Operational interfaces for EV Smart Charging across extended e-mobility value chain

Giovanni Coppola, Federico Caleno, Teresa Casacchia
Enel Distribuzione
{giovanni.coppola2, federico.caleno, teresa.casacchia}@enel.com

Alessandro Di Giorgio, Andrea Mercurio, Francesco Liberati, Letterio Zuccaro
Department of Computer, Control and Management Engineering, Sapienza
{digiorgio, mercurio, liberati, zuccaro}@dis.uniroma1.it

ABSTRACT

This paper provides an overview of the architectural design and use cases underlying advanced smart charging techniques to be implemented in the Enel Distribuzione's EV charging infrastructure, which, in Italy, is currently deployed under the regulated business model described in [4]. The aim of this development is to demonstrate the operational interfaces between EVSE Operator back-end systems and DSO legacy systems that enable the provisioning of smart charging services to final EV Customer, taking into account constraints across the whole e-mobility value chain. The proposed system architecture (designed in the framework of the FP7 EU funded project MOBINcity[1]) will be implemented and field tested in Fall 2014 in a subset Enel Distribuzione's infrastructure, leveraging optimization algorithms provided by La Sapienza, University of Rome.

EVS AS MOBILE LOAD MANAGEMENT TOOL AT LV/MV LEVEL

Electric mobility ramp up as a promising future European core market will result in a widespread increase of high-density power loads impacting on the current operation and planning of Low Voltage (LV) and Medium Voltage (MV) electricity grids. This, if not properly managed, might significantly rise the system costs of electric mobility adoption, possibly jeopardizing it. As a consequence, Distribution System Operators (DSOs) are expected to play a relevant role in the transition from fossil fuel based mobility to electro-mobility, facilitating the Electric Vehicles (EVs) hosting capacity of the grid and improving its resiliency against such a new pattern of energy consumption from EVs. With this regard, pioneer Information and Communication Technology (ICT) platforms are currently in operation, mainly focused on providing EV charging services at the grid Points Of Delivery (PODs) by means of Electric Vehicle Supply Equipment (EVSE) (also called charging stations), which monitor and manage charging sessions information for billing purposes. These systems are run by the EVSE Operator and their extension to allow accurate and profitable smart charging is key to maintain a reliable operation of the electricity grid, without increasing the system adoption costs of electric mobility.

This paper describes the ICT architecture and interfaces specifications resulting in an incremental innovation of the current Enel Distribuzione's EV charging infrastructure management system (EMM, Electric Mobility Management system), which is a real-time, multi-tenant ICT platform responsible for the operation and maintenance of charging stations. The aim of these operational interfaces is to support a reliable business process that control EVs charging according to constraints set by all business partners involved in the electric mobility value chain. These interfaces provide a worldwide first experiment of an end-to-end operational framework involving the DSO, the EVSE Operator, the EVSP (Electric Vehicle Service Provider, who holds a Business 2 Customer – B2C – relationship with the final EV driver) and the Customer himself. This architecture is going to be field tested within MOBINcity, an EU-funded Framework Programme 7 initiative in which the University of Rome La Sapienza and Enel Distribuzione are jointly investigating this concept. Smart charging schemas can be large-scale implemented, allowing the DSO to demand load modulation to either the EVSE Operator or the EVSP as a grid stability ancillary service. The EVSE Operator or the EVSP, according to the specific business model implemented, profitably turns Customer's time flexibility into charging fees reduction or other B2C incentives.

To the purpose of running EV charging processes according to given boundary conditions, an external control entity, a Smart Grid EV Integration System, is designed. Such system interfaces towards the current Enel Distribuzione's EMM system, as depicted in Fig. 1, and must find the suitable tradeoffs between target Load Curves requested by the DSO, Customer preferences and, whenever accountable, EVSP and EVSE Operator constraints.

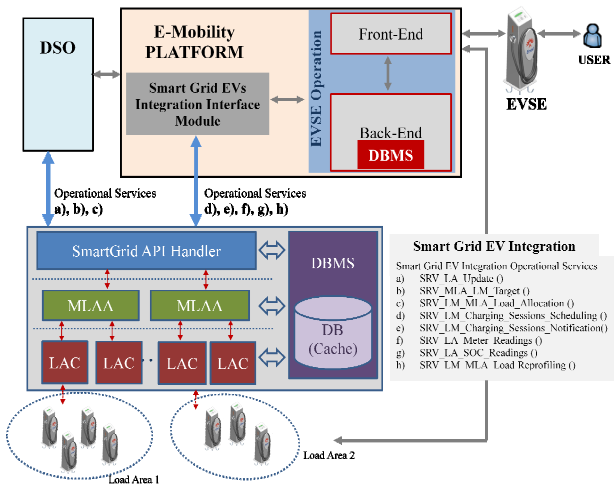

Fig. 1 Proposed Improvement of e-mobility system for smart EV charging.

At a later stage, such a System can be directly hosted in

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the EMM as a sub-system responsible of trading load according to the DSO needs.
The Smart Grid EV Integration System offers a set of electric mobility management services to the EMM system through the Application Programming Interface (API) Handler, which is a module intermediating the legacy systems and the new components hosting the control algorithms. At a first level, the Load Area (LAC) hosts the control functionalities that optimally manage the aggregated power curves of EVs charging in a Load Area (LA), which is a list of PODs associated to EVSEs. At a second level, the Macro Load Area Aggregator (MLAA) hosts the control functionalities that aggregate flexibilities from a cluster of LAs in order to provide Active Demand (AD) Products to grid players. This multi-level control structure guarantees scalability and provides the flexibility needed to meet different use cases, triggered by several actors at different levels. In particular, the following two use cases are discussed in this paper:

- *Scheduling of charging sessions*, dealing with real time control of EV charging, which allows the EVSE operator/ EVSP (i) to follow the Load Curve targeted by the DSO at LA level and, (ii) to satisfy the drivers' charging preferences (demanded energy, EV driver time of departure from the charging station), in reaction to the charging requests made by the drivers.
- *Load reprofiling*, dealing with the composition of AD products to be released to grid entities (retailer, DSO, generation companies), making use of PODs clustered in multiple LAs as a balancing group.

The use cases are enabled by the establishment of the operational ICT interfaces depicted in the architecture of Fig. 1 and further detailed in this paper. The control methodologies at the basis of the Smart Grid EV Integration (sub) system of a generic e-mobility platform, such as the one depicted in Fig. 1, are model predictive control and distributed optimization, taking into account (i) the DSO power flow constraints, (ii) the customer preferences and (iii) the inner priority grid management criteria. The solution, tested on a simulation basis and currently under implementation, provides grid players with a new degree of freedom in the management of distribution grids and is expected to be hosted by the EVSE Operation system, communicating with the DSO via web services designed on purpose (Smart Grid EVs Integration Module of Fig. 1 as a component inside the EVSE Operation box).

ARCHITECTURAL OVERVIEW

As common in Smart Grid systems, MOBINcity adopts a two level control approach for load management, being the load constituted by EVs at EVSEs. In order to ensure a scalable methodology, loads are aggregated at the level of either Area (LA) or Macro Load Area (MLA) according to - and -. At lower level, each LAC optimally schedules and manages the charging processes of the EVs at EVSEs in a given LA, considering EVs user needs and local micro generation. At higher level, each MLAA balances, in advance to a specific time horizon, the aggregated load, the Distributed Energy Resources (DER) and the grid energy target. Additionally, under requests of authorised actors such as the DSO, the MLAA composes and releases in real-time AD products, as defined in - and -. As the LAC and the MLAA are innovative software modules that extend the capabilities of the EMM system to manage the operation of charging stations, in the near future they are foreseen as desirable components of any EVSE Operator back-end systems. The two level approach of the MOBINcity project tackles the issue of optimally allocating the EV charging sessions thanks to the centralized approach for charging sessions scheduling of the LAC on one side, and the de-centralized approach of load balancing and AD product composition of the MLAA on the other side. The latter also enforces scalability and privacy compliancy of the system.

DETAILED USE CASES

This paragraph details the selected use cases, which are enabled by the execution of operational interfaces implemented between the EVSE Operator and the DSO.

Scheduling the charging

This use case deals with the dynamic computation [3] of the charging load profiles at EVSEs level, trading off each EV charging processes against current active Customer preferences and DSO's desired Load Curve in each LA. Such a control action, together with the dynamic computation and update of the load profiles of all the EVSEs within a specific LA, is under the responsibility of the LAC software module, which is hosted in the Smart Grid EV Integration System.
The computed load profiles are stored in a local Database (DB) and exchanged with EVSE Operator Back-end by means of a dedicated web service (service *SRV_LM_Charging_Session_Scheduling* of Fig. 1). The EVSE Operator Back-end is in charge of translating the load profiles into information compliant with the communication protocol implemented between the EVSE and the EVSE Operator Back-end. At the current stage of EV market and international standards, these means of translating the load control at EVSE level into Pulse Width Modulation are compliant to the requirements of ISO/IEC 61851 Ann. A.
The LAC controls the load profiles at EVSE level based on two main objectives:

- Cost minimization and satisfaction of User Preferences ("requested energy" and "time window available for the charging process"), as specified by the users when asking for the smart recharging service.

- Tracking of a reference load curve aggregated at LA level either set on a day-ahead basis or updated during the day by the DSO as a consequence of a reprofiling request (see the next use case).

The LAC computes EVSE load targets by solving a discrete-time model predictive control problem. Outputs of the LAC problem are:

- The load profiles at EVSE level (target power curves).
- The related costs of the charging services.

The basic interaction of this use case is reported in Fig. 2. The scenario takes into consideration a LA with a number of EVSEs where EVs with different charging technologies (3.3 kW and 22 kW) arrive and make a charging request, specifying the final desired state of charge (SOC) and the available time window. The task of the LAC is to manage the charging sessions of all the vehicles connected to the EVSEs in the LA, respecting the constraints given by the user preferences and the grid, while following a desired aggregated power profile at LA level. As shown in Fig. 2, when a new EV arrives, the controller (the LAC) reads the user preferences and retrieves the current SOC from all the EVs connected in the LA. Then it solves an optimisation problem, returning an optimal charging load profile for all the EVs connected in the LA. The new load profile and the updated ones are applied starting from the next time step. Fig. 3 describes the controlled aggregated load evolution in a LA with respect to the reference load profile.

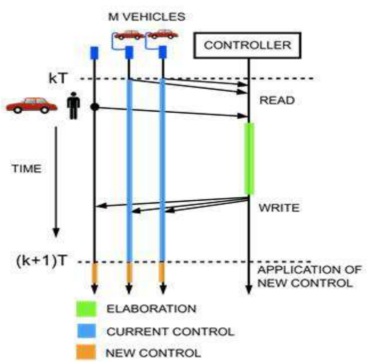

Fig. 2 Scheduling the Charging use case basic interaction.

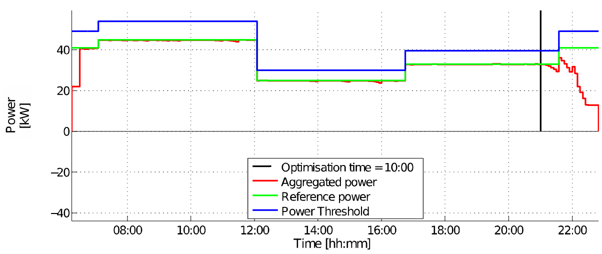

Fig. 3 LA load evolution (in red) under LAC control.

Charging Load Re-Profiling on DSO's Request

This section describes the basic process that allows the MLAA to compose a determined AD product by aggregating the LACs flexibilities upon a specific request of the DSO. The procurement activity is triggered by the DSO, which detects a possible critical situation on the grid and asks the MLAA to release a specific AD product on a Macro Load Area (theoretically the MLAA could be part of an EVSE Operator back-end, hence the DSO would interact with EVSE Operator business actor). The MLAA verifies the flexibilities of the LACs on the relevant Macro Load Area and composes the AD product. The DSO either approves or rejects the AD product. If the AD product is approved by the DSO, the MLAA sends the re-profiling dispatching signals to the LACs. This use case takes place in advance with respect to the time of the activation of the AD product, according to the proper time-lines of the DSO. An AD product is defined in - and - and is represented in Fig. 4. The EVSE Operator System allows the MLAA to know the constraints on the AD product on the relevant Macro Load Area in terms of maximum and minimum flexibility allowed in a specific time frame.

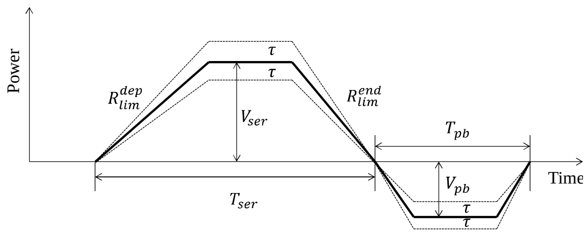

Fig. 4 Standardised AD product.

The procurement activity of the MLAA and the composition of the AD product are based on the interaction of the following systems and actors:

- MLAA, which collects the flexibilities from LACs and accordingly composes the AD product.
- LACs, which offer to the MLAA their flexibility for the composition of the AD product (i.e. a number of reprofiling alternatives, and the associated cost).
- DSO, which may pose some limits on the composed AD product.

The flexibilities procured by the LACs are stored in a local DB of the EVSE Operator Back-end System and later used to pay off the LACs that contributed to the AD product composition.

The innovative approach selected for the MOBINcity project is based on the solution of a pool-based local energy market in LV network (i.e. the Macro Load Area) where each LAC offers different levels of flexibilities (at different costs) on the time interval of interest. The MLAA then composes the received offers trying to reach the required modification to the aggregated load by using a discrete optimisation method

called *set partitioning*.
The interaction is possible thanks to software modules resident in the LAC and the MLAA and it is an asynchronous interaction. Input data for the LAC re-profiling problem (i.e. generation of a list of alternative reprofiling offers to the MLAA, with the associated cost) are:

- AD product duration according to Tab. 1 (from the MLAA).

The outputs are:

- List of offered flexibilities, each flexibility is a composition of a $2 \times n$ matrix and the related cost (real number, €), where n is the duration of the AD product, expressed in number of sampling time intervals, the first row reports the offered modification of the reference load profile of the LAC (kW) and the second row specifies the time interval which the set-point values of the first row refer to. In terms of load profile, the flexibility can be expressed either as the new load profile or as a difference with respects to the current profile.

Input data for the MLAA re-profiling problem are:

- AD product parameters according to Tab. 1.
- List of offered flexibilities (from LACs).
- AD product additional limitations (from DSO optional).

Output data are:

- List of procured flexibilities, specifying the selected offer from each of the LACs involved in the re-profiling activity.

Fig. 5 summarises the interaction from a simulation of an MLAA with 10 LACs. Fig. 5.a represents the requested AD product, the composed AD product and the error between the two profiles. Fig. 5.b reports the flexibilities selected by the MLAA from the LACs' offers and composed to deliver the AD product.

Tab. 1 AD product specifications.

Parameter	Meaning
T_{dur}	Duration of the product power shape
V_{ser}	Product volume or volume range, V_{ser} (kW, MW). The sign associated with the service volume can be either positive or negative
V_{pb}	Payback volume, V_{pb} (kW, MW). The maximum allowed amount of energy payback the delivery of the AD product is allowed to generate. In this paper, we prefer to take V_{pb} as a reference value for the payback level, rather than a threshold
τ	Tolerance on the values of V_{ser} (i.e. volume ranges between $(1-\tau)V_{ser}$ and $(1+\tau)V_{ser}$ are acceptable) and V_{pb} (paybacks volumes between $(1-\tau)V_{pb}$ and $(1+\tau)V_{pb}$ are acceptable). For simplicity, the same tolerance is set for V_{ser} and V_{pb}
R_{lim}^{dep}, R_{lim}^{end}	Deployment and ending ramping limitation range (kW/ minute, MW/minute). These are limitations on how fast/slow product power deliveries can be started and ended
Π	Deployment energy price (€/MWh or €/MW). This is the price to be paid to the MLAA for the service of AD product composition

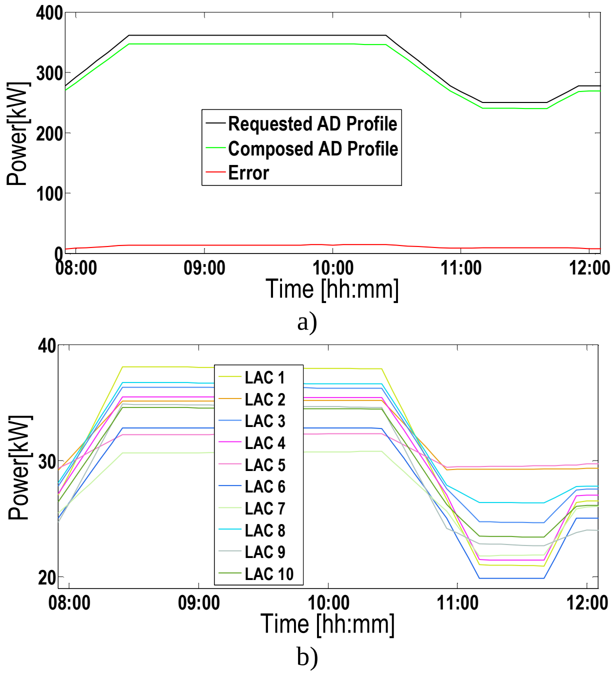

Fig. 5 Example of Load Reprofiling.

SMART GRID EV INTEGRATION OPERATIONAL SERVICES

The definition of a set of web services exposed by the Smart Grid EV Integration System to both the EMM and the DSO systems through an API Handler (refer to Fig. 1) sets the basis for the implementation of the above uses cases. Some of these services might be absorbed within the internal operation of EMM system in future system releases. Hereby follows a short description of this web services package:

- *SRV_LA_Update*: a service that specifies the set of EVSEs belonging to a LA. The service allows EVSE Operators and DSOs to talk a common language when trading time flexibility against load management.
- *SRV_MLA_LM_Target*: a service that defines the reference load consumption for each LA for, at maximum, the next 48 hours
- *SRV_LA_Meter_Readings*: a service that provides metering data at EVSE level. The service is called with a specified periodicity, for instance every T_{UPD} minutes, therefore the load curve is a vector of T_{UPD} power values.
- *SVR_LA_SOC_Readings*: a service that updates the state of charge of all the EVs currently charging in the LA. The service is called every T_{UPD} minutes.
- *SVR_LM_Charging_Request_Notification*: a service called whenever the EMM has to manage a new smart charging request.
- *SVR_LM_Charging_Sessions_Scheduling*: a service periodically called by the EMM in order to evoke the Smart Grid EV Integration System computation/update

of the load profiles to satisfy all the smart charging requests currently on-going in a specified LA.

- *SRV_LM_MLA_Load_Allocation*: a service called on a day-ahead basis to provide each LA with a power reference for the specified day.
- *SRV_LM_MLA_Load_Reprofiling*: a service made available by the MLAA and aimed at modifying the power references of LAs so that an AD product can be composed by the MLAA and released by the MLA.

For each service, a defined set of inputs and outputs are specified (i.e. the attributes of the service request and response messages). As an example, Tab. 2 and Tab. 3 respectively report the request and the response messages related to the service *SVR_LM_MLA Load_Reprofiling*, specifying the use case *Charging Load Re-Profiling on DSO's Request* described above.

Tab. 2 Message *SRV_LM_MLA_Load Reprofiling_Request*.

Attributes	Type	Constraints	Description
Load_Reprofilig_Request_ID	string	Multiplicity:1	Identifier (ID) of the Load Reprofiling Request Instance
MLA_ID	string	Multiplicity: 1 Max length: 20 char. Mandatory	ID of the MLA defined by the DSO
Requested_AD_Product	BO AD Product	Multiplicity:1	Specifications for the AD product to be composed

Tab. 3 Message *SRV_LM_MLA_Load Reprofiling_Response*.

Attributes	Type	Constraints	Description
Success_Result	Boolean	1 success 0 failure	Availability to release the AD product
MLA_AD_Product_List	BO Load Allocation Result	Multiplicity:*	List of load curves results at LA level
Composed_AD_Product	BO AD Product	Multiplicity:1	Specifications of the composed AD product

The definition of the services is based on the specification of the so called Business Objects (BOs), which define a set of attributes relevant to different information service interfaces. As an example, the BO *Load Allocation Result* in Tab. 3 is specified in Tab. 4.

Tab. 4 Business Object *Load Allocation Result*.

Attributes	Type	Constraints	Description
Load_Allocation_Session_ID	string	Multiplicity: 1	ID of the Load Allocation session
Load_Area_ID	string	Multiplicity: 1 Max length: 20 char. Mandatory	ID of the LA defined by the DSO
LA_Target_Load_Curve	BO Load Curve	Multiplicity: 1 Mandatory	Load curve at LA level as computed by the MLAA

CONCLUSION AND FUTURE WORK

This paper presented an architectural proposal that enables trading of smart charging services to benefit final EV Customers. Within an extended e-mobility framework value is propagated from the DSO, who sets boundary conditions for the LV/MV grid management at Load Area level, to the EVSE Operator, who implements load control over active EV charging processes within the Load Area. The EVSE Operator implements a trade off between DSO requests, EV Customer preferences and EVSP constraints dynamically managing EVs charging sessions in respect to the target Load Curve set by the DSO for a specific Load Area and timeframe. This is an extension of the Enel Distribuzione's "EMM" e-mobility platform, as described in [4], which strategic aim is to provide Smart Grid services to EV users, EVSE Operators/EVSP and DSOs in a viable and scalable way. This extension will be field tested in Q4 2014, within the "MOBINcity" FP7 project. Accountable and easy to implement control algorithms have been designed, which rely on first-level controllers, which are devoted to command the ongoing charging sessions in respect of both the user preferences and the DSO constraints, and second-level controllers, which aggregate local flexibilities in order to provide active demand products. Simulations have shown the feasibility of the approach, which assures benefits to the grid thanks to the active demand implementation without impairing the quality of charging service and customer experience, considering that customers are trading time flexibility with pricing incentives. Future works will deal with a more accurate selection of balancing strategies among LACs, especially taking into account the current demand level at each Load Area. Areas of improvement also include: to integrate such a mechanism in the Enel Distribuzione's EMM system and bring these functionalities in operation in order to execute them over more than 2,000 EVSEs worldwide, given the capability of the EMM to interface with several other DSO systems; to include network constraints; to define mechanisms of advanced AD product composition and release processes.

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