SMARTplug: Using smart devices for a managed charge of electric vehicles

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Abstract

Electric vehicles are seen as an option to reduce greenhouse emissions from the transportation sector and their number on the road is growing in a daily basis. However, with their widespread adoption the increase in the demand for electricity to charge these vehicles could pose significant challenges to the electrical grid in terms of additional load due to unmanaged charge strategies. In order to mitigate this problem, the charging of the electrical vehicles must be managed. This paper presents the development of a hardware and software architecture to dynamically control the charge of electric vehicles to maintain the proper operation of the local distribution grid, by reducing the possibility of power outages due to overload, in a Smart Grid context. The hardware consists in two modules, a meter and controllable plugs both with communication capabilities, while the software consists in a load forecast and scheduler module. The load forecast is calculated based on the power consumption behavior and is used to assign the best time slot to charge the vehicle. The system aims to minimize the load peaks and flatten the load profile.

Based on the user preferences, system characteristics and consumption forecast, the system will assign the most suitable time slot to charge the electric vehicle. For the case of multiple electric vehicles, the system will schedule their charge based on a calculated priority level, in order to maintain a reliable operation of the local electrical grid.

1. Introduction

Electric Vehicles (EVs) are expected to have a large share in the future of the transportation system in order to reduce the share of Greenhouse Gas (GHG) emissions associated to personal transport and also due to the increasing costs of fossil fuels [1] [2]. This electrification of the transport system will cause an additional load on the electric grid, since the EVs will require a connection to the grid to charge the batteries. Currently, due to the EVs low penetration rate the additional load imposed to the grid by the vehicles charging is not an issue, however in the future, with a higher penetration rate, this could bring serious consequences to the grid reliability due to overload [3] [4]. The main problem is not in the extra energy required to charge the batteries, since the grid has enough capacity, but the peak load of the charging [5] [6].

Since the majority of EVs will be charged at home, it is expected that the vehicle will be plugged in when their owners get home, at the end of the afternoon. This behavior will lead to a considerable additional load that can overload the grid. In order to mitigate these problems, the charging cycle of EVs must be managed in some way [7]. This concept of coordinate charging is being explored due to the wake of smart grids, where the exchange of information using several communication technologies can improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity [5] [8]. Coordinate charging can also be beneficial for grids with a large share of renewable energy sources by absorbing the excess energy produced [9].

Alternatives to uncoordinated charging are currently being investigated by using devices with bi-directional communication capabilities to perform a coordinated charging [10] [11] [12]. This type of coordination is intended to minimize the negative impacts on the grid, due to a large number of vehicles charging at the same time by distributing this charge over a large period of time, flattening the load peak. Efficient operation in a smart grid environment usually is focused in reducing energy losses and increasing efficiency [13] [14], in this paper the focus is in maintain the grid stability by avoiding the overload due to the uncoordinated introduction of additional loads.

2. Motivation and Problem Definition

Intelligent control over the introduction of new loads into the grid has the potential to provide economic benefits since peak demands affect the grid investments and operational costs [15] [16]. Minimizing demand peaks by distributing the load over a longer period of time will contribute to reducing the transmission and distribution losses, since these losses grow with the square of the current, and stress in the grid equipment [17] [25]. In order to flatten the load profile, some utilities apply different price rates depending on the time of day to encourage customers to shift the use of certain appliances, such as washing machines, to off peak hours when electricity price is cheaper. This approach contributes to the reduction of peak demand, however this implies active consumer involvement which can be difficult to manage. Relying on consumers to manage their energy consumption to off peak hours can work during an initial period, where they are motivated by the novelty and savings that can be achieved, however after this initial period they will start to revert to old habits. Using an automated system that takes into account user preferences, to manage the loads is a better solution since the system will automatically adapt by continuously evaluating the grid status and could also allow the utility to disconnect/connect loads in certain situations [18] [19] [22].

Since EVs are a significant load (around 3.6 kW during the charging cycle of the EV, which can last up to 6-8 hours), the use of an automated load management system can contribute to an automated demand response program controlled by the grid. This demand response system refers to the ability to reduce loads at peak times to lighten the need for peaking generation sources. These power plants are usually gas turbines that burn natural gas, due to their fast response, and since they only supply power occasionally, the price per kilowatt hour is much higher when compared with the price for base load power plants. The shift of these loads to off peak hours can also contribute to a reduction of GHG emissions due to an increasing in the efficiency of gas and coal power plants [24].

Loads equipped with communication and control capabilities can be aggregated and dispatched to help to manage the grid. This load aggregation can provide the same regulation as ancillary services, nowadays provided by power plants. This regulation is very valuable since it provides real time matching between load and generation. Without this equilibrium the grid frequency will drift up or down affecting the quality of service [20] [21] [25]. Despite the benefits for the network in terms of increased reliability, this service provided by EVs is also beneficial since it will have a financial revenue associated [22].

Nowadays this regulation is achieved by forecasting the load based on past data and dispatch of generation accordingly, however this load following approach becomes more difficult as the share of renewable generation increases. The intermittent nature of renewable energy sources, such as wind and solar, makes very difficult to predict with certainty their contribution to the total generation and can require more conventional generation sources used as backup to provide ancillary services and regulation to the grid.

The introducing in the market of vehicles with the capability to be plugged into the grid associated with a daily commute distance under 50 km (which requires up to 10 kWh of energy) for the majority of the users will make the EV one of the major energy consuming devices in a household. An EV charging, using a Level 2 charging station will draw 3.6 kW of power during around 3 hours per day for a 50 km commute. Based on the commute profile of the users, is reasonable to expect that EVs will be plugged in at least during 8 hours per day (or more if the EV is also plugged in at work and not necessarily charging during this period) which is more than the required time to restore the energy spent, resulting in a flexibility that also can be harnessed to provide grid services while ensuring the requirements of the user.

EVs could be an excellent demand dispatch resource given their potential for rapid response (can be turned on or off in a matter of seconds), the significant amount of power that they can draw during large periods of time and expected market penetration. It is possible, that in the future, a significant part of the ancillary services to provide regulation to the grid will rely on EVs.

3. SMARTplug System Architecture

This paper presents the development of a hardware and software architecture for demand response, where the main goal is to manage in real time the additional load introduced by EVs when charging at home, avoiding triggering the installation protections due to overload (Figure 1). This management also intends to flatten the load profile by shifting the peaks to the valleys based on user preferences, EV battery State of Charge SoC and local installation power capabilities. The system requires the following parameters from the user:

- Contracted power: Defines the maximum amount of power that can be used from the grid without tripping the installation protections. If at a given moment the present or foretasted power reaches 80% of this value, the electric vehicle is disconnected or the time slot is considered invalid for charge, respectively.

- Vehicle charger power: Specifies the amount of power that the electric vehicle will draw during the charge cycle (for a Level 2 charger this value is around 3.6 kW).

- Battery SoC required: Specifies the maximum state of charge for the electric vehicle.

- Unplug time: This time defines the deadline to achieve the required battery state of charge.

- Energy tariffs: Specifies the different costs of the consumed energy to different time periods. If several time slots are suitable to charge the electric vehicle, the chosen one will be the one with the lower tariff.

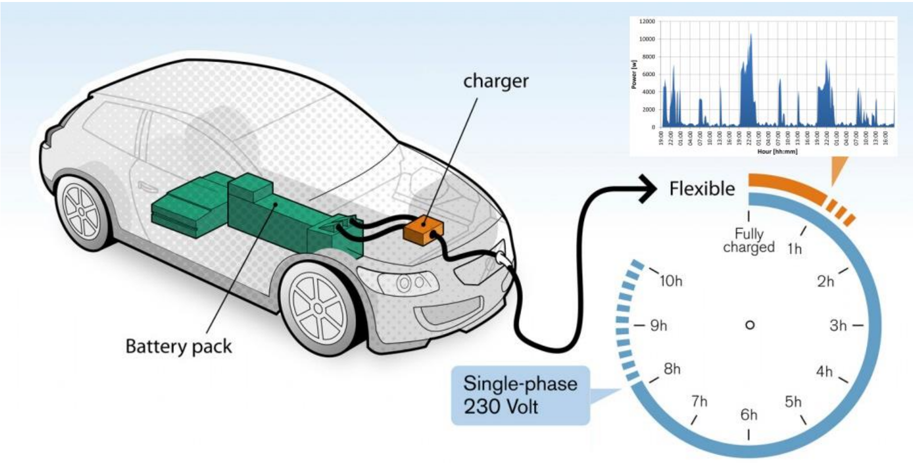

Figure 1: Scenario where is possible to implement the SMARTplug system. The system is aimed for a residential environment, with a single or multiple charge points.

Hardware Architecture

The system, described as SMARTplug, is composed by two main devices, an energy meter and a smart plug (Figure 2), both with communication, data storage and local processing capabilities. The energy meter is installed on the feed point of the infrastructure, to measure in real time the global energy consumption, while the smart plug will replace the standard plug used to charge the EV. The energy meter will also store the load diagram from at least the previous three weeks. Depending on the number of charging points for EVs, it is possible to have multiple intelligent plugs in the same infrastructure, but only one energy meter is required. For a single charging point it is possible to integrate these two devices into one to avoid complexity and reduce costs.

The stored data is used to forecast the load during the time when the electric vehicle is plugged in and to assign a time slot to charge the EVs. If the EV is plugged in eight hours and only requires two hours to achieve the desired SoC, the time slot chosen will be the one with the lower tariff, with the lower footprint and the lower impact on the load diagram in terms of peak power.

Both devices have a dedicated energy measurement unit that calculates all the relevant parameters (voltage, current, energy, power and power factor). The micro-controller communicates with the energy measurement unit through RS-485, and stores the power data each minute. The smart plug additionally has a solid state relay used to turn on and off the power. The communication between the two devices is currently done by RS-232, but another communication interfaces could be used.

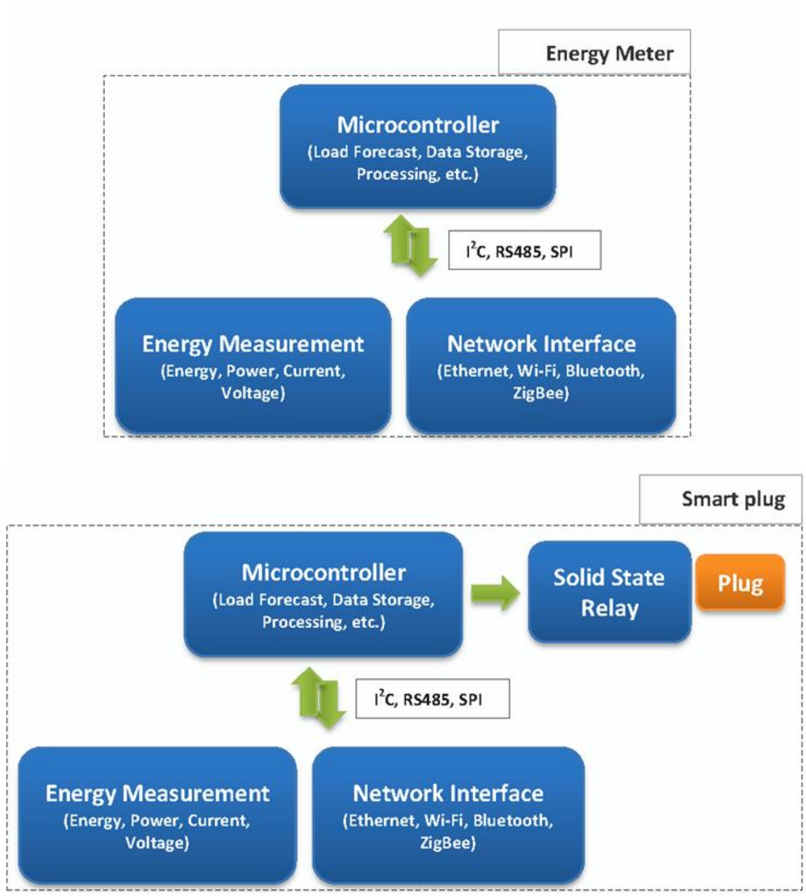

Figure 2: SMARTplug system architecture with the energy meter (top) and the smart plug (bottom).

Software Architecture

In terms of software architecture, the SMARTplug system has three main components: a load forecast module, a classifier module and a scheduler module. The Load Forecast module is responsible to forecast the load based on previous data. This module uses the power data stored by the energy meter, excluding the contribution from EVs charging stations, for the global power consumption. The forecast is performed by using the average previous data for the same time frame and taking into account if it is a weekday or weekend, since the load diagram varies significantly from weekday to weekend. The forecast is performed with a five minutes interval, despite the data being stored each minute.

The Classifier module (Figure 3) is responsible by the analyses of the time slots where the charge of the EV may occur and classify them as valid or invalid. This module will run when the EV is plugged in and based the load forecast, electricity price, contracted power and power draw by the vehicle will determine a set of valid time frames to charge. The load forecast for a given timeslot considers the past five identical timeslots (e.g. the load from the previous five days at 15:00 hours) and is calculated using Equation 1.

Equation 1
$$\boldsymbol{L_t = \sum_{n=1}^{5} \propto_n \cdot L_n}$$

Where L_n is one of the past timeslots and $\propto_n$ the weight factor considered for that timeslot. A given time slot is only valid if the contracted power is higher than the load forecast plus the power draw by the vehicle. The availability of a time slot is calculated using Equation 2:

Equation 2
$$\boldsymbol{A_{vt} = P_{cont} - (F_{pt} + SM) - P_{ch}}$$

Where P_{cont} is the contracted power, F_{pt} is power consumption forecast for time T, P_{ch} is the power of the EV charger (3.6 kW for Level 2) and SM is a safety margin (0.2 kW). From Figure 3 in the validation of availability, depending on the ratio between A_{vt} and P_{ch}. a grade is assigned. The values for the grade were chosen arbitrarily to penalize time slots with high energy tariffs and demand forecast.

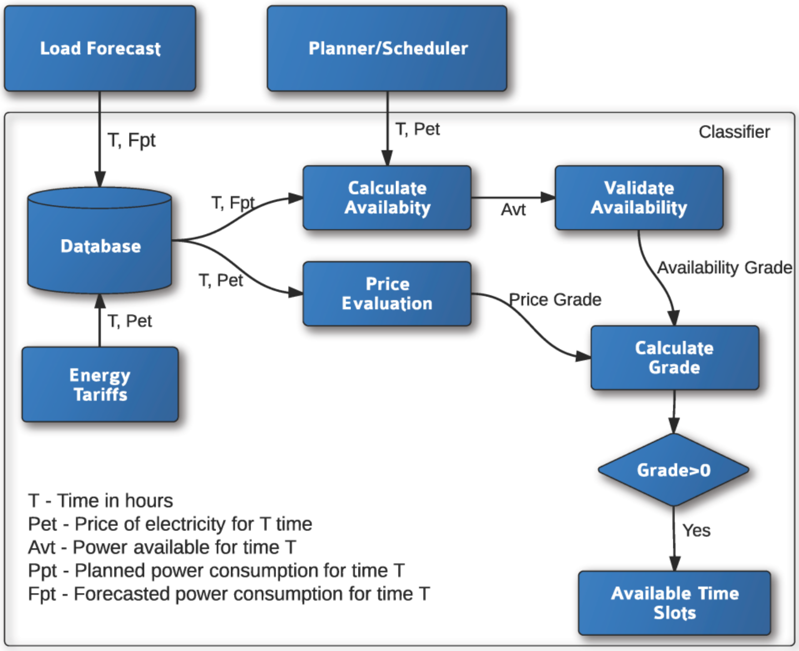

Figure 3: Diagram for the classifier implemented in the SMARTplug system. The classifier determines the valid time slots to charge the EV based on the load forecast, electricity price and planned power consumption.

The Scheduler module (Figure 4) is responsible by the generation of a charge plan. After the validation of the time slots, the planner will assign the best slot to charge the vehicle, based on load requirements (in this case the load is the EV).

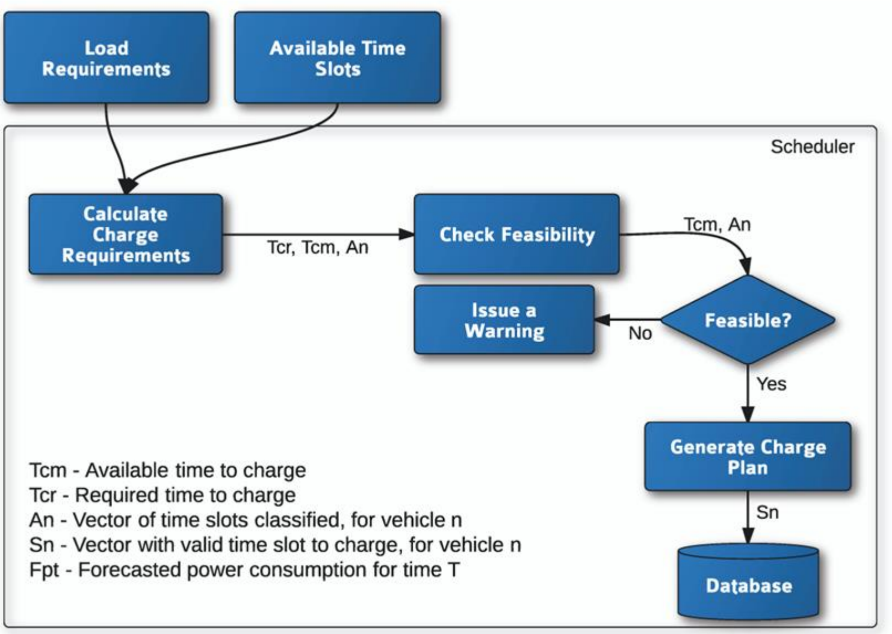

Figure 4: Diagram for the scheduler implemented in the SMARTplug system. The scheduler generates a charge plan based on the available time slots and load requirements.

The load requirements are the capacity of the battery, the SoC of the battery when the vehicle is plugged in, the required SoC and the time of unplug. Based on these parameters the charge requirements are calculated using Equation 3:

Equation 3

$$\boldsymbol{T_{cr}} = {\left(\boldsymbol{B_{cap}} - \boldsymbol{B_{cap}} \times \frac{\boldsymbol{SoC_{ini}}}{\boldsymbol{100}}\right)} \Big/ \boldsymbol{P_{ch}}$$

Where T_{cr} is the required time to charge in hours, SoC_{ini} is the initial SoC in % and B_{cap} in kWh is the useful battery capacity (on the Nissan Leaf from the 24 kWh only 20 kWh are useful). The feasibility is only validated if a set of available time slots required to charge the vehicle are less or equal than the ones available. If several sets of time slots are available to charge the vehicle, the chosen one will be the one with less impact in the load diagram.

Load Diagram Analyses

To understand the extent in which the management of the additional load introduced by EVs could be controlled by a system with minimal intervention by the user, it is important to have detailed information regarding the energy consumption during a large period of time. Figure 5 represents the load diagram for an average European household [23].

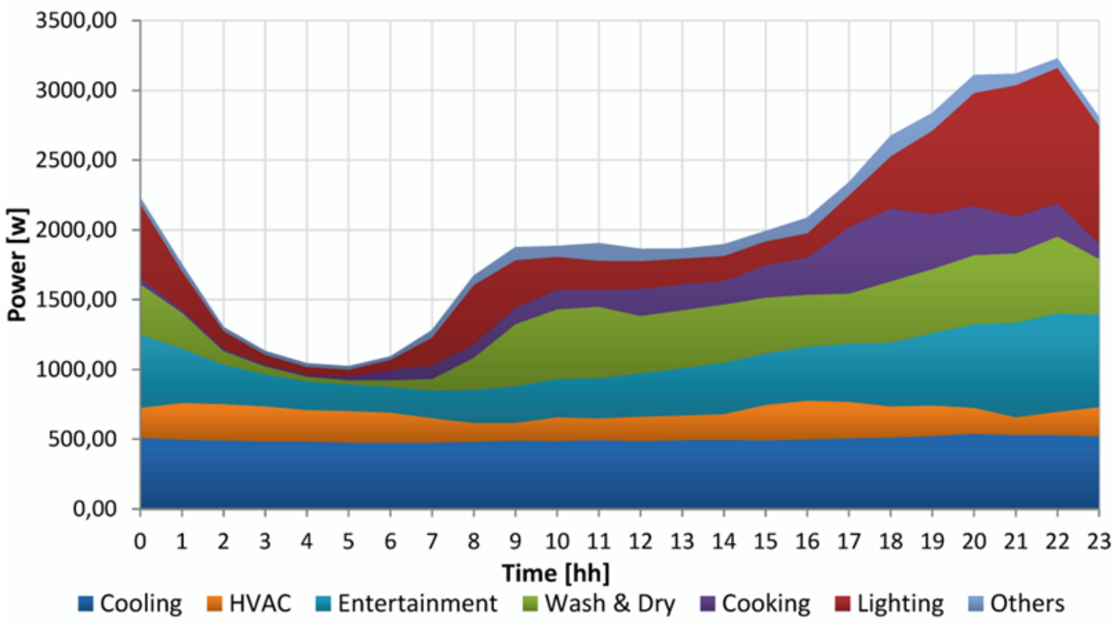

Figure 5: Load diagram, by type, for an average European residence during a day [23].

From Figure 5 it can be seen that the majority of the power consumption occurs between 17:00 and 00:00 and between 01:00 and 07:00 the consumption reaches its minimum. By analyzing the load diagram, is visible that the best time to charge an EV is between 01:00 and 07:00, however this implies that the user must plug in the vehicle or program it to charge during this period. Despite this being a valid solution, this implies active participation from the user, and as referenced before, cannot be guaranteed that the charging will occur at optimal times.

Figure 6 and Figure 7 show an extract of a load diagram for two residences that were monitored, A and B, for a weekend and three days of the week [23]. These load diagrams are only for the household loads, excluding EVs. By observing the load diagrams it is visible that the consumption is concentrated in specific points in time and is very similar from day to day. For a given residence the load diagram tends to be very stable for works days and weekends. Based on these facts and using consumption data gathered over time, the consumption for the next 12 hours can be predicted. Without access to this information it would be very difficult to the user to choose the ideal time to start charging the vehicle. The benefits of an automated system over the common approach, where the user is responsible for the process of start charging the vehicle, is that the system can choose the best time to charge the EV taking into account several variables.

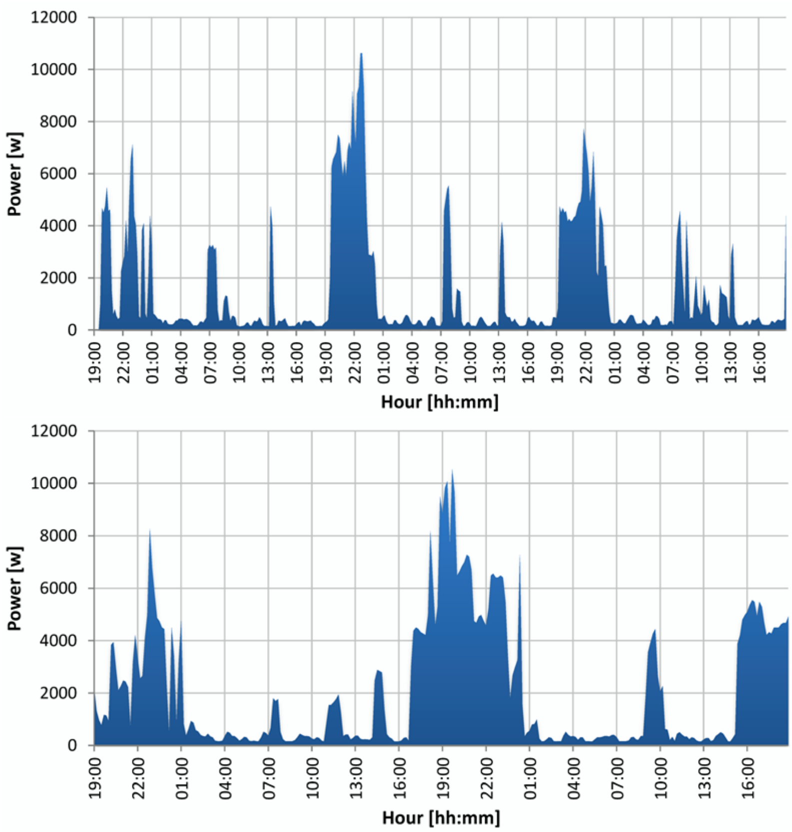

Figure 6: Load diagram for three weekdays (top) and for a weekend (bottom), for residence A.

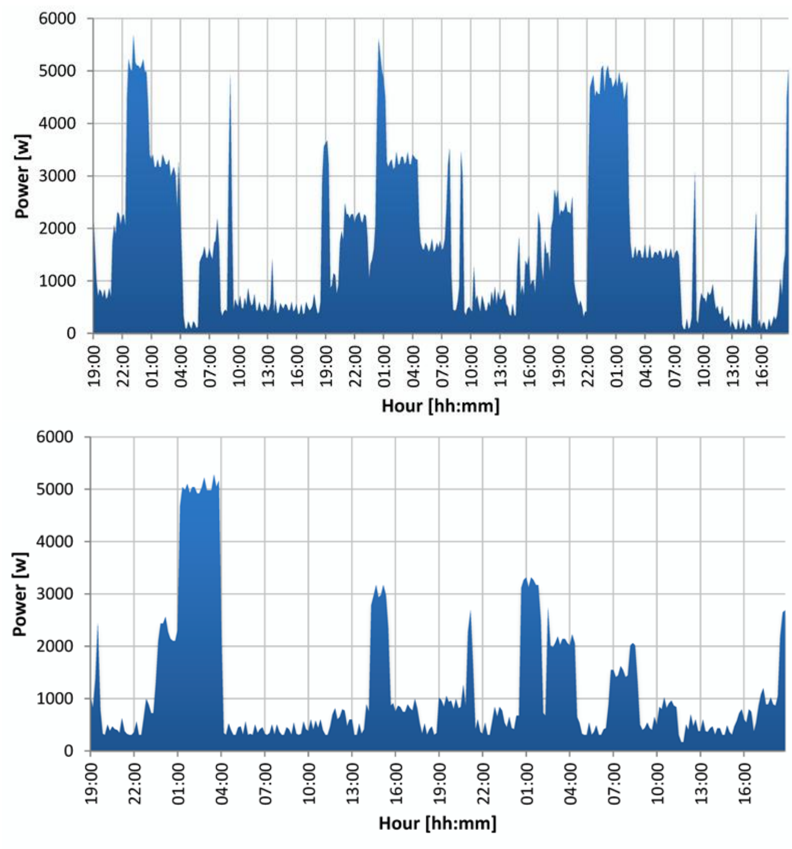

Figure 7: Load diagram for three weekdays (top) and for a weekend (bottom), for residence B.

To assess the impact that an EV can have in the energy and power consumption of a residence, the load profile during the charging cycle must be analyzed. Figure 8 presents the load profile of a Nissan Leaf for full charge and for a partial charge. The full charge absorbed 20.6 kWh of energy from the grid at an approximately constant rate of 3.6 kW during a period of five and a half hours. The profile of a partial charge is identical to the one of a full charge, except in the duration. This partial charge has absorbed 5.5 kWh during one and a half hour. For an EV with an energy consumption of 150 Wh/km, a charge of 20 kWh will provide a range of about 130 km, while a charge of 6 kWh will be suitable for 40 km.

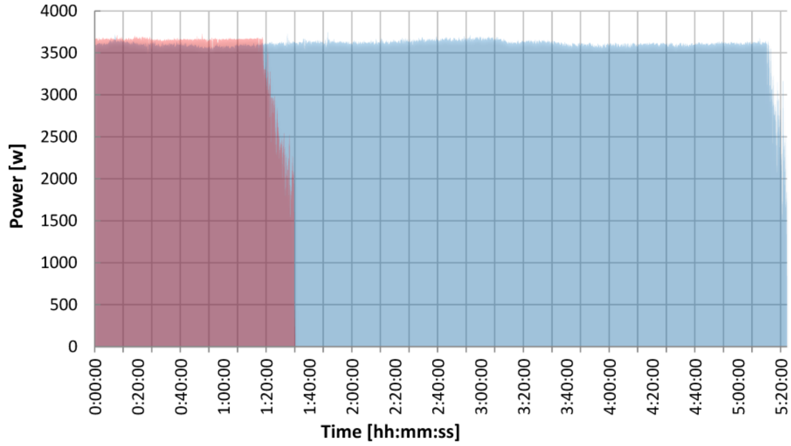

Figure 8: Charge profile for the Nissan Leaf over a full charge cycle (blue), with an energy consumption of 20 kWh over five and a half hours, and a partial charge cycle (red), with an energy consumption of 5.5 kWh over one hour and a half.

Figure 9 and Figure 10 present the impact of the additional load imposed by the EV in different scenarios, where the EV is plugged at 19:00 and must be fully charged at 08:00. The managed charge is based on the load forecast while the real load profile is presented for comparison. Figure 9 represents the impact of a partial unmanaged charge, where the vehicle starts charging when is plugged, and for a managed scenario, managed by the SMARTplug system.

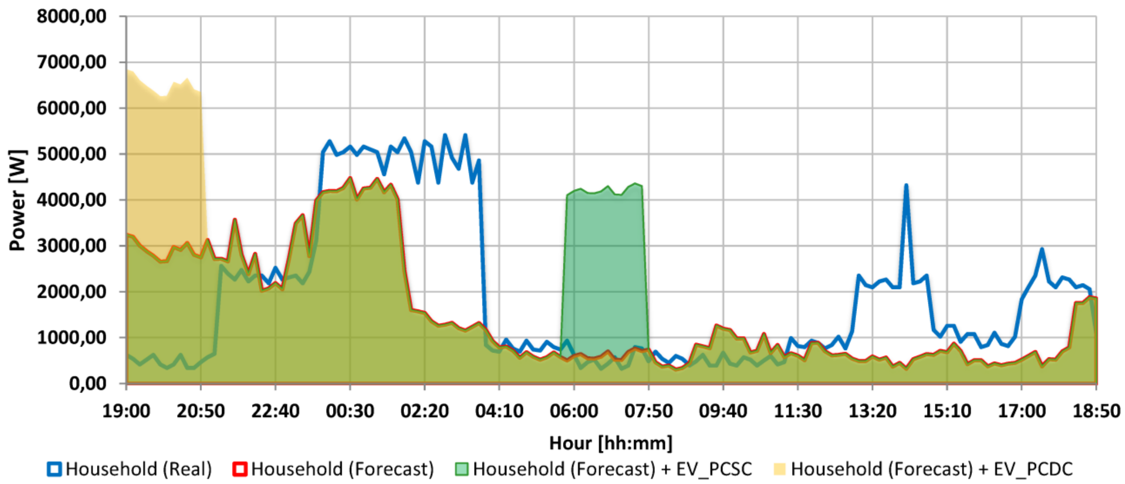

Figure 9: Load diagram (real and forecasted) for a household with an EV unmanaged (EV_PCDC) and managed (EV_PCSC) partial charge. The vehicle is plugged in at 19:00 hours and must be charged at 08:00. The charge takes two hours and consumes 7.2 kWh.

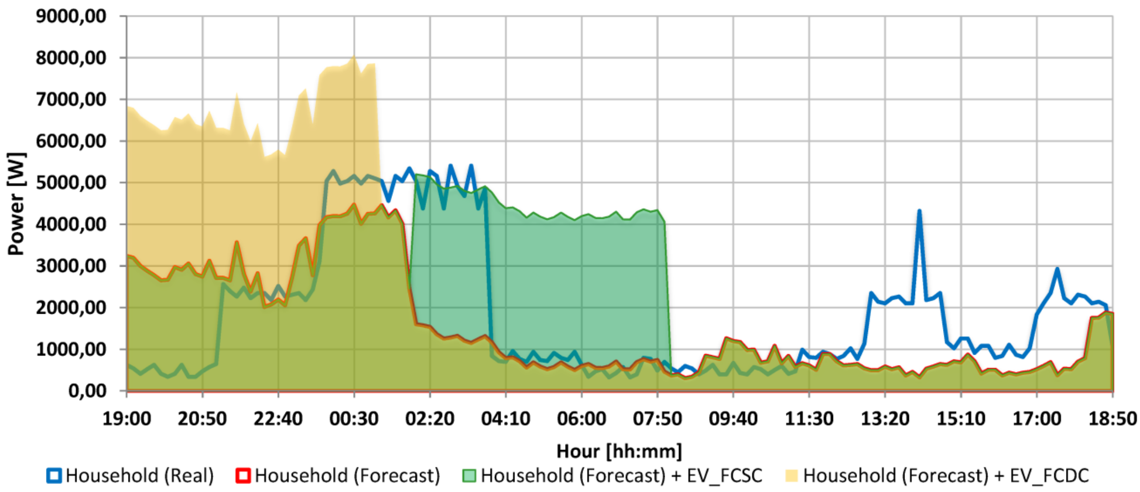

Figure 10: Load diagram (real and forecasted) for a household with an EV unmanaged (EV_PCDC) and managed (EV_PCSC) full charge. The vehicle is plugged in at 19:00 hours and must be charged at 08:00. The charge takes six hours and consumes around 21 kWh.

Observing Figure 9, it is noticeable that the managed charge has a better performance than the unmanaged charge since it will occur in the valley of the load diagram that take place during the night, when the energy is cheaper. The managed charge also reduces the peak power required to charge the vehicle, since it only tries to charge it when the forecasted power consumption for the household, in a given time period, is minimum. If the vehicle is plugged in only at 23:00 hours the peak power will be much higher and the household protections could be tripped due to overload. The benefit of a managed charge is more visible for full charge cycles where a large amount of power is drawn over a long period of time (Figure 10).

In this approach a simple forecast algorithm was used and by observing the load diagram from Figure 9 is noticeable that for given time periods the load forecast will not follow the real load accurately. This happens for periods where the load variation for a given time period is not very constant during the past days. Upgrading it to consider the different types of loads found in a household and include a model based on their use could improve the load forecast, however this approach would require a more extensive configuration of the system.

If multiple EVs are charge at the same time, the algorithm takes into account the charge plan of the remaining (their load is considered in the load forecast) vehicle. The system will give priority to the vehicles with tighter deadlines to achieve a pre-determined battery SoC. If a given vehicle cannot meet the user requirements, the user intervention is required to change the parameters.

4. Future Work

Despite the system architecture described previously being intended to be used in a residential infrastructure; it can be scaled to be implemented at the grid level. Since the same working concept could be applied (a smart meter installed on the feed point manages the smart plugs). In this case, the system architecture is divided into tiers and areas based on the power level and feed transformers, where each tier is associated with a power level and areas are associated to a given feed transformer. This approach decentralizes the decision making, where only the transformers directly affected by the power overload in a given area take action (by broadcasting a command to turn off loads). The control of the system, by a centralized entity, is also possible by introducing virtual loads into a given area to bind off loads. This capability is key for the implementation in a smart grid environment. The scalability of this system to manage other type of loads can be easily implemented, by installing additional smart plugs and setup a load profile, since each load has its own requirements. In terms of software, adjusting the time granularity, for the load forecast and planner/scheduler algorithm, based on the load diagram will contribute to reduce redundant calculations and speed up the algorithm.

Depending on the loads types, it is also possible to implement a strategy that will adjust the amount of power that each load requires in order to maintain the stability and avoid disconnecting loads. The use of a load balancing algorithm is also possible by charging the vehicle between power peaks.

5. Conclusion

In the future EVs will have an active contribution in the electrical grid management, due to a significant penetration ratio, by being able to absorb and inject power in a smart grid environment (Nissan already has a device that allows the EV to provide electricity to a household). However, nowadays even with a low penetration ratio of EVs and with the smart grid in an embryonic stage it is already possible to develop solutions that can implement some concepts from the smart grid. The capacity to inject power into the grid will lead to additional cycling of the EV battery, and contributes to accelerate the battery aging, however this impact will depend on the frequency that the grid will require this service. Due to cheaper electronics, standardization and mass use of communication infrastructures it is possible to develop a system than can be integrated in a smart grid, by implementing state of the art concepts without or with minimal intervention from the consumer, simply by updating the software in the device. By using a system similar to the described, the charging of an EV is straightforward and situations that can pose a risk to the household electrical system can be mitigated.

Despite the system architecture presented be originally targeted to provide a managed control of the charging cycle of EVs, it can easily be adapted to manage other loads in the household, however, this additional capability must take into account the load characteristics. With the evolution of the smart grid, both in terms of communication and management algorithms, this system can also be upgraded to integrate the new control strategies by simply updating the software and installing a new network interface card. Currently, demand side management requires the active consumer involvement, which is not very effective. By relying on a system that only requires the consumer input to specify its preferences, it can be shown that the additional load due to the charge of EVs can be easily integrated in the daily load diagram of a household without contributing to increase the peak demand. The system is also able to detected abnormal situations and notify the consumer (when it is not possible to meet the charge requirements) or act accordingly (when the EV is charging and overload situation is imminent the charge is stopped).

6. Acknowledgment

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