Integrating the Electrical Vehicles in the Smart Grid through Unbundled Smart Metering and multi-objective Virtual Power Plants

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Abstract--This paper presents a solution for integrating Electrical Vehicles in the Smart Grid through unbundled Smart Metering and Virtual Power Plant technology dealing with multiple objectives. Within this frame, EV can benefit of cost-effective energy during the charging period but can also provide multiple ancillary services to the network, by wisely using their storage capability and their flexibility in coupling to the grid. Simulation of an EV providing services under a multi-objective VPP is also presented, with analysis and conclusions about the technical feasibility of such applications.

Index Terms -- Electrical Vehicle, Unbundled Smart Metering, Virtual Power Plant, Distributed Energy Resources, Ancillary Services, Network Services, Intelligent Energy Portal, Smart Grid, Active Networks, Cyber-Energy System

I. INTRODUCTION

It is well known that environment related limitations require several simultaneous measures since no individual action is sufficiently strong to solve the entire problem. Smart Grid is a synergy between the traditional power system and the new information systems, developed initially in the software IT field, but rapidly extending to the nowadays energy networks.

The electrical vehicles are reinventing the hundred years tradition industry and shows promising potential for supporting the clean energy (renewables) or energy with reduced CO\(_2\) footprint. Their mobility needs a key technology: the storage, a priority research topic in the last period that has proven to have viable solutions. Storage is a technology that fits to the Smart Grid needs, especially for flattening out the load curve as well as for various types of services such as black start support or islanding.

The grid connection possibilities, the benefits and the disadvantages of the electric vehicles are actual discussed topics in literature. As countermeasure for avoiding the danger of new peaks in the load curve, as the electric vehicles spread through the market in charging start hour, authors of [1] propose few solutions such as a) the regional charging time shift method be introduced in the midnight charging time zone, and b) inverse load flow by the discharge of the contract private use EV might be carried out as an energy shift in daytime. Particle swarm algorithm based optimization of the V2G scheduling for charging/discharging in parking lots is proposed in [2]. As the parking lots have constraints of space and maximum absorbed current, the authors proposes a method to schedule the number of electric vehicles for charging/discharging at a certain instant, to comply the current limit and to maximize the spinning reserve necessary to manage the system load fluctuations.

The potential of the electrical vehicle gives lot of business ideas, being encouraged by a competitive power market. An optimal methodology for charge control of PHEV, under the deregulated power market conditions, is proposed in [3]. The influence of the electrical vehicle on the electricity spot price is studied in [4]. The paper presents a Belgian example applying the grid-connected cars as a means for storing electricity, which could eventually result in lowering the spot price and its volatility on the electricity market, considering two different arbitrage strategies. An aggregated electric vehicle (EV)-based battery storage representing a V2G system is modeled in [5] for the use in long-term dynamic power system simulations for active power balancing. Power market implications are studied also in [6], where the authors propose a stochastic time-series based method to simulate the volatility of intermittent renewable generation and distributed storage devices along timeline. As also dealing in this paper, a proposal for integrating electric vehicles into the power grid using an advanced metering infrastructure functionalities is presented in [7].

The vehicle-to-grid technologies have been already discussed and implemented in pilot sites. A considerable step is on the way with the EDISON project, an international effort with important involvement of Danish TSO, started in 2008 [16].

This paper presents a new approach which allow open and democratic access for various players to develop and deploy flexible solutions, by means of open and configurable elements such as unbundled meters, intelligent energy portals and standardized service oriented architectures based on web technologies, mainly on SOAP/ Web Services [8]. With this approach, different business models can be deployed in the same time, by using multi-objective VPPs, for providing tertiary reserve, network voltage control, black start support, congestion avoidance etc.

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II. ELECTRICAL VEHICLES CONNECTED TO SMART GRID VIA MULTI-OBJECTIVE VIRTUAL POWER PLANTS

The concept of Virtual Power Plant (VPP) has been refined in the European integrated R&D project FENIX, which was a four year research project (2005-2009) under EU FP6 program [9]. The project aimed to validate the concept, as method of integration of the distributed energy resources and their promotion in the actual energy context.

There are several reasons for supporting virtual power plant technology as a measure for maximizing potential aspects of electrical vehicles:

a) System security, avoiding black-outs

Dispatch of EV resources using existing control centers: Each EV alone has electrical rated power well under the dispatch levels of interest for TSO (Transmission System Operator) and DSOs (Distribution System Operators) (usually, TSO operates only with dispatchable units with a minimum power of 4 up to 10 MW). Using the VPP technology, aggregation of a large number of EVs, with tens of kWs connected, may create an EV pool, dispatchable in case of network need and under appropriate incentives conditions.

Real-time visibility: the aggregators make visible for the TSO and DSOs small resources, integrated in the VPP, through aggregated and/or detailed real time data [10]. This visibility encourages a more deterministic behavior: an adequate aggregation can have characteristics close to those of the classical power plants, thus reducing un-predictability through integration of various resources and through active actions inside the virtual power plant.

b) Vitalize energy resources to provide ancillary services

Each EV alone has flexibility in modulating the power consumption or production well under the levels accepted by the ancillary services markets (where only power bands over 10 MW are usually accepted). However, through aggregated bands, controlled by VPP, such services can be offered commercially and performed technically by the VPP layer.

The Virtual Power Plant offers a mechanism through which the distributed energy resources (DER, including EVs) are integrated in the energy markets and in the operating platforms of the power system.

Figure 1 shows the aggregation idea for a number of DERs, consisting of CHPs (Combined Heat and Power units), photovoltaics, flexible consumers as well as electrical vehicles, with their controllable charge-discharge schedule. The aggregated DERs are therefore represented by an equivalent classical group (in this example connected to the 110 kV substation), with standard characteristics such as total active power $P$, total $P$ flexibility, cost characteristic, reactive power control capability, etc.

Typical examples of DER units are: wind power plants (Wind), micro-hydro power plants (μHyd), small combined and CHP plants, photovoltaic cell based power plants (Solar), fuel cell based power plants (FuelCell), diesel generators sets (Diesel), flexible consumers (FlexCon), storage devices, capable to store / release energy (StorDev).

The electrical vehicle becomes a new type of DER, as a stand-alone resource or integrated in an already existing DER, connected to its internal power network. The electrical vehicle can act either as flexible consumer (recharge period influenced by market signals) or as flexible storage, by tacking advantage of its huge storage potential.

The main objective of VPP is therefore to ensure the proliferation and appropriate integration of various DER by maximizing their contribution in the power systems, through their aggregation in virtual power plants and through decentralized management.

The virtual power plant has an aggregated characteristic of the output active and reactive power, of the available system services, of the dynamic characteristic of the whole (for instance the reaction time) and of the VPP commercial aspects. Through these characteristics, the virtual power plant concept is a specific technology of the larger concept of intelligent network, which is promoted through the European technology platform „Smart Grids” [13].

III. ELECTRICAL VEHICLES PROVIDING ANCILLARY SERVICES IN THE SMART GRID

The electrical vehicles connected to the power network, have the attractive characteristics that they can:

− consume energy for charging the batteries in appropriate periods; this is a function of storage for later use of energy;

− provide energy back to the network, by using inverter to transform DC energy from batteries back to AC energy suitable for the power network in appropriate periods;

− adapt the power factor during the active energy injection, thus allowing also network services such as secondary voltage control with local reactive power production.

From Smart Grid point of view, the electrical vehicles can be seen as important players. EVs are expected to give a new hope in the CO2 fight. However, from the point of view of the power system, besides the already known problems with the unpredictable renewables, the EVs bring a new challenge. If most of the charging actions take place during the home-to-office and back travels, during short periods of time in dedicated charging stations designed for EVs, it is expected that the daily load curve of the system will show even higher difference between load peaks and load valleys.

The best solution for the power system, if this is possible also for the car driver, is to use the night for charging the batteries then to use the energy during the day for
transportation but also for providing generation services upon request, in order to support the ancillary services need especially during the peak periods.

In countries with large power capacity installed in wind power plants, there is already the danger that during the night, when the wind blows more frequently and when the load is usually going down, the total power generation exceeds the demand. As today policy is to set higher dispatch priority for the wind generation compared to the other types of energy source, there are instants when base load power plants, especially nuclear, may be required to shut down or curtail output. In such situations, in order to avoid undesired fluctuations of these power plants, negative price incentives are used [15]. It is therefore opportune to charge the EVs’ batteries during the night, when energy can be extremely cheap, then, if necessary, to use them during peak hours as ancillary services.

Figure 2 shows that during the night there is a time period when the production in renewables (blue) + the nuclear production (brown) is over the regular consumption (black curve). During critical periods, the energy surplus can be consumed by the EVs as storage synchronized to the network. The Q1 energy stored during this period can then be partially consumed during regular travel in the morning (Q2 energy) and the surplus can be also used for provision of ancillary services in emergency situations or during peak hours (Q3 energy). Moreover, during peak power periods the energy is produced near to consumption points and, in addition, reactive energy can be controlled too with smart inverters of the EVs, thus providing additional network services such as secondary voltage control and congestion avoidance.

Additional recharging and discharge cycles may be scheduled during the flat period of the day and during the travel back to home.

With electrical cars aggregated in regional VPPs, this scenario may be applicable to integrate the EVs in a coordinated way, thus improving the system security and providing additional income to the EV owner.

Different studies have proved that today investment in large power plants have a better ROI if ancillary services are also considered. The same idea is considered to maximize the benefits of the EVs, if the ancillary services that can be provided by the EVs could be integrated in a VPP.

IV. TECHNOLOGICAL SOLUTION

In order to maximize the benefits of the EV’s flexibility, storage capabilities and multiple-objective potential functionalities, their connection with the Smart Grid needs a technical design beyond the traditional utility-oriented solutions.

There are two major improvement ways for allowing flexible business cases and appropriate dynamics in developing and promoting plug-in solutions for EVs:
- a “democratic” multi-user readable Smart Meter (SM), with basic configuration and functionality, unbundled from the Smart-grid functionality. This is an alternative to the existing approach of complex meter-to-utility concept and will be further developed;
- a “democratic” energy web approach, which allows mobilization of wide human resources, using standard web technologies to develop specific applications, to accelerate the deployment and to improve innovation. Both concepts are developed in the next sections.

The “democratic” unbundled Smart Meter

In the traditional philosophy of the Smart Meters characteristics, appropriate functionality which is supposed to be needed, is considered for the meters. This brings a danger to over-specify the functions of the new meter, in order to support various new smart grid needs. However, the dynamics of the smart grid functionality makes the SM obsolete in the next 3-4 years before its ROI period, usually 8-10 years, thus new SM and smart grid functionality is delayed until the initial investment is fully recovered. Furthermore, un-mature vision about the way in which the SMs can support deployment of new SG business models can lead the future SG in a wrong direction with inappropriate investments. This paper proposes a solution to be considered in parallel with already in progress SM deployments.

But what is a smart meter? The following functions need to be considered in order to clarify this concern (Fig. 3):
- the basic functionalities of the classic electronic meter;
- the basic functionalities which endows the meters with intelligence so that they may be called “Smart”;
- the extended functions of the SMs.

As shown in Figure 3, the smart meter has only two new basic characteristics as compared to the classic electronic meter:
− remote communication: as a must, the new meters accept a remote communication protocol (the standard meter has a local communication unit and optionally, a remote communication);
− access to the real-time data (also known as “instrumentation data”), e.g. u(t), i(t), p(t), q(t), etc.

Extended functions are possible to both classic and smart meter, that is digital inputs and outputs, to be used for additional logic in the meter or for readout / command from remote location.

As it can be seen in Figure 3, the basic functions of the SM are all related to its basic meter functionality (BMF) - that is energy measurement. These basic SM functions can be developed by meter manufacturers with the same (necessary) precautions as for BMF, so as to be still considered as metrological device. All these functionalities are part of the so called “metrological area”, so they are protected by standard metrology measures, such as physical seals for the metering part, for the terminal cover and for the critical parameters which affect the measurement (the “Metrologic Smart Meter”).

In the smart grid, in order to allow deployment of EV functionality, additional characteristics are required: continuous communication with other energy related factors, for optimizing the charge-discharge cycles and maximize the income from storage services, through VPP technology (as today the market is adapted to support) or based on individual strategies (for future situations).

**Energy business logic for local management of EV connection to the smart grid**

The “energy business logic” is expected to be subjected to frequent changes in the scope, as the technical trend and the business models may significantly vary during the development of both smart grid and EV concepts. Some meter manufacturers try to guess and standardize these functions, such that they can be included as extended functionality in their smart meters.

In Figure 4, an improved way of coping with the changing models of the Smart Grid and EV potential is proposed: to reduce the SM functionality to that shown in the “Metrological area” and consider adding a distinct logic entity, or logic unit, which hosts all additional functionalities, entity which does not need to be “metrology-based”, but which is flexible and upgradable. This separate logic unit is connected to the Metrologic Smart Meter, through a standard communication interface, as well as to the Energy Web. This separated unit can host all energy business logic, by running local software agents. The dotted area highlights the today “classic Smart Meter”, which is able to cover only minimal smart grid functionality, thus being inappropriate for flexible smart grid and EV to grid support.

The proposed dissociated (unbundled) meter configuration – with a metrological entity and a flexible area, can have functionalities similar to the more complex ones of the existing “custom” smart meters, but with important advantages:
− accurate metrologic function of the basic smart meter;
− flexible functionality on the non-metrological upgradable area, to assist changing algorithms for the smart-grid functionality.

The unbundled meter can be considered also as a “democratic” meter because it allows third party developers to add new functionalities to the whole local energy cluster, tackling the advantage of the more simpler (and thus cost effective) basic Smart Meter, which make room for investments in the flexible part.

In this frame, the unbundled meter can support much better the use of an EV specific capabilities, as illustrated in Figure 5. In this figure, the energy business logic is performed by the flexible part and is now called “Intelligent Energy Portal” (IEP), running all energy agents needed by various resources to support functionalities for both DER as a whole and for the EV in particular.

![Fig. 4. Unbundling the smart meter – the concept.](image)

![Fig. 5. EV integration in the Smart Grid with an unbundled architecture.](image)
An electrical vehicle into the smart grid is assisted through the IEP. Any change in the energy business logic can be considered through a new upgrade in the IEP, thus allowing high flexibility and protection of investment in both smart meter (which remains intact) and IEP, which shall be implemented on a standard Operating System platform (such as embedded Linux), able to run different agents.

Based on this architecture, the IEP can take advantage of:
- existing standard smart meter (which has the entire basic functionality to cover entire logic necessary at upper levels);
- new business models, which can be coded as new agents, uploaded to the IEP via internet;
- connection to all energy and ancillary services market players, for exchange data, using machine-to-machine (M2M) techniques.
- connection to different generations of EV-to-grid functionalities, by changing the EV software driver only, in a simple manner, similar with changing the printer driver to allow printing from a different printer.

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An architecture that includes an IEP is also promoted in [14], under the name “Energy Box”, as innovative device both for the energy supply network and for the client energy services devices. The philosophy presented in this paper gives however a more general meaning to this “box”, considering it the main intelligence for all local running agents serving different purposes, performing services for different markets.

The IEP uses the local energy resources, such as EVs, local generators and flexible loads, and ensures the communication with all Energy Web participants, especially in connection with the various available markets.

Figure 6 depicts the general overview for EVs integration in the smart grid using multi-objective VPPs. EVs are seen as DER in the field and are treated similar to other generation facilities which can offer energy on regular basis or upon request, such as CHPs, PVs (and sometimes their energy stored in batteries), micro-hydro, wind turbines, fuel cells, etc. All these resources can be integrated in VPPs through the local IEP, which runs specific software agents and exchange information with other participants through internet, within the so-called Energy-Web. Figure 6 shows two VPPs, suggesting that competition is also possible for such aggregation services.

With such approach, the VPPs expose sufficient large aggregated power and flexibility, such that they can directly be integrated in the EMS-SCADA and Automated Generation Control (AGC) of the TSO as well as in the DMS-SCADA of the DSO. This brings the VPP, and their EVs’ reserve, at the same level with the traditional large generation, as presented in the figure as directly communicating with the same TSO and DSO entities.

The access to various markets (energy, ancillary services and network services) for the EVs is therefore possible via a multi-objective VPP integration level.

An important aspect of this architecture is the Energy Web, which uses standard web technologies. It allows easy implementation of the so called Service Oriented Architecture, based on the widely industry accepted Web Services (WS) family of standards, especially through its Simple Object Access Protocol, used for exchanging structured information based on XML message format.
In this frame, a democratic-web based Smart Grid is enabled, allowing thousands or more developers to offer a myriad of different services related to the power grid, in a so called Cyber-Energy System, formed as a synergy between the Power System and the Information System. It is the pattern of democracy in the new Cyber-Energy System, comparing with the traditional top-down controlled system. In contrast, large generation and other classic entities frequently use dedicated or switched communication lines with specialized data protocols, which are accessible only for a smaller community of developers.

V. CASE STUDY

Let us consider a VPP aggregating a group of EVs, by controlling their $P$ and $Q$ independently through the power electronic inverters. This makes possible the provision of two services: a) automatic generation control ($P_{control}$) and b) voltage control ($Q_{control}$).

A typical EV is considered for the simulation with the following technical characteristics: energy stored in the battery: 20 kWh, range of travel: 200 kilometres, fast charging: 30 min for 80% charging status, slow charging: 8 hours.

The charging of the EV assumes a network connection through a 16 A / 230 V AC plug socket, which allows a maximum power of ±3.68 kW.

For the provision of ancillary services, a period of $T_{as, day}$ = 8 hours, between 9:00 am and 5:00 pm, when most of the EVs are in the parking place, is analyzed. During this 8 hours period, the EVs are requested to perform simultaneously $P_{control}$ and $Q_{control}$, but they are limited to a ±3.5 kVA peak power only. This means that the EVs can provide at any time both upward and downward regulation between -3.5 kW and +3.5 kW, totaling a 7 kW active power band, called here $P_{band}$. The $P_{control}$ is performed similar to the Romanian AGC (called also secondary frequency control), and the $P$ setpoint is called $Order$. In a real application this type of control can act as a second level of AGC, but with smaller response time and with the $Order$ being received from the VPP controller.

In the $P_{control}$, the active power produced by the EVs is given by:

$$P_e(t) = \begin{cases} \text{Order}(t) \times P_{band} & \text{if } \text{Order} \geq 0 \\ 0 & \text{if } \text{Order} < 0 \end{cases} \quad (1)$$

as a consequence of a positive $Order$ received from the VPP with $Order = [0 \ldots +50\%]$, whereas the active power consumed from the power grid is calculated with:

$$P_e(t) = \begin{cases} 0 & \text{if } \text{Order} \geq 0 \\ -\text{Order}(t) \times P_{band} & \text{if } \text{Order} < 0 \end{cases} \quad (2)$$

as a consequence of the $Order$ received from the VPP, with $Order = [-50\% \ldots 0\%]$.

Therefore, the total active energy produced by the EVs through the VPP as ancillary service is:

$$E_{as, P} = \int_{T_1}^{T_2} P_e(t) dt \quad (3)$$

and the total active energy consumed as ancillary service is:

$$E_{as, P} = \int_{T_1}^{T_2} P_e(t) dt \quad (4)$$

On the other hand, the voltage control is provided by using a 7 kVAr reactive power band (from -3.5 kVAr to +3.5 kVAr), called $Q_{band}$, that can be delivered by each EV. When the $P$ and $Q$ amounts requested by the VPP controller exceed the maximum limit of 3.5 kVA, priority is to provide $P$, while $Q$ is recalculated such that the apparent power must be $S_{EV} \leq 3.5$ kVA.

The reactive energy produced or consumed by the EVs, as a consequence of the reactive power order, $Q_{ORD}$, received from the VPP is given by:

$$E_r = \begin{cases} \int_{T_1}^{T_2} |Q_{ORD}(t)| dt & \text{if } P^2(t) + Q^2_{ORD}(t) \leq S^2_{EV} \\ \int_{T_1}^{T_2} \sqrt{S^2_{EV} - P^2(t)} dt & \text{if } P^2(t) + Q^2_{ORD}(t) > S^2_{EV} \end{cases} \quad (5)$$

Under these conditions, the energy that is available in the EV battery at a certain time is:

$$E_{Bat}(T_i) = E_{Bat}(T_f) - \int_{T_1}^{T_2} (P_e + P_{loss})(1 - \eta_{PROD}) dt + \int_{T_1}^{T_2} P_{cons} dt - P_0(T_f - T_i) \quad (6)$$

where, $T_i$ and $T_f$ are the start and current times (the final time of the 8 hours simulation interval is $T_f$), $\eta_{PROD}$ is the energy efficiency during the energy production and $\eta_{cons}$ is the energy efficiency during the energy storage (consumption from the network). In our study we have considered $P_0=0.2$ kW (no load losses), $\eta_{PROD} = 70\%$ and $\eta_{cons} = 90\%$.

Four different typical days are taken into consideration for simulation: the case of small un-balanced $Order$ during the whole 8 hours interval – Scenario 1A, an adjusted Scenario 1B derived from 1A that assumes high balanced average $Order$ on the 8 hours interval, Scenario 2 with more consumption (average $Order$ much under 0) and Scenario 3 with more production (average $Order$ much over 0).

The simulations on the 8 hours time frame was performed with an integration periods of 5 seconds.

In all scenarios, assumes that initially (at $T_1 = 9$ a.m.) the energy stored in the batteries is 75%, after using 25% for travelling to the office. The scenarios are valid if after 8 hours of VPP ordered services the battery still has > 25% energy and it is not over 100% in the calculations. Scenarios 2 and 3 have been considered in order to test these limits.

Figures 7.1a, 7.1b, 7.2 and 7.3 show the simulations for the 4 scenarios during the 8 hours time frame. The results can be used to calculate the daily energies and the revenues for the EV owner, after performing the multi-objective algorithms controlled by the VPP. The revenues may be due both to the active energy production and the $Q$ production based on VPP orders.

The simulations show the way in which the EVs can respond to the VPP request to cover the load in real time. It is assumed an EV-to-grid integration as presented in chapter IV.
Fig. 7.1a. EV participation in a multi-objective VPP: Basic scenario 1A (duration of 8 hours).

Fig. 7.1b. EV participation in a multi-objective VPP: Basic scenario 1B (duration of 8 hours).

Fig. 7.2. EV participation in a multi-objective VPP: Scenario 2 (duration of 8 hours).
The Unbundled Smart Meter concept is an important technology to be considered for accommodating electrical vehicles into the power grid through multi-objective Virtual Power Plants as well as to help the grid with services which can bring benefits to both.

Existing architectures for Smart Grid with its basic local intelligence represented by the Smart Meter does not address well the EV potential, such as multi-agent performing VPP support and other energy-related services for various energy markets, thus necessitating new local functionalities, other than the traditional SM supports.

The paper proposes an alternative solution, with a local functionality based on a Smart Meter unbundled architecture, splitting it into a standard or basic smart-meter + a flexible “Intelligent Energy Portal” (IEP), where the latter can optimize energy production, storage and consumption at the DER level, including EV specificity, by harmonizing the consumption / production measured at the DER border with the power network, tacking into consideration the EV logics and the energy market mechanisms.

The reason for flexibility and energy business models to be deployed through IEP is that only such separate entity can cover the whole diversity and problematic of the DER (internal consumption, internal production, EV battery cycle), combined with the energy market inputs, acquired through the energy web.

With the proposed architecture, the EV integration in the Smart Grid is supported by local basic meter, local intelligence running on IEPs and central energy services aggregators, enabling new integrated features such as VPP functionality - for interfacing with existing power systems technical and commercial platforms.

A case-study simulation shows that combined ancillary and network services provided by EVs, such as $P$ and $Q$ control via multi-objective VPP, are technically possible.

VI. CONCLUSIONS

The Unbundled Smart Meter concept is an important technology to be considered for accommodating electrical vehicles into the power grid through multi-objective Virtual Power Plants as well as to help the grid with services which can bring benefits to both.

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VII. REFERENCES


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