Advanced Metering Infrastructure Functionalities for Electric Mobility

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***Abstract*—The Smart Grid vision along with the future deployment of Electric Vehicles presents numerous challenges in terms of grid infrastructure, communication, and control. In this context, Advanced Metering Infrastructure solutions are envisioned to be the active management link between utilities and consumers. This paper presents a survey of potential AMI functionalities particularly developed to foster the large scale deployment of EV in Smart Grids. For this accomplishment, the concepts of Automated Meter Reading, Automatic Meter Management and Smart Metering are revisited. Furthermore, different EV charging approaches are outlined and included in the functionalities under the Vehicle-To-Grid framework. Finally, AMI use cases are described under the Vehicle-to-Home perspective.**

***Index Terms*— Advanced Metering Infrastructure, Smart Grid, Electric Vehicle.**

NOMENCLATURE

DER	Distributed Energy Resources
EV	Electric Vehicle(s)
SM	Smart Meter
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
DSM	Demand Side Management
AMM	Automatic Meter Management
V2G	Vehicle-To-Grid
V2H	Vehicle-To-Home
SG	Smart Grid(s)
HAN	Home Area Network
LAN	Local Area Network
DC	Dumb Charging
MPT	Multiple Prices Tariff
SC	Smart Charging
DSO	Distribution System Operator
HMI	Human Machine Interface
SOC	State Of Charge

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I. INTRODUCTION

THE electric grids are suffering a modernization process in terms of generation, transmission, distribution and use of electricity. This modernization is being driven by Smart Grid initiatives, which are also fostering the integration and active management of DER. This vision along with the future integration of EV presents several challenges to grid communications, monitoring and control activities.

One of the strongest vectors of the Smart Grid concept is the SM, which consists of an abstraction usually associated with some sort of AMI. The AMI concept itself is not a novelty and derives from the natural evolution of earlier AMR, providing a two-way communications with the meter. The expected massive deployment of AMI solutions is a unique opportunity to define features and functionalities that can enable the large scale deployment of DER and EV, as well as more ambitious DSM solutions [1].

This paper presents potential AMI functionalities particularly developed to foster the large scale deployment of EV in Smart Grids, where the concepts of AMR, AMM and SM are revisited. In addition, basic and advanced AMI functionalities are described under the V2G framework, where electric vehicles are supposed to be capable to inject power in the grid. These functionalities consider both possibilities of charging at public and domestic environments. This work also addresses the AMI use under the V2H framework. The V2H concept is a particular case of the V2G, where the domestic/home environment is the main focus.

The document is organized as follows. Section II presents an overview of communications in power distribution systems. Section III focuses on the definition of AMR, AMM and AMI under the scope of Smart Grid framework. Section IV and V present a set of AMI functionalities for V2G and use cases in V2H, respectively. Section VI presents the final remarks.

II. COMMUNICATIONS IN POWER DISTRIBUTION SYSTEMS

The considerable complexity of electric power grids was, up until recently, coordinated with limited communication systems mainly due to the static nature of the business in the last decades [2]. However, the electric power grids have been changing into a more dynamic system and communications became a major focus in the SG context. Despite new requirements in terms of infrastructure, the expected increase in the number of participants with distinct goals, roles and geographic dispersion when accessing power grids will also demand different sets of (historical or real-time) data [3] and information flows. As a matter of fact, at the distribution level, communications will have to handle two major types of information flows: a downstream control data exchange from the service provider to end consumers, and an upstream monitoring and metering data exchange from the consumers to the service provider.

The development of communications solutions based on bidirectional data exchange of monitoring and control data provides the support for centralized and decentralized forms of grid operation. These strategies will impact the operation of the grid in normal and abnormal or emergency states of operation. In addition, the standardization of technologies and protocols in power distribution communications, are a key driver in implementing interoperable SG devices and systems. Nowadays, there are already standards and specifications with considerable consensus and maturity to support the visions of smart grids [4].

In the SG context, concepts like AMI and SM have gained considerable notoriety. This paper focuses on functionalities associated to AMI and in particular to SM, designed to deal with electric mobility. These functionalities, along with suitable communication systems, will enable a more detailed characterization of consumers, enhancing the control strategies of the distribution network. They will provide the necessary foundations which can allow SM to implement an open gateway for the exchange of energy services between the service provider and the consumers, contributing to an even more dynamic and competitive market.

III. AMR, AMM AND AMI

The increased usage of pervasive communication systems in the electric grid, particularly at distribution level, has been driven by the need of more accurate and detailed information about consumers. This finer grained characterization of energy consumption has motivated the enhancement of metering infrastructures, which intend also to provide the basis for the development of active DSM solutions.

New concepts and definitions were introduced, along with the design of more advanced metering systems. For instance, the AMR initial concept enabled meter information to be retrieved in an automated process, through a walk-by handheld system or by a more sophisticated drive-by mechanism. The definition has been updated to include the technology that enables the collection of data from metering devices to be transferred to a central data base.

The AMM concept introduced additional complexity as it was added downstream data exchange from the energy provider to the end consumer, for management purposes. It was initially designed to manage the remote collection of data, but the concept was extended to include limited forms of control or influence the customers' energy consumption.

More recently the AMI concept was defined as basis for the previous AMR and AMM. The AMR and AMM are subsystems of the AMI in which the first is responsible for metering activities and the latter for the overall management of the infrastructure. In a more extensive definition the AMI includes the supporting hardware and software which ensures the measurement, storage and processing of the consumption data of the end user, integrating electricity, gas, water and heat meters. It is responsible for the interaction with the consumer, using different types of interfaces, as well as for the interaction with the service provider, using communication systems [5]. In terms of communications networks, the AMM is responsible for the management of a HAN, with all associated devices, which in turn will interact with the service provider LAN, as depicted in Fig. 1. Emerging HAN technologies are designed to support these information flows.

The AMI concept is often associated to other terms such as smart metering. Given different market issues and different perspectives regarding which type of characteristics the metering infrastructure should have, these are inherently similar concepts. The SM designation will be used henceforth in this paper, as it is often used under the scope of Smart Grids. The following sections detail the functionalities of SM for V2G and its use cases in V2H scenarios.

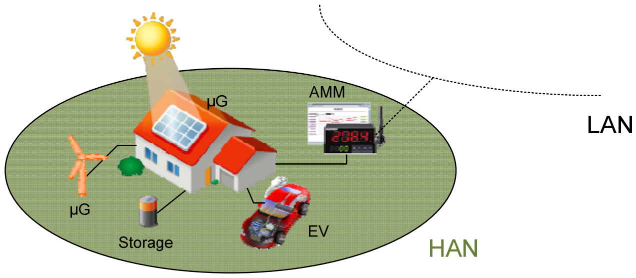

Fig. 1 AMM establishing a connection between a domestic HAN and a utility LAN.

IV. METERING FUNCTIONALITIES FOR V2G

Smart meters, such as the ones envisaged in the InovGrid project in Portugal, [7] can be used to support the integration of microgeneration either for billing purposes, since the energy sent to the grid from the microgeneration units is often remunerated differently from the consumed energy, or for managing grid integration of microgeneration. The functionalities provided by SM, represent a broad subject which is being currently addressed by numerous entities. For instance, the importance of these functionalities is highlighted in [8], where the national minimum functionalities for smart meters in Australia are deemed.

In this work the particular SM functionalities for V2G, are addressed. Hence, three different types of smart meters are proposed to deal with the EV charging approaches contemplated in the MERGE Project [9] as illustrated in Fig. 2. The first, a basic version of the smart meter, will include all the necessary functionalities to cope with the less demanding charging approaches, i.e. the DC and the MPT, in domestic environment. The second, an advanced version of the smart meter for home charging, will incorporate enhanced functionalities in order to deal with the more elaborated charging strategies, i.e. Smart Charging (SC) and V2G. The third, an advanced smart meter for public charging points, has the same vehicle management functionalities, but with less complexity as it does not have to control household related appliances or microgeneration units.

In the Dumb Charging mode EV owners are completely free to charge their vehicles whenever they want. In addition, electricity price is assumed to be constant along the day, what means that no economic incentives are provided to EV owners, in order to encourage them to charge their vehicles during valley hours, when the grid operating conditions are more favourable to an increment in the energy consumption. Charging starts on the moment each EV plugs-in and lasts until battery full capacity is reached or EV gets disconnected by its owner.

In the MPT charging mode EV owners are also free to charge their vehicles whenever they want. However, as electricity price is assumed not to be constant during the day, there are periods where its cost is different. This is an indirect incentive based mode of shifting EV energy demand from the peak to the valley hours, aiming to avoid overloading the grid and the generation system during those periods. The electricity prices along the day (prices for each specific tariff period) are fixed by an initial contract established between the client and the trader.

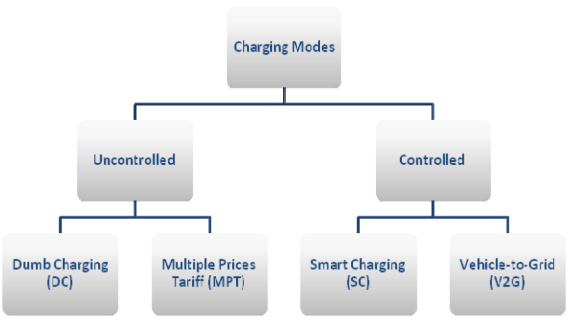

Fig. 2 Charging modes for EV.

The uncontrolled charging modes do not allow system operators to manage EV charging towards a more efficient operation. This type of contracts will only allow EV charging halt in case there are severe network problems, namely when voltage levels surpass the technical limits and overload problems occur. The disconnection of uncontrollable EV will only take place, as it will be explained later, after all the flexibility available on controlled EV is explored.

Both DC and MPT EV customers should have the possibility of choosing between two tariffs: normal and premium. The reason behind the existence of these two tariffs is the fact that some clients may not want to be disconnected at all and so a premium client will, by means of an increase in the tariff, be sure that his EV will not be disconnected unless there is a generalized lack of power.

A Smart Charging strategy envisages an active management system, where there is an aggregator agent serving as link between the EV owners, the electricity market and the DSO, as explained in detail in [10]. In this approach it is assumed that EV batteries' charging is actively managed, adjusting the rate of charging, instead of an on-off solution. The DSO periodically receives information about all the elements connected to the grid including its state, possibly exploiting and transposing the concepts or similar ones to those used for the management of MicroGrids [11] and Multi-MicroGrids [12]. The aggregator and the DSO then may request from the EV the services that they may need.

In order to guarantee the adherence of EV owners to the SC, the tariffs to be adopted for this strategy should include a bonus on the price of electricity for the clients committed with the SC mode. This way, the system will have the flexibility to charge EV during the period they are connected, instead of the charging taking place automatically when they plug-in. This type of management provides a more efficient usage of the resources available at each moment, enabling grid overload prevention and voltage control.

The V2G mode is an extension of the previous one, where the aggregator controls not only the charging of the batteries, but also the power that EV might inject into the grid. From the grid perspective, this is the most interesting way of exploiting EV capabilities. Besides helping managing branches' congestion levels and voltage related problems in some areas of the grid, EV have also the capability of providing peak power in order to make the energy demand more uniform along the day.

A differentiation must exist between the SC and the V2G charging modes due to the more demanding conditions of the V2G option. While the SC only contemplates different charging rates for EV, the V2G approach also involves the injection of power into the network. As this mode of operation is likely to reduce the batteries lifetime expectancy, it is necessary to provide EV owners with economic incentives, like reduced electricity prices, in order to foster EV owners' adherence to the V2G charging mode. In Fig. 3 is illustrated the interaction of the EV with the DSO and market via the aggregator.

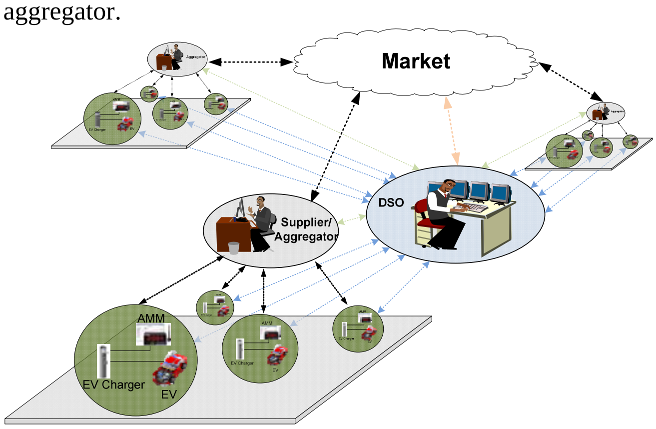

Fig. 3 Framework for EV charging management and control.

The definition of a smart metering solution for coping with EV energy flux billing and also to help manage the integration of EV in electrical grids does not preclude the discussion on the interest of having additional simple meters installed on board of the vehicles. In fact, these meters can be very important for EV charging billing in public areas and would be very helpful in avoiding frauds in home charging. Three versions of the SM are presented below. The first two relate to basic and advanced versions of SM in the home environment. The latter refers to the version of SM for public charging.

A. Basic smart meter version for domestic charging

A basic smart meter version can be adopted allowing EV owners to charge their vehicles at home, in a slow charging mode, without providing any ancillary services to the system. This version will only support DC and MPT charging modes and the following functions were deemed as the basic functionalities that the smart meter should provide universally:

- **Basic HMI** – A data display allows customers to be aware, in real time, of their local energy flows, as well as access to billing information and to information related with scheduled maintenance, interruptions and other important events. It will allow the client to access an application with the available charging modes, enabling the choice of the proper one (DC or MPT only).
- **Energy measurement** – Unidirectional (grid to EV) consumed energy must be metered for grid management and billing purposes.
- **Bidirectional communications –** The SM infrastructure is a potential gateway conveying upstream information to the DSO or to an aggregator entity (15 min average power consumed, charging period, amount of energy absorbed from the grid) and provide relevant downstream information from the DSO/aggregator side to customers (scheduled maintenance, interruptions or other important events, billing information, available charging modes and set-points to halt the charging process).
- **Periodic metering report** – Metering data must be reported to the DSO, via aggregator, at least in every 15 min, to allow the evaluation of average power flows and consumption levels, allowing the DSO a better assessment of network operating conditions and the aggregator the necessary billing and trading information.
- **Gateway to local system –** The smart meter should be capable to interact with other meters such as gas, water and heat meters. It should be designed to promote manufacturer independence and interoperability using standardized protocols and technologies.
- **Data storage –** The smart meter must be able to store the energy consumption values for defined periods of integration (15 min for instance), historical of billing information, data related to regulated quality of service indicators (nr. and duration of interruptions > 3 min, periods where voltage is out of acceptable bounds, nr. of times that the EV was disconnected by the DSO) and logging of other events.
- **Seamless connectivity** – The EV is able to establish communication with the infrastructure in an autonomous way. The communications are established without having the direct intervention of the user either in the connection process or in the selection of the specific transmission mode or technology.
- **Privacy and security** – In order to tackle privacy and security issues, the following characteristic should be ensured:
  - Authentication – EV must register when accessing energy services. The network will either authorize or refuse a specific EV connection to the grid. In case of successful authentication the EV is assigned a unique ID.
  - Data encryption – The data exchanged between the EV and the aggregator must be encrypted to ensure privacy and resistance to tampering, especially in shared medium communications which are prone to eavesdropping.
- **Logging –** In order to account for the quality of service and technical issues, the smart metering must incorporate logging of events which can be classified as: regular and unauthorized.
- **Clock –** Real time clock to support tariff activities. The clock should be synchronized with upstream certified entities.
- **Firmware updates** – Remote update of smart meter firmware for bug correction or to add new functionalities should be possible. The firmware specifically related with the measurement modules cannot be modified.
- **Contract selection –** Through the HMI, the client should be able to access an application where information on available charging modes is provided. The client is able to choose the more adequate charging mode (DC or MPT only).
- **Communication fault procedures** – The charging management and control may be compromised, due to its dependency on the communication infrastructure. A mechanism to detect such failures must be included, which will keep the operating state for the following 30 minutes. After this period, if communications are not re-established, all EV will have their charging rate set to 50% of its rated power. This prevents that a high number of EV charging simultaneously jeopardizes the network operation.

B. Advanced smart meter version for domestic charging

The advanced smart meter is an extension of the basic version and will allow EV charging at home in the SC and V2G charging modes.

In order to cope with the advanced features inherent to the SC and the V2G charging modes, the basic smart meter version has to be enhanced with extra functionalities to face the increased interaction that will exist between the EV owner and the aggregator/DSO, the large amounts of data being exchanged between parties, the remote definitions of the SC and V2G parameters, the load monitoring and management in a V2H perspective and the roaming feature.

The following advanced functionalities are envisioned to be developed as an extension to the basic version of the smart meter to satisfy the new requirements:

- **Advanced HMI –** In addition to the basic HMI, this extended version should allow consumers to be aware in real time of their household and EV energy flows, as well as to manage them in a V2H perspective. The data display allows the consumer to access an application with information on available charging modes, enabling the choice of the most suitable one (DC, MPT, SC and V2G).

- **Bidirectional power measurement** – Bidirectional (grid to EV and EV to grid) active power must be metered for grid management and billing purposes.
- **Enhanced bidirectional communications** – The information exchanged in SC and V2G charging modes is more complex than in DC and MPT. The upstream information sent by the SM to the DSO and aggregator entities concerns the period during which the EV will be connected to the grid and the required battery SOC at the end of that time. The downstream information from the DSO or aggregator side to customers will be scheduled maintenance, interruptions and other important events, billing information, information on available charging modes, set-points to adjust EV control parameters and V2G and smart charging set-points.
- **Extended data storage** – The smart meter must be able to store the values of the energy absorbed and injected into the grid for defined periods of integration (e.g. 15min), historical of billing information, the battery status, data related to regulated quality of service indicators (nr. and duration of interruptions above 3 min, periods where voltage is out of acceptable bounds, nr. of occurrences where EV SOC at disconnection moment is lower than 95% of the initially specified value) and other logging of events.
- **Extended logging** – In order to account for the quality of service and technical issues, the extended version of the smart metering must incorporate logging of events which can be classified as: regular, unauthorized and emergency.
- **Improved contract selection feature** – The contract selection feature in the extended version should include the possibility of choosing between all the existent charging modes: DC, MPT, SC and V2G.
- **Load monitoring and management** – The smart metering infrastructure should be able to turn on and off specific appliances or EV according to the established usage profile of each user, in a V2H perspective.
- **Communication network management and support** – The smart meter should be responsible for the establishment and configuration of a communication network. The metering infrastructure should take care of the normal operation of the local network. It should also ensure the necessary actions towards emergency support by automatically monitoring all the data links. It is also envisioned that the smart meter infrastructure will support the integration of sensor networks to enable the control and automation of loads and connected energy resources.
- **Remote parameters definition** – The advanced smart meter should be prepared to receive every 15 min downstream signals to adjust EV control parameters, as a result of the possible participation of EV in the secondary frequency control, V2G and smart charging set-points.
- **Roaming** – An advanced smart meter should allow EV to be connected to different supplier/aggregator (see Fig. 3), that will establish a specific dialog with the local system operator. The EV might connect to a visiting network having the same services and features provided as if it was connected to the original/home network.

C. Smart meter version for public charging points

The SM version for public charging points will need to be prepared to charge EV of all sorts of clients, requiring high flexibility to handle all existent charging modes.

The SM for public CP shares some of the previous functionalities of the advanced domestic SM such as bidirectional power measurement, enhanced bidirectional communications, extended logging, remote parameter definition and roaming. However the public version of the SM also envisages changes in other functionalities:

- **Basic HMI** – The same characteristics of the basic HMI in the domestic environment are available here. However the range of available charging modes is extended to include all possibilities.
- **Data storage** – The smart meter must be able to store the values of the energy absorbed and injected into the grid for the defined periods of integration (e.g. 15min).
- **Improved contract selection feature** – The contract selection feature in this extended version should include the possibility of choosing between all the existent charging modes: DC, MPT, SC and V2G. In addition EV owners may opt for a pre-paid service.

V. METERING USE CASES FOR V2H

The V2H idea is a particular case of the V2G concept where the domestic/home environment is the main focus [13]. The previously mentioned functionalities for V2G provide the basis for V2H metering use cases.

In both V2G and V2H, the smart metering is considered as an abstraction of an AMM system. Such AMM system is responsible for the establishment of a communication network, setting up a HAN that will interconnect EV, appliances (App), storage devices and microgenerators (μG). In addition, the AMM is responsible for the link between the domestic HAN and the utility LAN. At last, the AMM will implement a series of control functionalities to deal with EV usage profiles, technical constraints, and customer-oriented services.

Although V2H is a novel concept, it can be envisioned to operate under three realistic use cases depending upon the availability of grid connection and microgeneration. These use cases are:

- EV + Appliances Management;
- EV + μG + Appliances Management;
- Isolated Management.

A. Use Case A: EV + Appliances Management

In this use case, the home is connected to the electric grid and EV are available for energy management. The AMM is responsible for managing the EV charging/discharging along with the home appliances, as illustrated in Fig. 4.

The EV battery can be used as a storage device that provides electric energy to the home appliances especially in periods where electricity prices are more expensive. Such approach must be limited by technical and EV profiled usage constraints. In fact, from the technical point of view, the electrical energy that can be supplied by EV is limited by particular characteristics of the EV batteries and the domestic electric network ratings. From the usage perspective, the EV might be needed for travelling purposes. Therefore, in order to foster the V2H concept, the AMM might allow users to deal with different EV usage profiles, which represent different technical constraints, as well as to decide the most adequate management strategy exploring available tariff schemes. The availability of such a management strategy allows EV owners to charge their cars in the periods where the electricity cost is lower (typically during valley hours) and use it during the higher price periods (typically in the peak hours), contributing to reduce the EV owners electricity bill.

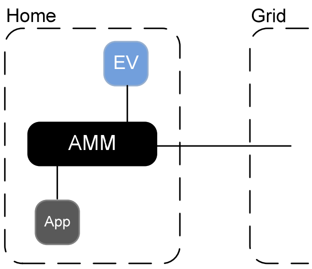

Fig. 4 Use case A: EV + Appliances Management.

Finally, it should be referred that special contracts with additional economical advantages can be established between the EV owner and the supplier/aggregators, in order to align the charging strategy accordingly. As a matter of fact, EV charging can be included in the typical on/off strategies deployed by the DSM strategy of the supplier/aggregator. Besides the on/off approach, supplier/aggregators might go further and implement a charging management approach based in: 1) a centralized management of the battery charging and 2) a local droop control approach [14], for the power absorbed/injected by EV from/into the grid. The droop control approach provides the system operator with the capability of fine tuning EV charging according with the grid's needs.

The electrical energy provided by the EV can be used for peak shaving and other purposes in the DSM strategies as well. Thus the AMM must devise a transparent interface enabling the domestic user to provide DSM services to the grid according to a home usage profile. This profile must contain information regarding the EV profile and the available appliances for remote control.

B. *Use Case B: EV + μG + Appliances Management*

In this use case, the home is connected to the electric grid with EV and μG available for energy management. The AMM is responsible for managing the EV charging/discharging along with available microgeneration and home appliances, as illustrated in Fig. 5.

Along with all the functionalities described previously, in this use case the AMM must account for the available microgeneration. The presence of microgeneration will bring additional flexibility for V2H management given that batteries can provide storage for renewable sources. For instance, the AMM must allow communication and control among EV and μG in such a way renewable energy can be stored in the batteries of EV, if this represents an economical advantage. This economical advantage might come from using stored energy to minimize the amount of electricity drawn from the grid when prices are high, typically during peak hours. Another economical advantage might come from selling of unneeded stored energy to the grid precisely when prices are also higher.

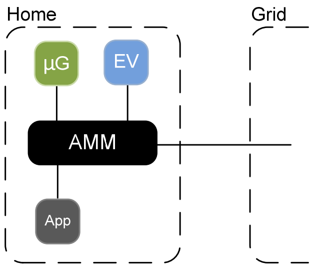

Fig. 5 Use Case B: EV + μG + Appliances Management.

A different situation where this AMM approach might be exploited is when μG are simultaneously producing energy near their higher limits and the energy consumption is low. In such conditions, voltages can surpass the upper bound values in low voltage networks, as in this type of grids R>>X. Therefore, if required, the DSM might send set-points to the μG units ordering them to reduce the energy production. In these situations, instead of having microgeneration curtailment, used to solve the overvoltage problems, EV might be used to take full advantage of the μG units' potential by storing the energy that otherwise would be spilled.

C. *Use Case C: Isolated Management*

In this use case, the home is isolated from the electric grid in the sense that no energy is exchanged with the grid. This isolation may arise mainly as a result of two reasons.

In the first situation it is considered that enough microgeneration and V2H is available to supply the domestic appliances and as such the AMM intentionally inhibits any energy exchange with the grid. This is only a hypothetical scenario, since the energy produced by the μG units is usually remunerated with very interesting feed-in tariffs, thus making more sense to sell it all to grid operator. In the second, an emergency event or fault in the grid forces the home to be physically disconnected from the grid. Both cases are illustrated in Fig. 6.

Unlike previous use cases, the domestic network will not be able to provide services to the grid, although the disconnection may represent an advantage to the system in some situations. In fact the AMM is responsible for performing frequency regulation and energy supply according to a priority list of home appliances. Ultimately if there is enough generation, the AMM will be able to ensure that the entire load is supplied.

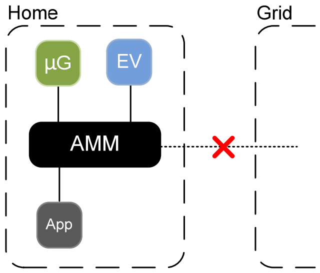

Fig. 6 Use Case C: Isolated Management.

VI. Final Remarks

Large deployment of EV will impose tremendous challenges to the operation and management of the electric power systems of the future. Such new scenario will require the development of an adequate and highly reliable communication infrastructure, in order to reduce the negative impacts that EV might provoke and to increase their potential benefits.

Given this new demand, provided that all the required functionalities are implemented, AMI solutions might be a very effective gateway to provide universal functions from measurement to communication in order to achieve a high level of coordinated energy management. This will include, under a V2H framework, the control of EV charging/discharging rates, the implementation of DSM policies and even the control of grid power injection.

Concerning EV, the real start-up/demonstration of the concepts presented in this work should involve, in a first stage, a progressive use of EV by fleets of cars like taxis, being progressively extended to the general public. This first stage will provide a way to learn and adjust AMI/SM solutions to massively extend the concept to the general public and to allow grid operators to improve the adopted solutions regarding the management and control of the power system.

Acknowledgment

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