A Technical Management and Market Operation Framework for Electric Vehicles Integration into Electric Power Systems

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I. Introduction

At the present time, the electrification of the transportation sector is assuming increasing importance to contribute for the solution of several environmental problems, like global warming and air pollution in highly populated areas. As the cost of renewable technologies is decreasing and their installed power rising, it is expected that electricity gets "cleaner" and cheaper, therefore making EV utilization economically more attractive. Assuming a scenario where a high number of EV connect to the electric power system for charging purposes, it will be necessary to adapt the existing network management and control mechanisms, as well as the electricity markets functioning, in order to efficiently accommodate this new kind of load into the system, while avoiding high investments in the reinforcement of new generation facilities and grid infrastructures.

The main goal of this paper is to provide a comprehensive and feasible framework for EV integration into electric power systems, both interconnected and isolated, providing a holistic perspective of this new reality with special attention on the electricity markets operation and on the networks technical management. In order to manage a large amount of EV parked in a large geographical area, where Medium Voltage (MV) and Low Voltage (LV) grids exist, the existence of aggregators will be necessary, in order to serve as an interface between EV and electricity markets. These new entities' main activities will be thoroughly described along this paper.

II. Grid Control Architecture and Market Framework for Interconnected Systems

The technical management of an electric power system having a large scale deployment of EV will require, for their battery charging, a combination of a centralized hierarchical management/control structure with a local control located at the EV grid interface.

The simple use of a smart device interfacing the EV with the grid does not solve all the problems arising from EV integration in distribution networks. These interfaces can be rather effective when dealing with the likely occurrence of voltage drops that may be caused by EV charging, by locally decreasing charging rates through a voltage droop control approach. However this local solution fails to address issues that require a higher control level, such as managing branches' congestion levels or enabling EV to participate in the electricity markets. For these cases, coordinated control is required and so a hierarchical management and control structure responsible for the entire grid operation, including EV management, must be available. Therefore, the efficient operation of such a system depends on the combination/coordination of local and centralized control modes. The latter control approach relies on the creation of an adequate communications infrastructure capable of handling all the information that needs to be exchanged between EV and the central control entities organized in a hierarchical structure.

When operating the grid in normal conditions, EV will be managed and controlled by a new (central) entity – the aggregator – whose main functionality will be grouping EV, according to their owners' willingness, to exploit business opportunities in the electricity markets [1], [4], [3]. If EV would enter this market individually their visibility would be small and due to their stochastic behaviour rather unreliable. Nonetheless, if an aggregating entity exists, with the purpose of grouping EV to enter in the market negotiations, then the services provided would be more significant and the confidence on its availability much more accurate. In this sense, a conceptual framework capable of dealing with EV presence was adopted, as explained later on this document.

Nevertheless, even considering the aggregators activities, a still high degree of uncertainty will exist related to when and where EV will charge, namely in LV grids. Due these uncertainties and assuming that networks will evolve towards a decentralized generation paradigm, the existence of a grid monitoring structure, such as the one developed for Microgrids (MG) and Multi-Microgrids (MMG), will be required. This structure will be controlled by the Distribution System Operator (DSO) and should be capable of acting over EV charging in abnormal operating conditions, i.e. when the grid is being operated near its technical limits, or in emergency operating modes, e.g. islanded operation [2].

The technical and market management proposed structures will be thoroughly described in the next sections of this document.

Normal System Operation

In order to manage a large amount of EV parked in a large geographical area, where MV and LV grids exist, the existence of aggregators will be necessary, in order to serve as an interface between EV and electricity markets. These aggregators will have the capability of grouping EV so that together they represent a load/storage device with the adequate size to participate in electricity markets, in a similar way as described in [1]. It is important to stress that the aggregator will always take into account the drivers requests, which will provide information about power demand and connection period via the smart meter. In the same regional area, several aggregators might co-exist and compete to gather as much clients as possible. This competition will be beneficial for the EV owner, who will be able to choose for his aggregator the company that better fits to his needs.

Given the complexity of the information that an aggregator needs to collect and process, a hierarchical management structure, independent from the DSO, is suggested in this document (Fig. 1).

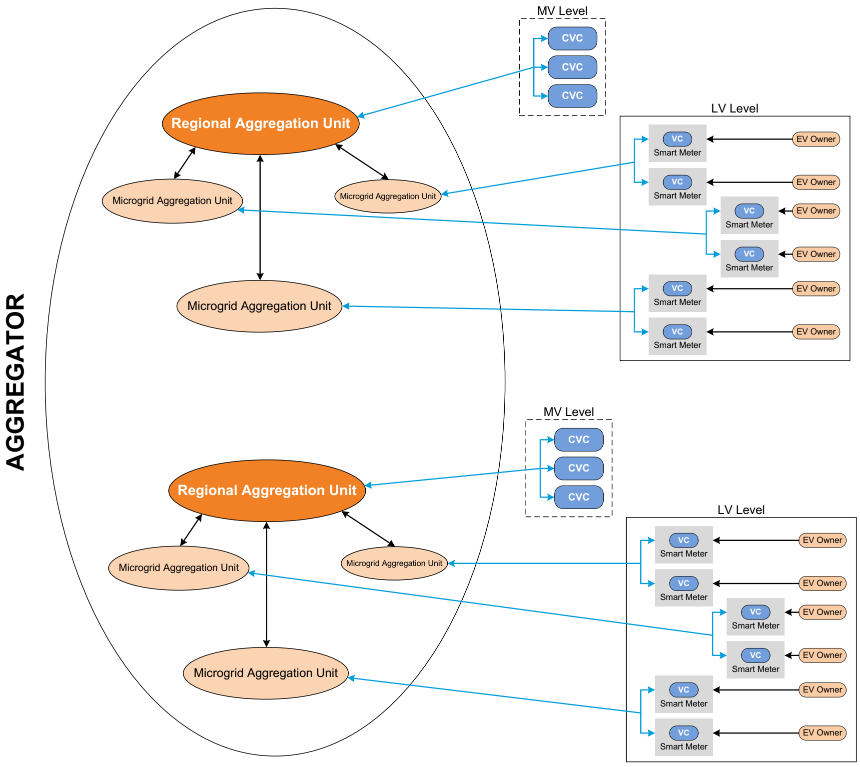

Fig. 1 – Aggregators' hierarchical management structure

Since each aggregator develops its activities along a large geographical area, e.g. a country, it will be composed by two different types of entities: the Regional Aggregation Unit (RAU) and the Microgrid Aggregation Unit (MGAU). The RAU is considered to be located at the High Voltage (HV)/MV substation level, with possibly 20000 costumers, communicating with several downstream MGAU which, by their turn, will be located at the MV/LV substation level, with around 400 costumers each. The RAU and the MGAU were created in order to decrease communications and computational burden that a real implementation of the concept would require. This will provide the aggregator pre-processed information regarding groups of EV located in the LV and MV grids. Each EV must have a specific interface unit – the Vehicle Controller (VC) – to enable bidirectional communication between the EV and the upstream aggregator. The VC may be located in the smart meter to which EV will be connected and the smart metering communication infrastructure should be used to support this architecture. In addition to the VC there is a new type of element, the Cluster of Vehicles Controller (CVC), designed to control the charging of large parking lots (e.g. shopping centres), and fed directly from the MV network. Individual controllers of EV under a CVC management do not have an active VC communicating with higher hierarchical controllers. For normal operation, the VC will interact with the MGAU and the CVC directly with the RAU [2].

The Market Operation column in the right-hand side of Fig. 2 presents an overview of the aggregators' market activities.

Based in historical data, the aggregators will forecast the market behaviour for the next day and will prepare their buy/sell bids. Having this defined, a prior negotiation with the DSO must exist to prevent the occurrence of severe congestion and voltage problems in the distribution networks. The aggregators will present their day-ahead proposal to the DSO, which will analyse it to evaluate its technical feasibility. If valid, the aggregator can proceed to the market negotiation. If not, the DSO will ask the aggregator to make the changes needed to guarantee a safe operation of the distribution grid in the next day. It is foreseeable that in this case the DSO will have to compensate the aggregator by this service. The DSO might even request the aggregator to change further its plans to decrease the distribution grid energy losses.

If the market prices of electricity are cost reflective (i.e. include the cost of electricity generation, transmission and distribution), a direct consequence of the hourly energy prices variation will be the flattening of the daily load diagram. As response to the energy prices, aggregators will naturally perform load shifting in order to provide energy at a lower cost to their clients. They will buy electricity from the market mainly during the night, at lower prices, to charge their clients' EV, and they may sell it during the day, at peak hours, taking advantage of their clients' EV storage capability. Aggregators will compete directly with electricity retailers for energy acquisition and with Generation Companies (GENCO) for selling energy.

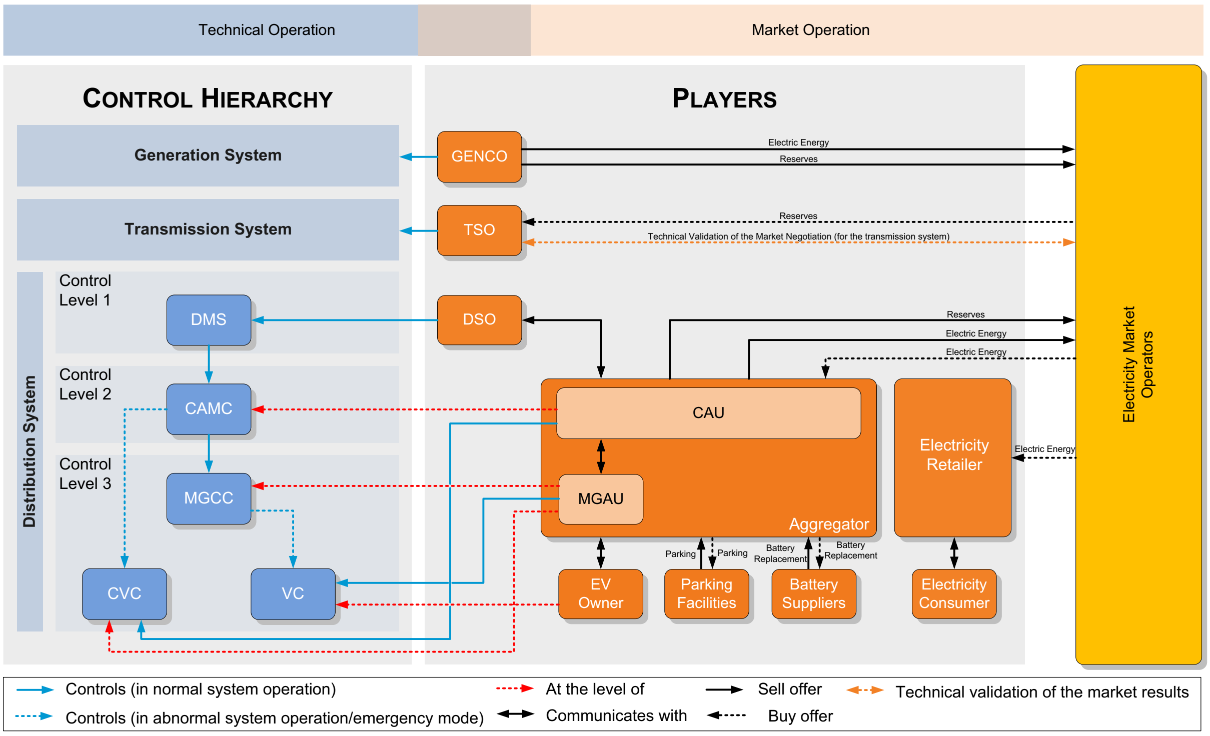

Fig. 2 – Technical management and market operation framework for EV integration into interconnected power systems

Taking advantage of EV capability to provide reserves, EV might offer also in the electricity markets these system's services to the Transmission System Operators (TSO), competing once again with the GENCO. Also with this approach it will be possible to have EV participating in secondary frequency control, through the link TSO → Aggregator. After market closure, the TSO proceeds to the evaluation of the load/generation schedules and, if problems on the transmission system are foreseen, it requests modifications to these schedules until feasible operating conditions are attained. Every day the aggregator will manage the EV under its domain, according to what was previously defined in the market negotiations and validated by the TSO, by sending set-points to VC or CVC related with rates of charge or requests for provision of ancillary services. To accomplish successfully such a complex task, it is required that every fixed period (likely to be defined around 15 minutes), the State of Charge (SOC) of each EV battery is communicated to the aggregator, to assure that, at the end of the charging period, batteries will be charged according to EV owners requests [2].

Parking and new battery supplying are also services that aggregators can negotiate in other markets, as mentioned in [1] and included in Fig. 2. Nonetheless, these parallel markets' negotiations will not be addressed in this paper.

Abnormal System Operation or Emergency Mode

When grid normal technical operation is compromised, market management can be overridden by the DSO, through the technical operation control hierarchy, described in the left-hand side column of Fig. 2. For these abnormal or emergency conditions, it makes sense to adapt the MG [4] and MMG [5] concepts. In fact, the MG and MMG already contemplate the existence of a hierarchical monitoring and management solution that includes a suitable communications infrastructure, capable of managing the presence of EV, either individually connected at the LV level or as a cluster of EV (fleet charging station or fast charging station cases) connected at the MV level. Within a LV MG, a MicroGrid Central Controller (MGCC) may control EV batteries through the VC. As depicted in the "Technical Operation" column of Fig. 2, within a MMG environment, the elements of the MV grid, including MG and CVC, can be technically managed by a control entity, named Central Autonomous Management Controller (CAMC), to be installed in the HV/MV substation. All the CAMC will be under the supervision of a single Distribution Management System (DMS), which is directly controlled by the DSO. It is important to stress that, in abnormal system operation conditions or in emergency modes, all the technical management and control tasks are a responsibility of the DSO, being performed by a main control entity, the DMS, and by the other distributed entities, CAMC and MGCC [5].

III. Grid Control Architecture for Isolated Systems

In small isolated systems the framework presented in Section II may not be applicable, as in some cases no real market participation is possible. Due to the specificities of the small systems, they are not able to accompany the changes that are occurring in the energy paradigm and electricity supply chain remains vertically integrated. However, these systems have evolved, by integrating whenever possible and in a very conservative way intermittent Renewable Energy Sources (RES) in their generation mix. So, the full RES potential is not explored, in order not to jeopardize the more fragile grid technical operation when compared to large interconnected systems.

The integration of EV in such systems is a natural occurrence as fossil fuel scarcity and environmental concerns are present in both interconnected and isolated systems. Being low resilience electricity grids the greatest beneficial and adverse effects are expected from the integration of these new loads. When EV are regarded as common loads then these systems may get even more fragile. Conversely, if properly controlled these system could even benefit from further integration of RES.

The next two subsections present the necessary adaptations of the previously exposed concepts, in order to manage EV in isolated grids. On one hand, the MG and MMG concepts will still be required in this type of operation. On the other hand, some of the functions that were shared among Aggregators must now be assured by the sole energy provider present in the island which typically is also the DSO.

Normal System Operation

As it was previously mentioned, isolated systems are vertically integrated. Therefore, the system operator is responsible for its management at the generation, transmission and distribution levels.

Therefore, it is only necessary the existence of the hierarchical control structure presented in the Technical Operation column (left hand side) of Fig. 2. As it is observable, the complexity of the control structure is smaller than in interconnected grids due to the inexistence of market interfaces and players.

In normal system operation VC and CVC are controlled by the system operator's sub-entities, MGCC and CAMC. Depending on the type of contract established with EV owners, the system operator may be allowed to control EV charging rate through those sub-entities. Day-ahead, the system operator will perform a smart charging algorithm using forecasted data on load (both typical consumption and EV) and generation profiles. During the day, it will update this solution providing real time pricing, so that consumers shift EV charging for cheaper electricity periods harmonizing the load/generation diagram.

In some cases, regulation may make EV response to the system operator's request mandatory, in order to provide safety of operation to system and, eventually, allow increased intermittent RES penetration. In these cases, the local government or the system operator may have to be co-owner of the EV batteries or provide a large incentive on EV purchase.

All the ancillary services presented for interconnected systems may also be provided by EV in isolated grids, provided that EV owners are granted sufficient incentives. The system operator control structure will be responsible for managing the provision of these ancillary services.

Abnormal System Operation or Emergency Mode

When grid normal technical operation is compromised, the system will be controlled in the same way as described for interconnected systems, section II. The main difference is that the system operator does not need to override market operation, as it is not present.

IV. Conclusions

This paper presented a full integration framework for EV on both interconnected and naturally isolated grids. In interconnected systems, the need for the Aggregator entity was discussed and its interactions with the technical and market structures described. For isolated systems, the required simplifications due to the non-existence of a market infrastructure were detailed.

In conclusion, this paper describes a possible framework capable of dealing with the several system operation conditions, providing EV the capability of being an active element within the grid, instead of a typical passive load. In this way, benefits for both system operators and EV owners are expected, by granting more resilience and controllability to the power systems.

V. References

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