SMART GRIDS WITH ELECTRIC VEHICLES: THE INITIAL FINDINGS OF PROJECT REIVE

A Project Funded by the Portuguese Ministry of Economy, Innovation and Development

F. J. Soares, C. Gouveia, P. N. Pereira Barbeiro, P. M. Rocha Almeida, C. Moreira and J. A. Peças Lopes

INESC TEC – INESC Technology and Science (formerly INESC Porto) and FEUP – Faculty of Engineering, University of Porto, Campus da FEUP, Rua Dr. Roberto Frias, 378, 4200 – 465, Porto, Portugal.

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Abstract: This paper provides a general overview of the initial developments in the REIVE project (Smart Grids with Electric Vehicles). The main focus of the project is on smart grid infrastructures for large scale integration of EV and micro-generation units. It is a natural evolution of the InovGrid project promoted by the EDP Distribuição – the Portuguese Distribution Network Operator – and allows the development of seminal concepts and enabling technological developments within the Smart Grid paradigm. This paper presents the management and control architecture developed to allow electric vehicle integration in smart grid operation. Additionally, it presents the major impacts in distribution grids of the simultaneous deployment of electric vehicles, micro-generation and smart grid technologies.

1 INTRODUCTION

The integration of Electric Vehicles (EV) in electricity grids presents numerous challenges in terms of grid infrastructure, as well as in terms of management and control capabilities of these entities (Clement-Nyns et al., 2010, Galus et al., 2010). The smart grids paradigm is possibly the only effective way to cope with these new challenges. The expected large scale deployment of intelligent equipment's on the grid in the near future is, therefore, a unique opportunity to define innovative features and functionalities (Lopes et al., 2006, Lopes et al., 2011), which will allow a larger and safer integration of micro-generation (μG) units and EV, as well as the implementation of more ambitious Demand Side Management (DSM) solutions and control strategies (Callaway and Hiskens, 2011, Xu et al., 2010).

The project REIVE – Smart Grids with Electric Vehicles (*Redes Inteligentes com Veículos Eléctricos* in the Portuguese designation) addresses this problematic in a holistic manner. It exploits synergies between all the elements that compose a smart grid, especially focusing on μG units and EV.

The project can be regarded as an extension of an on-going project led by the Portuguese Distribution System Operator (DSO) – the InovGrid project (Messias, 2009). InovGrid is focused on the development of a fully active distribution network introducing advanced DSM strategies where common energy consumers are able to play an active role in the consumption management and also be micro-producers. The interaction between consumers/micro-producers units and the network operator is assured through the functionalities provided by the strategically developed equipment, such as "energy boxes" and "distribution transformer controllers", as well as a proper communications infrastructure. The smart grids framework envisaged in the InovGrid project allows not only to optimize consumers energy consumption, but also improving transmission and distribution networks effectiveness, decreasing technical losses, reducing metering costs, postponing network investments, improving and monitoring quality of service, among other benefits.

Following the findings of the InovGrid project, a

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demonstration pilot was launched, named InovCity, in Évora, which is a city in the south of Portugal with c.a. 32000 customers. The main objective of InovCity is to test the solutions developed in the InovGrid project and to quantify the technical and economic benefits yielding from the approaches implemented (Giordano et al., 2011).

The project REIVE aims at upgrading the functionalities of the InovGrid's "energy box" and developing a technical platform, where innovative features that allow the progressive integration of µG and EV are developed and tested. Both technical and commercial domains are addressed. The strategic value and scope of the project covers contributions:

- For the industrialization of technologies and products by industrial partners;
- To the mobility paradigm shift, by setting technical conditions from the grids side for increasing levels of EV deployment;
- To reduce CO_2 emissions, by allowing the sustained usage of EV penetration combined with further integration of intermittent Renewable Energy Sources (RES).

The project REIVE also contemplates the implementation of a smart grid in a laboratorial environment, where it will be possible to test the performance of new control and management concepts for facilitating DER and EV integration in LV networks. Additionaly, the laboratorial facilities will also be used in order to develop new prototypes for smart grid network controlers and power electronic interfaces for EV and µG, which will integrate the functional specifications undertaken during the project development.

This paper presents the initial findings of the project REIVE, with a special emphasis on the control architecture developed, on the impacts resulting from large scale depployment of µG units and EV in distribution networks and on the smart grid test bed that is being conceptualized for near future implementation in laboratorial environment.

2 MANAGEMENT AND CONTROL ARCHITECTURE

As referred in the previous section, the project REIVE seeks to develop advanced management and control mechanisms to facilitate the large scale integration of EV and µG units in the power system, using, as basis, the concepts and approaches developed within the InovGrid project. The InovGrid project was initiated in 2009 by the Portuguese DSO, with support of INESC Porto, Janz, Efacec and Logica.

The advanced infrastructures and functionalities developed within InovGrid enable the implementation of new commercial services, allowing the active participation of the consumers/micro-producers in both the electricity market and system operation. From the system operator point of view, the concept developed promotes a more efficient renovation of the distribution network infrastructures and management systems, implementing investments that enhance reliability and efficiency, and increasing the capabilities of remote control and automation systems.

The architecture of the system is represented in Figure 1. It expands the utilities monitoring and control capability downstream the MV network to the consumers premises. This architecture is constituted by 4 layers, defined according to the identified players: the Energy Boxes (EB) installed at the clients premises, the Distribution Transformer Controllers (DTC) installed at the MV/LV substations, the Smart Substation Controller (SSC) installed at the HV/MV substations and the central systems, namely the Distribution Management System (DMS) and the commercial systems for clients account managment purposes, which includes only commercial information. As shown in Figure 1, this architecture relies in communication network allowing the communication within the same layer and with the other layers.

2.1 Energy Box

The EB is a smart metering equipment to be installed at the consumers/micro-producers premises with bi-directional communication capability. The EB functionalities include remote metering of power, as well as other parameters related to the number and duration of interruptions and also voltage monitoring functionalities. In addition, the EB also includes other functionalities for consumer management purposes, such as: remote modification of the contracted power, remote modification of tariff regimes and remote interruption of fraudulent clients. The EB was conceived modularly, thus allowing the inclusion of a set of interface modules, which enable the interaction with other home energy management systems. Three different versions of the EB were developed, which are capable of providing different services, in order to face different customers' needs: an EB for simple consumers (EB1), an EB for customers that own micro-generation units (EB2) and an EB for customers that

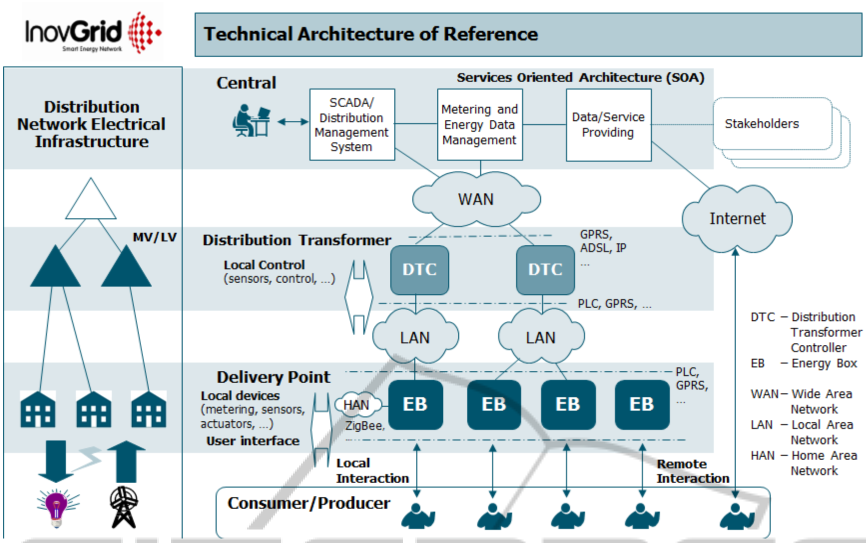

Figure 1: InovGrid advanced management and control system architecture.

own EV and wish to participate in controlled EV charging schemes, such as smart charging (EB3).

Differentiating the EB according to their functionalities enables the customers to acquire an EB adapted to their specific needs, avoiding the obligation of all customers acquiring equipment with an increased cost and with useless advanced processing capabilities.

The EB is prepared to receive control signals from the entities in the upper hierarchical levels of the control architecture developed within InovGrid (see Figure 1), which will vary according to the version of the EB. EB1 include the base EB functionalities such as remote metering and the possibility of performing an on/off control over the EV that are charging. This EB also allows the remote change of commercial agreement conditions such as change of tariffs or contracted power. EB2 and EB3 include several interface modules capable of receiving specific control signals from the entities in the upper hierarchical levels that will enable the µG unit's dispatch and the EV participation in controlled charging schemes. In addition, EB3 also enables the provision of several ancillary services by EV, like reserves delivery.

2.2 Distribution Transformer Controller

The DTC is installed at the MV/LV distribution network substations. It receives and processes the data collected from all the EB downstream and sends it to the higher control layers. At the same time, it will also receive information from the central systems and distribute the information or the resulting control signals to the downstream EB. On more advanced version of the InovGrid system, the DTC will also include functionalities that enable them to manage the operation of the local networks, both in normal and emergency conditions.

2.3 Smart Substation Controller

The SSC is responsible for coordinating the active players of the MV networks as well as the DTC installed in the MV/LV substations. The SSC functionalities include intelligent algorithms to optimize energy flows and network topology, as well as self-healing algorithms, in close coordination with network operators via the SCADA/DMS. It also has the capability of performing coordinated voltage control and detecting faults in an effective manner, contributing to smaller restoration times and reducing the number of clients affected by the faults.

The SSC is in fact very similar to the Central Autonomous Management Controller (CAMC) entity, developed within the MORE-MICROGRIDS Project, which main purpose is the management of the Multi-Microgrid (Gil and Lopes, 2007).

2.4 Integration of EV in the InovGrid Architecture

The large scale deployment of plug-in EV will require new charging interface infrastructures, such as fast charging stations, public and domestic charging points and private charging stations dedicated to EV fleets. With exception of the fast charging stations, all the other infrastructures will provide a slower charging, that can take up to 8 hours. For this reason, it is expected that EV will be connected to the grid for large periods of time, being potentially possible to exploit their storage capacity in order to enable a better usage of the network infrastructures.

Yet, the decision of the EV participating or not in controlled charging schemes will always be a decision taken by their owners. For this reason, several possible charging schemes should be available in order to fit the specific needs of the EV owners.

In the non-controllable charging strategies, the EV is envisioned as a conventional load, being the EV owner free to charge the vehicle in any time of the day. In the dumb charging mode the EV behave has any other appliance, having no restrictions or incentives to shift their charging to the lower consumption periods. In order to provide load shifting, a multiple tariff policy may be implemented to incentivize the EV to charge the batteries in the periods were the electricity price is lower. This method is based on the dual tariff scheme implemented in several countries, where during valley hours the electricity price is lower. However, as this is not an active management strategy, the success of this method depends on the EV owner willingness to take advantage of this policy, and thus only part of the EV load would eventually shift towards valley hours.

In the controllable strategies the EB3 will receive specific control signals to control the EV battery charging. The objectives may be commercial or to ensure the secure operation of the system. The smart charging strategy envisions an active management system, where there are two hierarchical control structures, one headed by an EV aggregating agent and other by the DSO.

In normal operating conditions, the EV charging will be managed and controlled exclusively by a commercial aggregator, whose main functionality is to cluster the EV, according to their owners' willingness, and exploit business opportunities in the electricity markets. In order to successfully respect the agreements, both with the clients and with the electricity market, the EV aggregator must be capable of sending set-points to the EB3 related with rates of charge or requests for provision of ancillary services. Whenever the security of operation is compromised, i.e. when the grid is being operated near its technical limits, or in emergency operating modes, e.g. islanded operation, the system operator overrides the aggregator control signal, in order to control the EV charging. This type of EV charging management provides the most efficient usage of the resources available at each moment, enabling congestion prevention and voltage control, while avoiding the need to invest largely in network reinforcements.

In the V2G charging mode, the EV charging interface admits bi-directional power flow, enabling the EV to inject active power into the grid. From the grid perspective, this is the most interesting way of using EV capabilities, given that besides helping managing branches' congestion levels and voltage related problems in some problematic spots of the grid, EV have also the capability of providing peak power in order to make the energy demand more uniform along the day and to perform primary frequency control. Nevertheless, there are also some drawbacks related with the batteries degradation. Batteries have a finite number of charge/discharge cycles and its usage in a V2G mode might represent an aggressive operation regime due to frequent shifts from injecting to absorbing modes. Thus the economic incentive to be provided to EV owners must be even higher than in the smart charging approach, so that they cover the eventual battery damage owed to its extensive use.

The additional storage capacity provided by EV has also the potential to enhance grids' resilience, namely regarding isolated systems, improving the frequency response and increasing the amount of renweable-based μG that can be safely integrated in the system (Lopes et al., 2009). The V2G control strategies for frequency regulation adopted in project REIVE are based on the ω-P characteristics represented in Figure 2. The EV will change its power output based on the isolated grid frequency in order to reduce the imbalance between generation and load. For frequencies around 50 Hz the EV charge its battery at its nominal power. A dead-band is considered in order to avoid the degradation of EV batteries resulting from frequent solicitations for small frequency deviations. When the frequency drops below the dead-band minimum, the EV reduces its power consumption and if the frequency drops further bellow the zero-crossing frequency (f_0), the EV starts to inject power into the grid. When the grid frequency increases to values superior to the dead-band maximum, the EV increases gradually its power consumption until the maximum possible power consumption is reached.

The parameters of the frequency-droop characteristic will depend on the EV charger characteristics and on the willingness of EV owners to participate in such services. These parameters may differ from grid to grid and can be remotely changed by the DTC, in order to coordinate the EV participation with the other grid frequency regulation mechanisms (load shedding schemes and availability of energy storage devices).

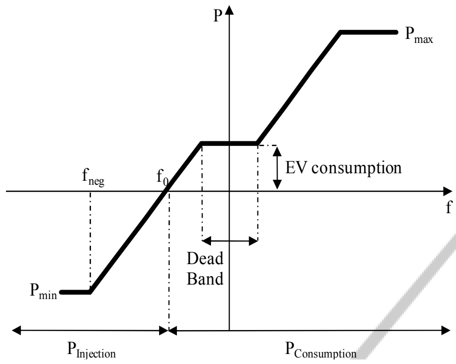

Figure 2: EV frequency-droop characteristic.

3 IMPACTS OF MICRO-GENERATION AND EV IN DISTRIBUTION NETWORKS

The large deployment of EV is very likely to provoke changes in the power demand patterns, causing changes in the grids' voltage profiles, branches' congestion levels and energy losses, namely at the distribution level, where the EV will connect for charging purposes (Lopes et al., 2011).

The identification of the control and management strategies described in section 2 of this paper was complemented by an exhaustive evaluation, in a steady-state framework, of the impacts that EV charging and μG will have in the system operation. The evaluation performed, required the development of an innovative methodology to assess the referred impacts in the Portuguese distribution system (LV + MV networks). Different EV charging strategies were also considered, as well as several future μG and EV penetration scenarios.

3.1 Methodology

The main objective of the steady-state studies performed under the REIVE project was to assess the impact of the μG and EV in the Portuguese distribution system. Due to the large extension of the network and consequent simulation complexity, some general assumptions were made, namely:

- Separate analysis of LV and MV networks;
- Only the LV and MV networks with the highest degree of representativeness of the Portuguese distribution system were selected;
- Load and generation diagrams are represented by a discrete time step of half an hour, being conducted one power flow for each time step.

Under these assumptions, the impact assessment studies were conducted for each selected network, using a simulation tool that provides a reliable and detailed characterization of the grid operating conditions. The outputs of this tool are voltage profiles, branches' loadings, grid peak power, energy losses and the identification of networks components that will possibly be operated near, or above, technical limits. The general methodology adopted is shown in Figure 3.

To obtain a detailed evaluation, three studies were performed considering: a) Only the connection of EV; b) only μG; c) both EV and μG connections. The first two studies, which address separately the EV and μG integration in the system, were performed in order to assess more accurately the individual impacts of each technology.

In order to assess the importance of controlling EV load, the dumb charging, multiple tariff scheme and smart charging strategies were considered in the studies a) and c). The V2G concept was not included in the steady-state simulations, since its main contribution is for the transient stability of the system, requiring dynamic studies that are currently on-going. As these studies were not concluded yet, their results will not be presented in this paper.

The developed tool combines a stochastic model based on a Monte Carlo method with the PSS/E tool for electric grid simulation purposes, according to the principles described in (Rosa et al., 2011). The algorithm associated with this evaluation suite is represented in Figure 4.

After evaluating the initial conditions of the grid under study, the stochastic model based on a Monte Carlo method is used to characterize the EV regarding different EV drivers' behaviours, EV charging strategies, battery capacities, charging rates and energy consumptions per distance travelled (kWh/km). Then, it simulates EV movement and charging for each ½ h period of a day.

Regarding the modelling of the μG units, the power produced by each μG unit is subtracted to the existing load at each bus for each time step of the simulation, as in (Barbeiro et al., 2010). μG units are allocated to the buses proportionally to the residential load installed in each bus and it is considered that they have unity power factor. EV are distributed through the grid according to a set of probabilities, proportional to the residential load installed in each bus. Therefore, the buses with higher residential loads installed will have larger µG units connections and a higher probability of having EV parked.

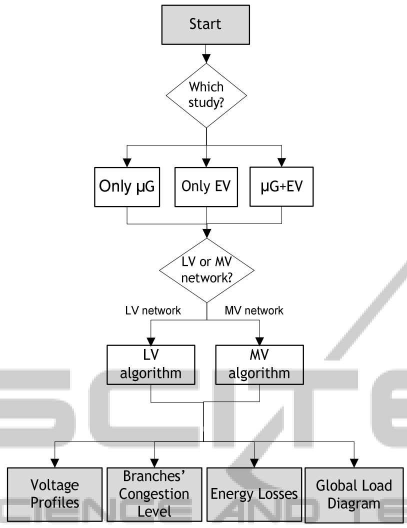

Figure 3: Methodology adopted for the µG and EV impact evaluation.

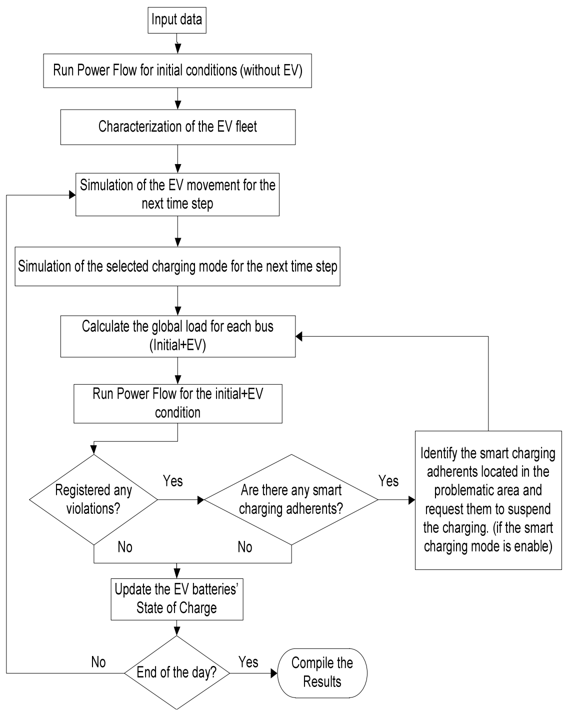

Figure 4: Algorithm to evaluate EV impacts.

3.2 Simulation Scenarios

The steady-state simulations required the definition of the EV and µG integration scenarios, as well as a detailed characterization of the distribution networks.

3.2.1 µG Integration Scenarios

In the analysed scenarios, 80% of all the µG units considered were assumed to be photovoltaic, while the remaining 20% were assumed to be micro-wind turbines. All the µG units are considered to operate at unity power factor and can be generally characterized by specific generation patterns, which depend on the technology specificities. The Decree-Law No. 363/2007 establishes the legal regime applicable to electricity production through µG units, stating for the year of 2008 a maximum power capacity of 10 MW that could be subsidized. This value is successively increased at a rate of 20% per year up to 2015. Based on this legal frame and as in (Barbeiro et al., 2010), two µG integration scenarios were considered:

- Scenario A – µG installed capacity at national level grows at a rate of 20% until 2015 and 3% from 2016 to 2030, reaching 250MW of installed capacity in 2030.
- Scenario B – µG installed capacity at national level grows at a rate of 65% until 2015 and 6% from 2016 to 2030, reaching 2000MW of installed capacity in 2030.

3.2.2 EV Integration Scenarios

Since the aim of this study is to assess the impact of the EV in the distribution grids, it is of utmost importance to define a reasonable set of hypothesis for EV integration until 2030. In this paper two scenarios of EV deployment were defined, considering two different automobile replacing rates and attending to the social and political circumstances.

Table 1: Nr. of BEV and PHEV (thousands of units).

	PHEV		***BEV***	
	2020	2030	2020	2030
High variant (103)	168	444	84	1035
Low variant (103)	114	422	76	281

Additionally, the scenarios defined differentiate the growth of the two main types of vehicles that are expected to be deployed: the battery EV (BEV) and the plug-in hybrid EV (PHEV). The number of EV expected to be integrated in the Portuguese fleet by 2020 and 2030 is presented in Table 1.

3.2.3 Portuguese MV and LV Distribution Networks

As it was previously referred, the presented studies were performed on a set of LV and MV Portuguese distribution networks, based on real data. For the LV simulations, five typical LV networks were used, classified according to their MV/LV transformer rated power, which is a satisfactory approximation of load density. Regarding the MV networks existing in Portugal, six typical MV networks were identified. The load and topological characteristic of these networks are assumed to be representative of different parts of the overall MV distribution grids in Portugal. In terms of distributed energy, the six MV grids approximately represent a geographical area totalizing approximately half the total energy consumption registered in the whole Portuguese MV distribution network. A detailed description of these networks can be found in (Barbeiro et al., 2010).

In 2010, the annual consumption in the entire Portuguese distribution network was approximately 44.7 TWh. Considering the evolution of the Portuguese electricity consumption in recent years and the current economic and financial situation, a load growth rate of 1.5% per year was considered for a time horizon from 2010 to 2030.

The load diagrams adopted for this study were based in the diagrams used in (Barbeiro et al., 2010). The study considers two different periods in a year – winter and summer. For the MV, it is possible to distinguish three types of consumers: residential, commercial (both at the aggregate level of the MV/LV substation) and industrial (consumers fed directly at MV level). In LV grids only residential and commercial consumers were considered, since the number of industrial consumers does not have significant relevance.

3.3 Results Analysis

Following the methodology previously described, this section presents the results obtained regarding the different EV charging strategies as well as the future integration scenarios of EV and µG.

The daily load curve presented in Figure 5 illustrates the consumption pattern for a typical winter day for the year of 2030 in a LV network with a 630kVA transformer capacity. In this scenario this network supplies approximately 63 plugged-in EV. From Figure 5 it is also possible to compare the impact of the considered charging strategies on the daily load curve.

As shown, adopting a dumb charging strategy will increase the peak power approximately 62 kW, since EV are likely to be charged at the end of the day. Adopting a multiple tariff scheme will result in a new peak at 22:00h, when the period with a lower tariff begins. When adopting a smart charging strategy, the EV charge occurs preferentially on the valley hours, contributing to keep the peak load almost unchanged.

Regarding the contribution of the µG units, in Figure 6 it is possible to verify that since the majority of µG units are photovoltaic systems, during the hours with greater sunlight exposure there is only a small reduction in the peak power. It is important to state that Figure 6 is referred to the scenarios b), where only the µG was considered.

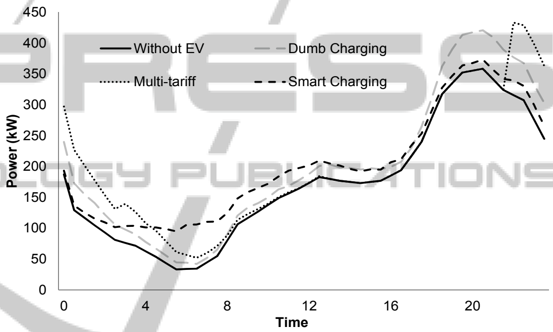

Figure 5: 2030 load diagram at the MV/LV substation of a LV network with 630 kVA transformer adopting different charging strategies.

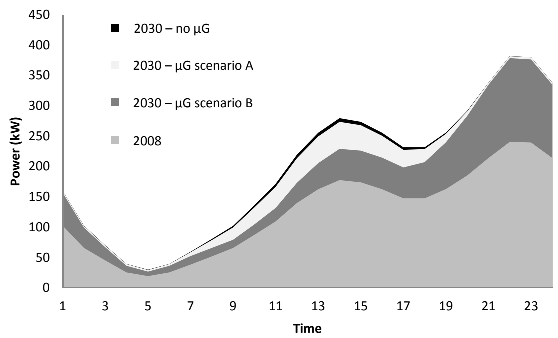

Figure 6: 2030 load diagram at the MV/LV substation of a LV network with 630 kVA transformer for the different scenarios of µG.

The evaluation of the branches overloading is also an important measurement of the adequacy of the Portuguese networks for future deployment of EV. In general, the branches' congestion levels increase in the scenarios without direct control of the EV charging.

Figure 7 shows an example obtained for a LV network with a 400kVA MV/LV transformer. The figures provide a comparison of branches loading in the peak hour of the scenarios without EV (upper-left picture) and with 14 EV, in order to provide a general overview of the three charging methods' impacts in this matter. In this case the maximum branch loading detected increased 45% with the dumb charging, 56% with the dual tariff and only 11% with the smart charging.

Adopting different charging strategies is also expected to increase the networks active power losses, since the power consumption increases.

As shown before, uncontrolled charging strategies increase the peak power consumption, increasing also the current and consequently the active power losses. However, controlling the EV load though smart charging strategies, complemented by local generation from the μG units, contributes to avoid significant increases in the network losses. The value of energy losses in the Portuguese distribution network (MV and LV) was 1782 GWh in the year 2008. This value represents approximately 4.14% of the total consumption in the entire Portuguese distribution network.

From the results obtained due to conventional load growth, in 2030, energy losses will reach the value of 4394 GWh. When considering the future deployment of EV, losses could reach 5209 GWh if EV charging is not controlled. In this case, the integration of μG could reduce losses to 4698 GWh in scenario A and to 4457 GWh in scenario B. This value can be further reduced if the smart charging is adopted, as shown in Figure 8.

As expected, the smart charging provides better results since it makes the load distribution along the day more uniform, consequently reducing the grid's peak demand.

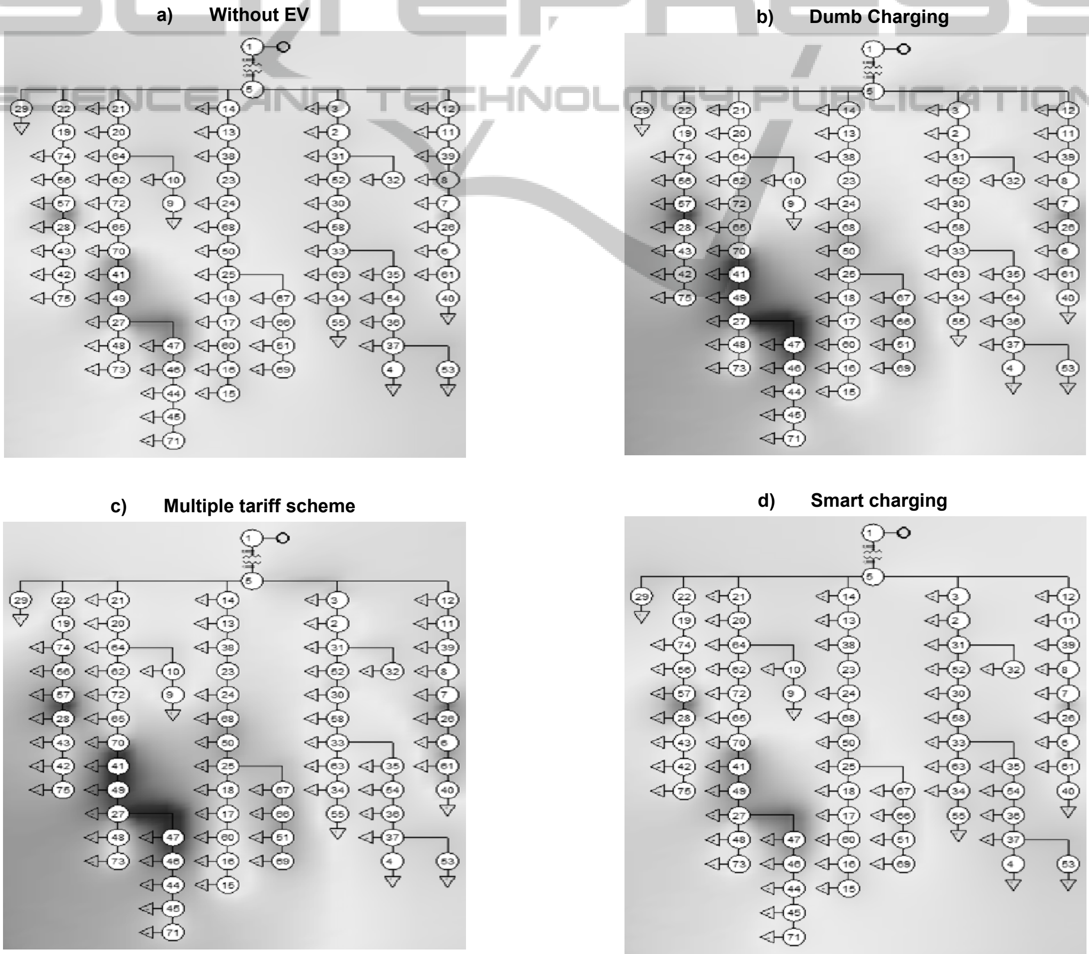

Figure 7: Lines loading for a LV network with a 400 kVA transformer (low EV scenario, Summer day, without μG and for the year 2030). Grading between light grey and black, stand for increasing values of congestion, from 0 to 100%.

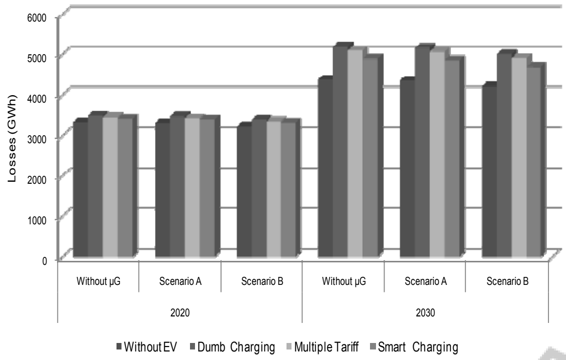

Figure 8: Total distribution network losses (MV and LV) for 2020 and 2030, High EV integration scenarios.

From the results obtained it was also possible to conclude that the µG and controlled EV charging also have a positive impact in the CO2 emissions and voltage profiles. When comparing the EV charging schemes (µG not considered), the results obtained show that the the smart charging can avoid ~110 ktons of CO2emissions when compared to the dumb charging. The µG, in turn, can avoid 70 ktons when comparing Scenario B with the case without µG (EV not considered). Contrary to the EV charging strategy adopted, the µG has little influence in the grids' voltage profiles. Although not presented in the paper, the results obtained showed that the smart charging can avoid possible voltage violations that are likely to occur if other charging schemes are adopted.

4 SMART GRID IN LABORATORIAL ENVIRONMENT

As previously stated, the REIVE project aims the conceptualization of innovative control and management algorithms for smart grid applications, where EV and micro-generation units present one of the most relevant roles. Additionally, the smart grid paradigm is necessarily supported by an adequate communication infrastructure, which will conditioned the possibility of developing more or less ambitious control and management schemes. Additionally, the deployment of EV and micro generation units in distribution grids introduce important impacts in terms of voltage profiles and branches congestion levels, thus requiring specific systems allowing interaction with these elements in order to control and manage their power interchanges with the grid. Therefore, the laboratorial infrastructure under development is the physical space that will enable pre-prototyping new power electronic interfaces for EV and micro generation units, which incorporate the capability of active interaction with the smart grid control infrastructure. The laboratorial infrastructure will allow the individual and integrated testing procedures for new concepts, control algorithms to be housed at the different smart grid hierarchical layers, communication architectures, technologies and protocols that will allow feasibility demonstration regarding functional and technical specifications developed within the project. In this sense, the main objectives of the REIVE laboratorial infrastructure are:

1) Development of applied research activities regarding the development of the microgrid concept as the base power system active cell for smart grids.
2) Development of advanced research activities regarding active integration of EV in the smart distribution grid control architecture.
3) Consolidation key competences regarding the natural moving from the actual distribution grid operational paradigm to a more active one, where the smart grid concept is fully envisioned.
4) Development of software modules for pre-prototypes of the smart grid key controllers for its different operational layers (such as MGCC, SSC, etc) and perform a preliminary evaluation of its performance in close collaboration with simulation results
5) Development of pre-prototypes of advanced interfaces for EV and micro-generation units, in accordance with the project on-going functional and technical specifications.
6) Actively support national and international standardization activities in different domains, according to the laboratorial developments obtained in the project
7) Technology transfer to the industry regarding innovative concepts for smart grid controllers and for EV and microgeneration interfaces under development within the project.

5 CONCLUSIONS

The REIVE project is dedicated to develop and test technical solutions and pre-industrial prototypes for the active and intelligent management of electricity grids with large scale integration of µG and EV.

Within the framework of this project, innovative tools were developed to identify the impacts of the µG and of the different strategies adopted for the management and control of EV. The steady-state results presented proved that µG and EV integration might bring important technical benefits to distribution grids, namely if the EV deployment is accompanied with the implementation of controlled EV charging schemes. The major benefits are related with the reduction of branches overloading, grids' peak power, energy losses and CO_2emissions.

The future work of this project is focused on the development of laboratorial prototypes of the software modules that will constitute the EB2, EB3, DTC and SSC controllers, together with the required interfaces in order to interact with the devices installed in the field (loads, EV, µG, storage devices). The usage of laboratorial facilities will allow extensive validation of the developed concepts and control strategies for facilitating µG and EV integration.

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