid, with only one house per node. Assuming that network’s loads are balanced and have the same initial value, the PEV’s penetration loads and PV’s production loads were randomly distributed by the grid connected clients.

PEVs Loads

In order to predict the grid’s load variation, it’s important to understand the PEV’s battery impact on client’s load [4]. Nissan Leaf was the reference PEV model used in the study. The Nissan Leaf battery has 24 kWh of capacity but only 21.3 kWh are used (lifetime battery issues). According to Nissan’s Technical Specifications (nissan.pt data) the total residential battery charge takes 4 hours, using a 32A current (quick charging) or 8 hours, using a 16A current (slow charging). Assuming a constant charging ratio and taking into account the worst case scenario (the 32A quick charging), the maximum charging power is:

$$32\text{A} \times 230\text{V} = 7{,}36\ \text{kW} \qquad (1)$$

Clients

In the study case it is assumed that to each grid’s house will be connected a maximum of one PEV. Taking into account the PEV maximum charging power, the contracted power settled for each house was 10.35 kVA. Relatively to micro-production, it was assumed that every producer uses a 3.68 kW PV micro-generator, with a daily production based on the Figure 1 curve.

The study presents three penetration levels of electric vehicles and PV production: 19%, 38% and 76%. Each tariff utilization is sensible to the defined kWh price. This means that user’s expected tendency is to charge their vehicle during GREEN period. BLUE should be the second on the list of most used periods, followed by RED, the less attractive tariff.

It’s expected that when a proposed tariff period starts the number of PEV connections to the grid is initially high and it will decrease with time. To simulate this consumers behavior was used an exponential probability distribution. The exponential distributions varies with the parameter λ, for higher λ values the distribution will be lower. A different exponential distribution was used for each tariff period, which randomly describes the hour that each PEV is connected to the grid.

Particularly for the Sun tariff were used two different exponential distributions during the same time period.
The first one describes the slow charging PEV's distribution and the second one describes only the quick charging PEV's distribution. For each Exponential distribution used in the study was defined a value for **λ** and a distribution starting time (absolute zero). The **λ** and absolute zero values assumed are described in Table 1:

Tariff	λ	Absolute Zero
GREEN	1,25	01h00
BLUE	1	22h00
RED	1	18h00
SUN (quick charging)	1	12h00
SUN (slow charging)	1	10h00

Table 1. Exponential Distribution Parameters.

For the GREEN Tariff is defined a superior parameter (λ), when comparing with others tariffs, due to the fact that for that period of the day (01h00-09h00) the user's majority is already at home, allowing them to start charging their vehicles at the tariff starting time. Particularly for the SUN Tariff was considered that the quick charging distribution begins at 12h00, instead of 10h00 (tariff opening time). This difference infers some realism to the case study, representing PEV users that charge his vehicle during their lunch time.

Total Load Curve

To calculate the network total load, the load's simultaneity factor was considered. By applying Portugal's LV clients connection rules, is defined a simultaneity factor of 0.36 for the distribution network loads. Particularly for PEV charging loads and PV production loads is defined unitary simultaneity factor. The network daily load variation developed (Figure 3**)** is based on **[5]**.

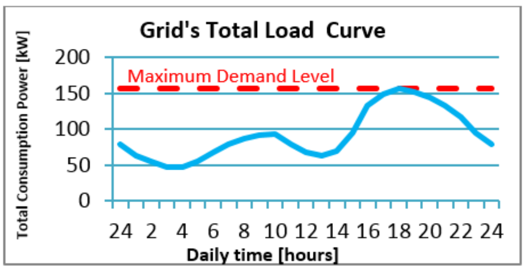


Figure 3. System's daily load curve without any PEV penetrations neither PV production.

Figures 3 to 5 present the daily load curves, total system losses, and the output current and network edge voltage, respectively.

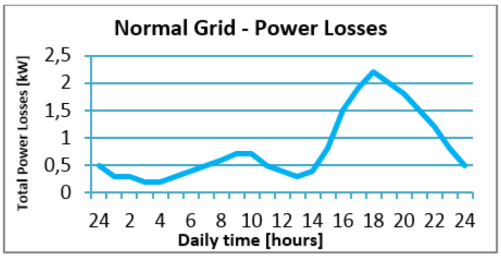


Figure 4. System's power losses, without any PEV penetrations neither PV production.

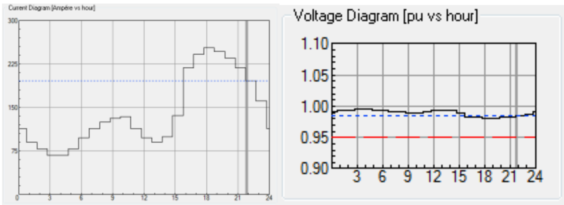


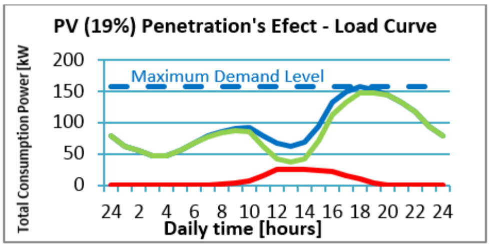
Figure 5. System's current (left) and voltage (right) variation, without any PEV penetrations neither PV production.

TESTS RESULTS

In this section are presented the tests results for cases studied. For each case where tested PEV and/or PV penetration levels of 19%, 38% and 76%.

Case A – Photovoltaic Production Effect

In this case three different levels of photovoltaic production's impact on the grid are studied.



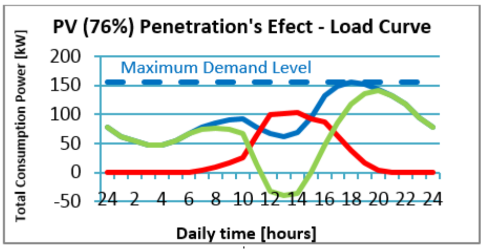


Figure 6, and 7**.** 19% and 76% PV production effect on system's load curve. No PV production (blue curve); Systems PV production impact (green curve); PV production (red curve).

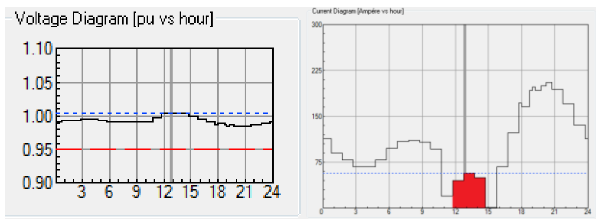


Figure 8. System's current (left) and voltage (right) variation, with 76% of PV penetration. The red zone indicates negative values of current.

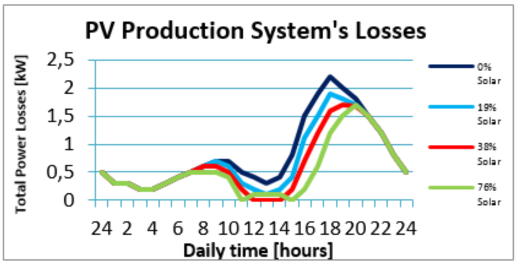


Figure 9. PV production effect on system's losses.

Figure 8 presents the 76% PV production scenario, it is the scenario with the biggest perturbation of the system's current and voltage. For the others PV penetration levels the perturbations were not sufficiently significant to perturb the system's good function.

Case B – Non-Optimized PEV's Charging Effect

In this case the PEV's non-optimize charging impact on the grid is studied without any PV production. The worst case scenario was hypothesized and simulated, with the simultaneously home arrive of all PEV users, putting their vehicles charging on quick charging mode (17h00-20h00).

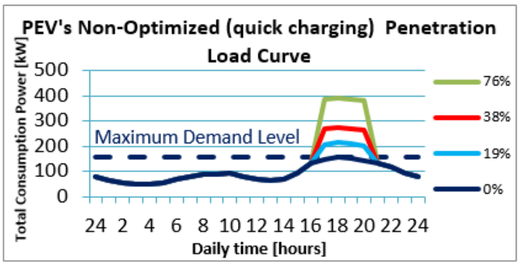


Figure 10. PEV's optimized (quick charging between 17h00-20h00) penetration effect on system's load curve.

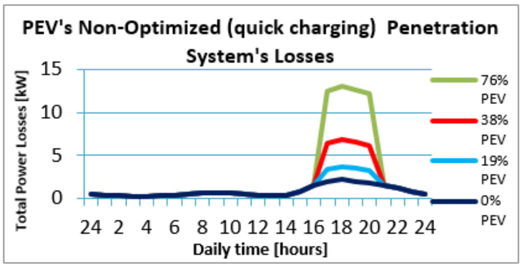


Figure 11. PEV's optimized (quick charging) penetration effect on system's losses.

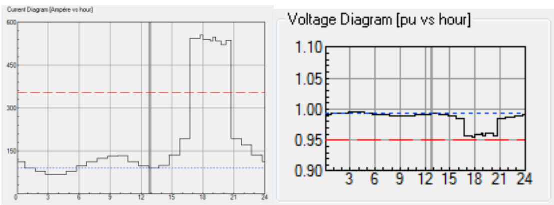


Figure 12. System's current (left) and voltage (right) variation, with 76% of PEV (quick charging) non- optimized penetration. The red line indicates the voltage and current constraint limits.

Figure 10 shows the grid's load effects for non-optimized quick charging mode, Figure 12 presents the voltage and current variation with 76% of PEV's penetrations level and the Figure 11 shows the system's losses.

Case C – Optimized PVE's (25% quick and 75% slow) Charging Effect

In this case the PEV's optimized charging impact on the grid is studied without any PV production. For the each PEV penetration level the loads control strategy was used through tariffs (GREEN, BLUE and RED) application. SUN Tariff was not tested because it only make sense to use it when PV production exists.

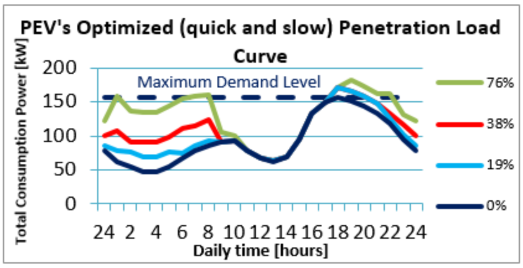


Figure 13. PEV optimized (25% quick and 75% slow) penetration effect on system's load curve.

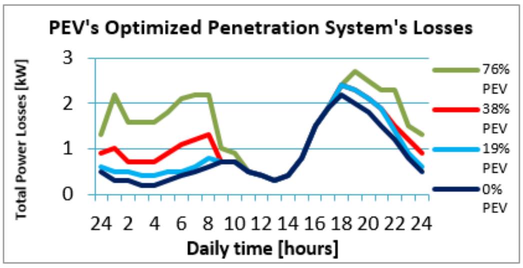


Figure 14. PEV optimized penetrations effect on system's losses.

Figures 13 and Figure 14 shows the grid's load effect and system's losses, respectively, for the proposed optimal grid exploitation.

Case D – Environment with PV Production and PVE's Penetrations Effect

In this case the PEV's optimized charging impact on the grid is studied with different levels of PV production. For the each PEV penetration level the loads control strategy was used through tariffs (GREEN, BLUE, RED and SUN) application. Only the 19% and 76% of PV panel's penetration results are presented in order to focus the analysis on the short and long term results.

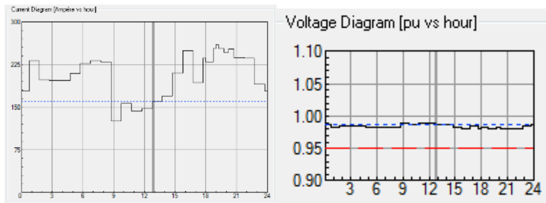


Figure 15. System's current (left) and voltage (right) variation, with 19% of PV penetration and 76% of PEV's optimized penetration.

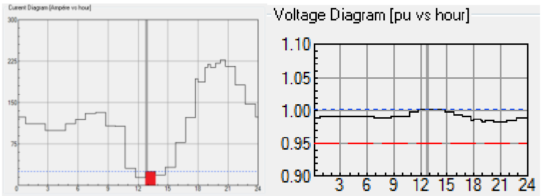


Figure 16. System's current (left) and voltage (right) variation, with 76% of PV penetration and 19% of PEV's optimized penetration.

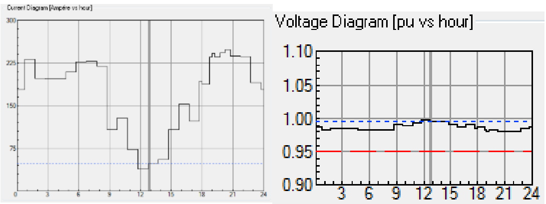


Figure 17. System's current (left) and voltage (right) variation, with 76% of PV penetration and 76% of PEV's optimized penetration.

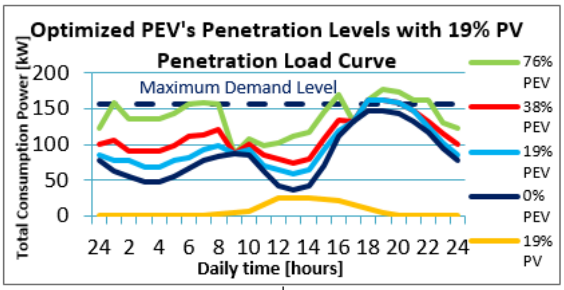


Figure 18. PEV optimized penetrations effect on system's load curve with 19% of PV production.

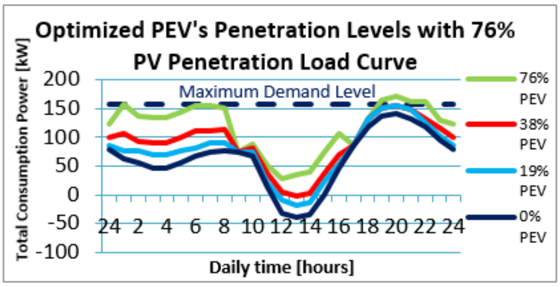


Figure 19. PEV optimized penetrations effect on system's load curve with 76% of PV production.

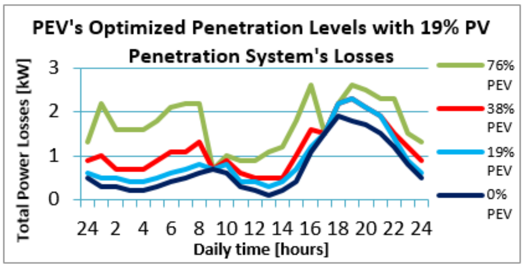


Figure 20. PEV optimized penetrations effect on system's losses curve with 19% of PV production.

Figures 18 and 19 shows the grid's load effect, Figures 15, 16 and 17 presents the voltage and current variation for each PEV's and PV's penetrations level. Figures 20 and 21 shows the system's losses for the same penetration levels of PV and PEV.

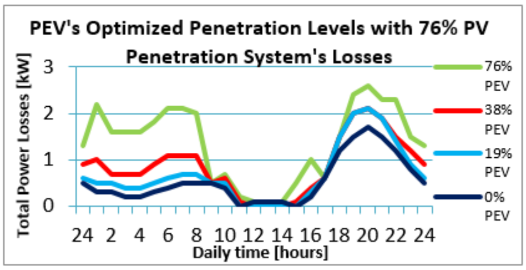


Figure 21. PEV optimized penetrations effect on system's losses with 76% of PV production.

CONCLUSIONS

This analysis showed that the electric grid reached its limits when subjected to non-optimized PEVs charging and presented energy excess for high PV production levels. The suggested customer DSM strategy accomplished the proposal goal, to manage the power flow, voltage, fault level and the stability of the grid, accommodating EV's charging load during periods of minor consumption and/or major photovoltaic production.

In fact, the test results showed the successful mitigation of the system overloads and reduction of network losses when compared to with the non-optimized simulations. The paper shows the impact on network assets caused by distributed energy resource (DER) penetration and operation, and how to shape customer behavior through economic mechanisms.

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