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Optimal management of the automatic generation control service in smart user grids including electric vehicles and distributed resources

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ABSTRACT

This paper presents an analysis and systemization of automatic generation control (AGC) in distribution networks (DNs) with high penetration of distributed resources, including electric vehicles (EVs). A methodology is developed that allows designing the AGC service at the distribution level, and an optimization model is proposed to assess the potential of AGC provision from EVs according to an objective of optimal economic management. A realistic case study is considered to analyze the proposed approach, and to illustrate both the potential of the methodology and the effectiveness of the optimization model. Results show that the proposed methodology represents a flexible tool that any system operator could use for the operational planning and the management of ancillary services such as AGC with EVs.

1. Introduction

1.1. Automatic generation control: moving from the transmission system to the distribution system

Traditionally, AGC is a well-known and established automatic procedure for secondary frequency regulation within the general framework of transmission systems' power balance and stability control. It is a basic tool for the real time control of electric power systems, including the regulation of system frequency and scheduled power flows over transmission lines that link numerous independent operating entities into a supply network [1–6]. In recent years, the technological development and related evolution of ICT services, at all power and voltage levels, have brought substantial improvements in both performance and applicability potential of AGC. Accordingly, and following the introduction of DG, it has been possible to envision a generalization of the AGC paradigm and an extension of its application to the sections of power system down the transmission network. As a matter of fact, from a SG perspective, the AGC implementation is nowadays referable to generation, balancing authorities, transmission providers and distribution entities.

Scaling the typical AGC control architecture from transmission to distribution – e.g. at a sub-regional level – this control can be considered as a structured, zonal centralized control. Then, in each area of the system subject to a disturbance, the control of generation, local transmission, distribution, and loads subsystems are structured hierarchically. As in the transmission system, internal control loops on lower subsystem levels are characterized by smaller time constants than those at a higher level, and operate in different time scales virtually decoupled and coordinated with the respective protection systems.

DNs significantly differ from the transmission system's context, for what concerns not only the topological and jurisdictional configurations of areas and related interconnections, but also the features of both generation and load resources. With respect to this, widespread ICT penetration and strictly coordinated providers' areas ("virtual power isles"), equipped with centralized control of distributed and interconnected sub-areas, are basic requirements for the applicability of AGC.

Abbreviations: AGC, automatic generation control; BM, biomass; BSS, battery swapping station; CLR, controllable load resource; DC OPF, DC optimal power flow; DER, distributed energy resource; DG, distributed generation; DN, distribution network; DRP, demand response program; DSO, distribution system operator; EV, electric vehicle; EVA, electric vehicle aggregator; EVC, electric vehicle customer; ICT, information and communication technology; LP, linear programming; LV, low voltage; MAS, multi-agent system; MG, microgrid; MV, medium voltage; PV, photovoltaic; RES, renewable energy source; SG, smart grid; SOC, state of charge; SUG, smart user grid; TSO, transmission system operator.

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[1] The main notation used in the paper is provided below for quick reference. Other symbols are defined as required throughout the text.

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Nomenclature[1]

Parameters

C_{GRID} unitary cost of automatic generation control from generation outside the smart user grid [€/MWh]
C_{CLR} unitary cost of automatic generation control from controllable loads [€/MWh]
C_{EVS} unitary cost of automatic generation control from electric vehicles [€/MWh]
$\Delta CLR1_{bid}$ contracted regulation band for controllable loads inside the smart user grid [MW]
$\Delta CLR2_{bid}$ contracted regulation band for controllable loads outside the smart user grid [MW]
ΔEVS_{bid} contracted regulation band for the electric vehicle station [MW]
$\Delta GRID_{bid}$ contracted regulation band for generation outside the smart user grid [MW]
ΔP^* requested amount of regulation [MW]
L^{sch}_{CLR1} scheduled power demand from controllable loads inside the smart user grid [MW]
L^{sch}_{CLR2} scheduled power demand from controllable loads outside the smart user grid [MW]
L_{cr} critical (uncontrollable) loads [MW]
L^{sch}_{EVS} scheduled electric vehicle charging [MW]
P_{BM} scheduled power production from the biomass power plant [MW]
L^{sch}_{GRID} scheduled power output of generators outside the smart user grid [MW]
P_{PV} scheduled power production from the solar plant [MW]

Variables

ΔL_{CLR1} optimal regulation share for controllable loads inside the smart user grid [MW]
ΔL_{CLR2} optimal regulation share for controllable loads outside the smart user grid [MW]
ΔL_{EVS} optimal regulation share for controllable electric vehicles [MW]
ΔP_{GRID} optimal regulation share for generators outside the smart user grid [MW]
L_{CLR1} final power demand from controllable loads inside the smart user grid [MW]
L_{CLR2} final power demand from controllable loads outside the smart user grid [MW]
L_{EVS} Final electric vehicles charging [kW]

In this complex framework, the AGC function can be related to the control architecture of a multi-area system, properly scaled to the distribution level through the physical elements generically involved in the process of security management, and specifically characterized by features sensitive to the control parameters, such as network extension and topology, type, size and allocation of generation facilities and loads. In each single area, the commitment for AGC ancillary services has to schedule the programmable power resources (typically RESs, as well as programmable DERs such as storage devices and controllable loads). In particular situations, beside the adjustment of power by different means such as generation, storage units or loads regulation, rebalancing operations can be supported by islanding procedures.

Performance speed and AGC effectiveness on interconnected areas are related to the ability of loads and generators' governors to respond to any power mismatch in the system both statically and dynamically. This ensures, on one hand, the provision of an adequate amount of power to the AGC requirement, and, on the other hand, the integrated collaborative participation of all the scheduled resources despite their technological and operational differences.

With the spreading and establishment of AGC also at the electricity distribution level, the DN and the HV transmission system will become more and more integrated, if supported by a coordination of the respective protection and control systems. This coordination, in fact, is necessary for making the individual protection and control components not only interoperable, but also organized in areas and sub-areas of functions subject to intelligent management, hierarchically distributed on multiple levels of automation, and suitable for islanded operation. It can be expected that the AGC functions carried out by the distribution system's control resources will be coordinated at a global system level, but at the same time these functions will also be flexibly operable as autonomous systems within isolated sections of the distribution grid.

In this work, a methodological development in the direction of AGC for distribution systems has been proposed in order to consider the EV technology and "zonal" AGC, referring to a circumscribed area of the DN, disregarding specific functional connections with the transmission system. The assumed reference framework is an electricity utilization area of unspecified extension, having as many energy resources as needed to make the participation of this area in the ancillary services market feasible and significant. For the modeling of this area, the paradigm of SUG is applied since it fully fits the methodological platform deriving from MG and SG concepts.

1.2. Background

In a restructured environment, AGC is generally procured as an ancillary service in the electricity market. At the distribution level, assuming that DGRs and CLRs are available to provide such a service [7], some modifications have to be introduced in the conventional AGC concept and implementation in order to achieve a proper dispatch of the available resources for AGC [8]. Control actions by generators and CLRs have to be evaluated, and accordingly the payment of the AGC service has to be distributed among these resources in proportion to their individual contributions [9].

Beyond the fact that AGC's technological and managerial scale at the distribution level has very different characteristics than the AGC for wide area systems, some specific aspects characterize the AGC role and implementation at the MV or LV levels. A point of common coupling between the TSO and the aggregator of distributed AGC resources is developed and discussed in [9]. This point of common coupling, which removes complexity in the communication requirements (both at operation and market levels), is carried out by the DSO. However, the limitations and the performance features of AGC applications in a large variety of configurations of distribution systems still are not clearly analyzed, particularly within prospective SG developments including coordinated control among largely distributed resources. Whatever system configuration is considered, the control set-points have to be selected according to the availability, the nature, and the maximum regulating capacity of such resources. For example, if including CLRs, the DSO can consider the load demand as a consistent resource for AGC.

Additionally, the AGC implementation at the distribution level is challenged by the growing impact of distributed EV charging, which offers both opportunities and hurdles. Since EV services integrate other dispersed energy resources that may comprise both generation units and stationary loads [10], in order to ensure a well-coordinated utilization of the controllable resources, aggregators are proposed to cluster and manage large numbers of distributed energy resources, as well as large numbers of EVs [11,12].

Using controllable thermal loads for AGC has been recently proposed in [13–15]. Such loads are typically used for frequency regulation, given their capability to store energy and to provide load flexibility with little impact on the habits of the customer.

The use of EVs to provide AGC has been investigated in [15–20]. In order to provide AGC, EVs should be an active element within the power system. If EVs enter this market individually, their impact would be small and also unreliable due to their stochastic production/consumption behavior. Instead, if an aggregating entity is available, with the purpose of grouping EVs to contribute to AGC, then the available resource would be more significant and the confidence on its availability higher. BSSs [21], which provide replacement of discharged EV batteries with fresh ones, seem particularly suitable for implementing AGC through EVs. In fact, in this case, the EVCs could reasonably contract the service leasing the battery from the BSS, and the EVA – on BSS's behalf – could arrange a recharge-controlled battery stock as a local reserve to be kept strategically available, ensuring fully charged batteries to drivers, and the support services for the grid at the same time. This possibility has been investigated in [22], and more recently in [23].

If AGC is provided by CLRs such as thermal loads or EVs, the principal challenge is the need of achieving a balance between the global control requirements from the grid and the local impact on the customers. In the case of thermal appliances, a certain temperature range shall not be violated, whereas for vehicles there may be restrictions imposed by a desired battery SOC for transportation purposes [15]. In case of BSSs, a number of batteries are always available but the SOC has to vary according to the service demand. Or, inversely, at equal SOC, the number of batteries varies according to the service demand. In any case, this variation can be easily controlled introducing battery swapping service facilities.

1.3. Purpose and contribution

In light of the discussion in the previous sections, the aim of this paper is proposing an analysis and systemization of the AGC provision in active DNs with high penetration of distributed resources, including EVs. This work specifically refers to physical EVAs [24] and to smart energy utilization areas (smart user grids, SUGs, [25]). The SUG is managed by a single operator that also provides the interface with the DSO. Therefore, this operator represents also the EVA for market trading, having the opportunity to decide which of the SUG resources can participate in the AGC service and for what amount, based on technical factors (resources capabilities) and economic aspects (costs versus benefits of AGC provision).

The proposed methodology allows building up a novel approach for designing the AGC service in DNs. In this methodology, the DSO, the SUG operator and the AGC resources are properly characterized and modeled. An optimization model is developed to assess the potential of AGC provision from EVs, according to an objective of optimal economic management. This model materializes into an LP algorithm suited for integration in the energy management system of DSOs.

A realistic case study is used to analyze the proposed approach and to illustrate both the potential of the modeling approach and the effectiveness of the proposed methodology. Specifically, the analyses carried out aim at illustrating how, in response to an imbalance signal sent by the DSO, the AGC resources within the SUG, and EVs in particular, would adjust their operating conditions in order to help stabilize the frequency at both system and SUG levels, while enabling the DSO to gain optimal economic performance and maintaining the SUG system in secure operating conditions. Particular attention is paid to the possible range of variation of resource capabilities and costs/benefits of AGC supply. In fact, globally, the analyses consider the need for the DSO to manage optimally – that is, at the minimum cost – the energy resources made available from the consumers participating in the zonal network's AGC service.

Results show that the proposed approach and developed model constitute an efficient and flexible tool that any EVA or DSO could use for the operational planning and the management of ancillary services such as AGC with EVs.

It is important to note that since the objective of this work is to address the definition of optimal management strategies of AGC resources for operational planning and operation, the model does not represent either the time constraints or the resources' reaction time to an AGC request. Nevertheless, the proposed modeling accounts for the limits of parameter variation compliant with a secure system's operation, and it is not difficult to enhance the method and related modeling for a broader purpose.

1.4. Paper structure

The rest of this paper is organized as follows. Section 2 addresses the methodology for AGC implementation in a DN, describing the criteria used to model the resources' contribution to regulation, and recalling the main concepts of the SUG paradigm [25] used in the case study. Section 3 presents the proposed optimization tool, including its detailed formulation for modeling the AGC according to the criteria discussed in Section 2, whereas the results of applying this tool to the reference case study are presented and discussed in Section 4. Finally, Section 5 summarizes the main outcomes of the study, drawing some conclusions and giving some highlights about possible future developments.

2. Methodology

2.1. Implementation and coordination of automatic generation control in distribution systems

In order to keep up with the complexities introduced by the new energy targets and the associated technological innovation, the DN is called to restructure its configuration and organization more and more in the direction of the technical and operational features of the transmission grid, according to the level of technological development and the progressive implementation of ICT. The AGC features are also following the same trend, and it can be envisioned that in the near future the AGC service will be implemented in the DN with the same policy and principles regulating the AGC at the transmission level.

In coordinating distribution-level AGC services through holistic logics that also consider the bulk transmission network, besides the need of a proper regulatory framework to refer to, different technical factors should be considered in the implementation of AGC and in the scheduling of the available resources, such as the power levels, the time of response, the mode and security of intervention. With respect to the methodological proposal of this paper, a substantial aspect arises from the static and dynamic equivalents of the virtual aggregation of energy resources such as DG, controllable loads, storage systems and islanding operations. To be valuable for AGC operation, such resources have to be programmable and real time controllable, as required by the electricity dispatching rules. Then, the coordination and interaction procedures between DSO and AGC providers should follow the same logics and practical features of the correspondent procedures between DSO and TSO. The compatibility of these AGC procedures is a basic condition for their hierarchical coordination, which can highly contribute to the static and dynamic security of the power system.

Though the implementation of AGC in a general systemic way that also includes the electricity distribution level is doubtlessly complex, the development of ancillary services including AGC in DNs is expected to have progressing enhancement. In this perspective, it is reasonable to assume that the AGC scheduling is being managed by the DSO through dedicated operation centers and with functions similar to those of a large-scale energy management system.

Another prospective problem in AGC for distribution is the adequacy of the dynamic performance of the available control resources, in order to meet the requirements of the DSO demand related to the system typology and size. The practical implementation of automatic functions of dynamic control for frequency regulation in distribution areas is basically related to an appropriate replanning of the DN, as required by the spreading of DG, and to the activation of smart procedures for managing load control and storage systems within separate but coordinated areas [26–33].

2.2. The smart user grid (SUG) paradigm – reference framework

For studies focused on active DNs with a multiplicity of different resources, a systemic approach should be used to address all the different components related to the AGC implementation in an ancillary service market framework. In this respect, this paper considers a distribution area hosting EVs, DGRs and CLRs. All these resources are managed by a public operator that also acts as the EVA, and they are organized according to a typical SUG configuration oriented to MAS architectures interfacing the DSO within an electricity market framework [34].

Any distribution area can be viewed and thus represented as a general structure made of several domains of major functionalities (generators, flexible/non-flexible loads, energy storage devices, transformers, MV FACTS, etc.) having different features, uses, behaviors and requirements. Each domain can consist of different tasks performed by individual agents that can interoperate with each other [24]. This structure, given the clear connection with MG and SG concepts, can be referred to as SUG [25].

The SUG integrates two main components:

- *Supply point:* it is the front-end of the SUG interfacing with the main DN. This point represents a physical element capable to: (a) exchange energy with the main grid; (b) control the state of the connection between the SUG and the main grid; (c) act as the SUG participants' representative.
- *Sub-SUGs:* they are entities representative of the individual domains and functionalities, which are aggregated via a proper architecture that mixes hierarchical and peer-to-peer relationships managed by MAS procedures [34].

The SUG can be considered as an aggregator of all the functionalities within an active DN that also act as an agent in the energy market, and any of its components – being it a MG, a multi-MG, or an individual energy entity – can be considered as a sub-SUG.

The concept of "aggregation" has already been proposed in several publications, in general with a different characterization based on the topic addressed and the study approach used [22,23,35–37]. The model of aggregator adopted in this paper somehow complies with the conceptual application developed in the ADDRESS project, which also defines the function of "aggregator" in a generalized form [38,39]. In fact, in [38] the aggregator is a virtual, intermediate entity that can flexibly represent various roles in the market, moderating at the same time the interaction with both DSO and customers. In this paper, the architecture of the SUG's paradigm can assume whatever physical and organizational configuration, with respect to which the aggregator's role can be managed even directly as the output of an optimization problem addressing the best market strategy for a DN anyhow configured. The features of a generalized aggregator's role for the market are integrated in the physical and organizational SUG's architecture. This offers the greatest flexibility in terms of structural composition and the highest suitability in terms of market-oriented tasks.

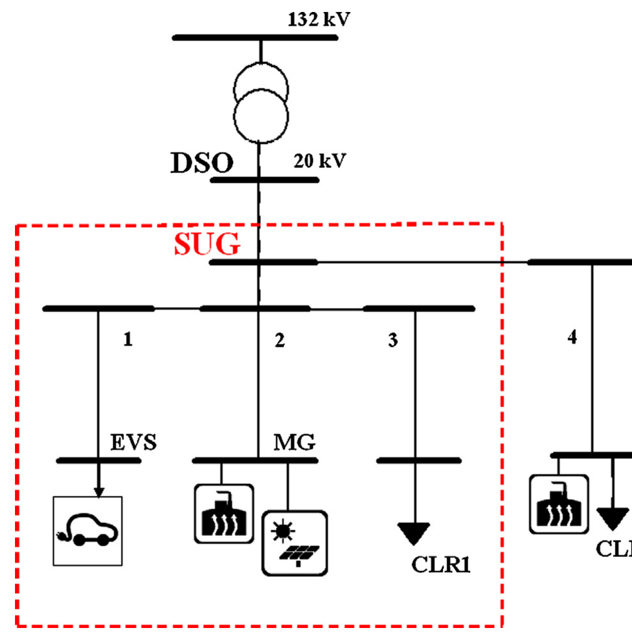


Fig. 1. Configuration of the four-feeder system.

In the specific case study of concern, the SUG is a flexible, direct and unique interface with the DSO for the AGC ancillary energy services provision. Taking into account the internal coordination among its agents, it realizes a strategy that entails different services, including AGC provision through the controllable resources. Such an operational strategy ensures the SUG operator the maximum economic benefit while maintaining the security of the area and the availability of all energy services to the final customers. The controllable resources within the SUG can contribute – to a certain amount – to AGC at both SUG and system levels. In principle, the DGRs owned by the SUG operator can provide the loads with flexible supply also for balancing purposes. However, in the case study under consideration, these DGRs are considered already producing their maximum electric power output, and therefore not included in the AGC provision.

For its part, the DSO can count on other energy consumers with DERs (DGRs and/or responsive loads) capable to provide AGC service support besides the SUG. In particular, according to the most generalized scheduling scheme of DSOs, the DGRs can be considered to provide both regulation-up and regulation down services.

The reference case study is configured as shown in Fig. 1, where the DSO has two different interfaces representing, respectively, the SUG and the pool of other active consumers. The scheme specifically represents three sub-SUGs: an EV charging/swapping station (EVS, sub-SUG 1), a set of CLRs (CLR1, sub-SUG 2), and certain DG (sub-SUG 3) within the MG. Specifically, the DG is composed by a BM plant and a PV plant, which are both dispatchable [37]. A fourth feeder represents the equivalent of other DGRs and CLRs (CLR2), which are complementary to the SUG's resources within the DSO's jurisdiction.

The following sections of the paper will explicitly refer to the aforementioned resources for the sake of clarity.

2.3. Criteria for implementation and coordination of automatic generation control

With respect to the framework in Fig. 1, a modeling approach to the AGC has to be developed for integration into the optimization tool for AGC management assessments. This approach is designed to identify how the operational strategy of the individual SUG resources should change following an AGC signal received from the DSO, and how the participation in AGC of these resources would impact technical and economic constraints due to the interfacing with the DSO. Regarding the time horizon characterizing AGC provision (order of seconds), the modeling concerns the "real time" system's operation.

In order to properly represent the AGC in a market framework, the following different components are considered:

(a) Equivalent generator model, representing the main DN as a single-bus connected to the SUG.
(b) Control system, schematically consisting of three levels – (1) centralized function for load dispatching, located at the DSO's site, operating as the interface responsible for the dispatch of the AGC signals to the SUG's and other distributed energy resources; (2) SUG's and other user areas' control centers, operating as interfaces interactive with the DSO and responsible for the information-communication between the central load dispatching center and the local AGC resources of respective competence; (3) local distributed control centers, operating as interfaces interacting with SUG's and other user areas' control centers. Two-way communication is assumed between the various interfaces according to the scheme of Fig. 1. The three control levels can be realized and managed through combined SCADA and remote control systems.
(c) Regulation share from the EVS within the SUG.
(d) Regulation share from CLRs, inside and outside the SUG.
(e) Regulation share from the DGRs outside the SUG.

In principle, the AGC signal has to be dispatched to the AGC resources based on their response speed and regulating capacity. In this work, a hierarchical criterion is assumed, according to which the AGC is "load-based". Therefore, the AGC is provided primarily by the CLRs and EVs, whereas the DGRs intervene only in order to cover the control that cannot be provided by the loads. This criterion can be represented introducing "contracted bands" for the regulation shares of the different resources. These contracted bands reflect AGC management processes that have clear connections with the typical procedures for AGC implementation at transmission level, particularly related to the dynamic characteristics of the participants to the SUG's AGC service, which are designed and scheduled to respond to the specification of contracted dynamics based on the DSO's requirements.

3. Automatic generation control management model for smart user grid systems

3.1. Modeling of regulation shares of main grid's generators' and related constraints

From a technical point of view, the amount of AGC that can be allocated to generation is constrained by: (1) ramp rates and (2) maximum regulation capacities of the participating units [9]. Therefore, in the ancillary service market, it is appropriate to consider the definition of the contracted band of regulation share for the external (outside the SUG) DGRs being mainly affected and set by the aforesaid two technical parameters [15].

According to the assumption of DGRs available for providing both up and down regulation, the constraints for the regulation shares of these resources can be formulated as follows:

$$-\Delta \mathrm{GRID}_{\mathrm{bid}} \le \Delta \mathrm{P}_{\mathrm{GRID}} \le +\Delta \mathrm{GRID}_{\mathrm{bid}} \tag{1}$$

Specifically, constraint (1) ensures that the regulation share of the DGRs stays within the band contracted by the DSO for the generation outside the SUG.

Note that, beyond the specific reference framework used in this work, should the SUG's DGRs be involved in the AGC schedule, the modeling of their respective regulation shares could follow the same scheme.

3.2. Modeling of EVs regulation shares and related constraints

Since EVs participation in DN's control issues is still at a conceptual stage, neither recognized rules nor references to determine the contracted bands of EVs exist. Therefore, different criteria could be proposed and followed, based on the specific aim and framework of study. In an ancillary market framework that also considers the DRP between EVA and EVCs, it is reasonable to assume for the EVs that the contracted bands of regulation capacity depend on both technical and economic factors. Technically speaking, for a given AGC signal, only EVs reaching an adequate SOC can provide regulation, but this regulation is constrained as EVs can be charged and discharged only within an admissible range, which must be considered by the EVA in offering the amount of AGC provision by EVs in the ancillary service market. In addition to this technical constraint, the contracted band is influenced by the type of agreement established between EVA and EVCs [18].

In case of unidirectional V2G, for which EVs are just seen as a "load" from the grid, the contracted band has to keep the possible variation of the expected schedule of EV charging from exceeding a desirable degree, which is related to the behavior of the customers. In the assumed DRP, the EVA has set up a strategy of AGC provision from EVs that prioritizes the proposition of the EVCs toward the charging and swapping offers, and this has allowed predetermining the contracted band ΔEVS(bid). Based on this criterion, for which the EVA makes available as much EVs regulation as possible, while respecting customers' convenience at every time, the regulation constraint for the vehicles of the EVS shown in Fig. 1 is formulated as:

$$0 \le \Delta L_{\mathrm{EVS}} \le \Delta \mathrm{EVS}_{\mathrm{bid}} \tag{2}$$

Constraint (2) ensures that, for any given AGC signal, the regulation shares of the controllable EVs stay within the "regulation down" limits contracted with the customers based on the DRP.

3.3. Modeling of CLRs regulation shares and related constraints

The thermal CLRs outside the SUG can be grouped into a thermal load aggregation featuring some inherent physical properties. The most important properties are: (1) the aggregated thermal capacity, (2) the amount of thermal load units, and (3) the aggregated rated power.

In the ancillary service market, considering the same approach used for the generation, it is reasonable to consider that both DSO and SUG operators establish contracted bands of regulation share for the respectively managed CLRs, which are mainly constrained by the aggregated rated powers of these resources [14]. Accordingly, the constraints for the CLRs' regulation share can be formulated as follows:

$$0 \le \Delta L_{\mathrm{CLR1}} \le \Delta \mathrm{CLR1}_{\mathrm{bid}} \tag{3}$$

$$0 \le \Delta L_{\mathrm{CLR2}} \le \Delta \mathrm{CLR2}_{\mathrm{bid}} \tag{4}$$

Constraint (3) ensures that the regulation share of the CLRs managed by the SUG operator stays within the contracted load control band. Similarly, constraint (4) limits the regulation share of the CLRs managed by the DSO and located outside the SUG.

To the best of our knowledge, no generalized standards or rules exist to assign load control band sizes, but different criteria can be proposed or recalled from the literature. A possibility is to use historical data on control signals over all the weeks of a year [14].

3.4. SUG-AGC management model

With a focus on assessing the coordination of EVs contribution to AGC at both local (SUG) and global (DN) levels, the developed optimization tool materializes into a DC OPF model, the objective of which is determining the optimal management of the AGC shares of the resources inside and outside the SUG, in such a manner that the DSO minimizes the costs of the AGC service while achieving system stabilization after an imbalance. Given its particular features, the proposed optimization model is referred to as the "SUG-AGC MM" (SUG-AGC management model).

Explicitly referring to the system components of Fig. 1, the SUG-AGC MM can be formulated as follows:

$\mathrm{Min}(\mathrm{Cost}_{\mathrm{AGC}})$

subject to:

constraints (1)–(4)

$$P_{\mathrm{PV}} + P_{\mathrm{BM}} + P_{\mathrm{GRID}} = L_{\mathrm{CLR1}} + L_{\mathrm{EVS}} + L_{\mathrm{CLR2}} + L_{\mathrm{cr}} \tag{5}$$

$$L_{\mathrm{CLR1}} = L^{\mathrm{sch}}_{\mathrm{CLR1}} - \Delta L_{\mathrm{CLR1}} \tag{6}$$

$$L_{\mathrm{CLR2}} = L^{\mathrm{sch}}_{\mathrm{CLR2}} - \Delta L_{\mathrm{CLR2}} \tag{7}$$

$$L_{\mathrm{EVS}} = L^{\mathrm{sch}}_{\mathrm{EVS}} - \Delta L_{\mathrm{EVS}} \tag{8}$$

$$P_{\mathrm{GRID}} = P^{\mathrm{sch}}_{\mathrm{GRID}} + \Delta P_{\mathrm{GRID}} \tag{9}$$

$$\Delta L_{\mathrm{EVS}} + \Delta L_{\mathrm{CLR1}} + \Delta L_{\mathrm{CLR1}} + \Delta P_{\mathrm{GRID}} = \Delta P^{*} \tag{10}$$

with

$$\begin{aligned}&\mathrm{Cost}_{\mathrm{AGC}}(\Delta L_{\mathrm{EVS}}, \Delta L_{\mathrm{CLR1}}, \Delta L_{\mathrm{GRID}}, \Delta L_{\mathrm{CLR2}})\\ &\quad = [c_{\mathrm{EVS}} \cdot \Delta L_{\mathrm{EVS}} + c_{\mathrm{CLR}} \cdot \Delta L_{\mathrm{CLR1}}]\\ &\quad + [c_{\mathrm{GRID}} \cdot \Delta P_{\mathrm{GRID}} + c_{\mathrm{CLR}} \cdot \Delta L_{\mathrm{CLR2}}]\end{aligned} \tag{11}$$

The objective function (11) to be minimized defines the total costs $\mathrm{Cost}_{\mathrm{AGC}}(\Delta L_{\mathrm{EVS}}, \Delta L_{\mathrm{CLR1}}, \Delta P_{\mathrm{GRID}}, \Delta L_{\mathrm{CLR2}})$ of the AGC service for the DSO. On the right side, the first term represents the cost that the DSO has to incur due to the AGC provision from the SUG, whereas the second term represents the cost the DSO has to incur due to the AGC provision from the external resources. Constraints (1)–(4) allow modeling the regulation shares of the individual AGC resources, as described in Sections 3.1–3.3. Constraint (5) ensures the system-level power balance. Eqs. (6)–(9) provide the optimal values (post-AGC) of: CLRs inside the SUG (Eq. (6)); external CLRs (Eq. (7)); EV charging (Eq. (8)); power production of external sources (Eq. (9)). Finally, constraint (10) ensures that the sum of the individual regulation shares satisfy the AGC request (ΔP^{*}).

The above formulation only considers the limits pertaining to the given problem and purpose of the study, i.e., AGC service allocation. Consequently, power flow, thermal and voltage limits are not represented.

The SUG-AGC MM is deterministic, as it considers predetermined, scheduled conditions, in full alignment with the purpose of the specific AGC management study targeted in this paper. In particular, since the model is specifically set for assessing – in a market framework – the potential of AGC provision from EVs coordinated with other available control resources, the latter can be assumed with similar reference data, with respect to which the sensitivity of the EV energetic potential can be focused.

It is important to note that, in the problem under study, the controllable resources are modeled assuming negligible influence or delay of their response to an AGC request from the DSO. The assumption is reasonable considering the presence – within the system, in particular the SUG – of adequate technologies and proper control procedures for smart systems, ensuring the real time operation of the AGC functions with no uncertainty in the control efficiency. In the real practice, there could be problems in forecasting the resources' availability, and in managing the uncertainty associated to the dynamics of their AGC service (especially that provided by the EVs, which is affected by the EVCs' driving conditions and associated EV battery charging needs). Dealing with these problems methodologically would require the use of: (a) statistical and predictive models to consider the probability of the occurrence of imbalances; (b) predictive techniques to consider the dynamic evolution of the system during the rebalancing process; (c) careful monitoring of the RESs on statistical and predictive bases. There is a large variety of methods to be properly selected in order to match the peculiarity of the concerned case study according to modeling and data identification issues. In this regard, machine learning methods can have a remarkable role should in the procedures for real time data acquisition [34]. With particular respect to the methodological approach proposed in this work, within the management procedures of real time frequency regulation and power flow balance supervision, the proposed model could be enhanced in operative terms by additional predictive logics for the consideration of alternative energy service real time strategy scenarios.

4. Case study

Numerical results of implementing the proposed AGC management approach to an active DN are presented and discussed in this section. In case 1, the SUG-AGC MM is applied to demonstrate its effectiveness and robustness in a base case which reflects the dataset and assumptions described in Section 4.2. Then, based on the outcomes of this first assessment, a parametric analysis is conducted in case 2, in order to evidence the sensitivity of the results to the EV DRP.

4.1. System configuration

The considered configuration of SUG is shown in Fig. 1. This SUG, representing a distributed commercial area, is part of a 20 kV 4-feeder DN connected to a 132 kV main grid and consists of: an EVS at feeder 1; an MG including a BM plant, a PV plant, and non-controllable (critical) loads at feeder 2; an aggregation of customers with CLRs at feeder 3. All these components are considered part of the same jurisdiction. The fourth feeder, as mentioned in Section 2.3, represents the pool of external energy consumers managed by the DSO and enrolled in the AGC service to support the SUG.

Within the SUG, the EVS has spaces and equipment to host and recharge a certain number of EVs at every hour, also supporting the SUG and/or the main grid in other energy services, such as AGC. This EVS is also equipped for swapping battery service. Critical and controllable loads vary during the day according to residential or commercial demand profiles, whereas generation varies according to the typical production profiles of the considered sources, as managed by the SUG operator or the DSO.

As anticipated in Section 2.3, the distributed resources participating in the AGC program for the SUG are EVs and CLRs. For the DSO's part, the pool of distributed resources participating in the AGC program includes aggregated CLRs and DGRs.

Table 1
Generation and load data.

t	P_{GRID}^{sch} [MW]	P_{PV} [MW]	P_{BM} [MW]	L_{CLR1}^{sch} [MW]	L_{CLR2}^{sch} [MW]	L_{EVS}^{sch} [MW]	L_{cr} [MW]
1	2.331	0	1.5	0.826	0.918	1.372	0.383
2	2.261	0	1.486	0.786	0.873	1.372	0.364
3	2.191	0	1.472	0.761	0.846	1.372	0.352
4	2.169	0	1.469	0.753	0.837	1.372	0.348
5	2.192	0	1.471	0.745	0.828	1.868	0.345
6	2.208	0.5	1.476	0.753	0.837	1.868	0.349
7	2.200	0.8	1.501	0.770	0.855	4.060	0.356
8	2.313	0.8	1.555	1.013	1.125	3.916	0.469
9	2.521	1	1.604	1.332	1.480	3.916	0.617
10	2.557	1.5	1.633	1.369	1.521	3.676	0.634
11	2.555	2	1.645	1.458	1.620	3.676	0.675
12	2.572	2.2	1.646	1.311	1.456	3.676	0.607
13	2.572	2.2	1.632	1.118	1.242	2.693	0.517
14	2.578	2.2	1.624	1.361	1.512	2.693	0.630
15	2.641	2	1.633	1.199	1.332	3.180	0.555
16	2.709	1.8	1.630	1.158	1.287	3.676	0.536
17	2.757	1.5	1.623	1.215	1.350	3.676	0.562
18	2.548	1.5	1.610	1.199	1.332	3.916	0.555
19	2.695	0	1.592	1.030	1.143	3.189	0.476
20	2.660	0	1.581	1.037	1.152	2.693	0.480
21	2.766	0	1.574	1.037	1.152	1.724	0.480
22	2.708	0	1.576	0.988	1.098	1.724	0.457
23	2.630	0	1.547	0.907	1.008	1.868	0.420
24	2.528	0	1.526	0.867	0.963	1.868	0.401

4.2. Data and assumptions

The database is modeled in accordance to the typical power levels (MWs) of commercial areas. Numerical values of assumed generation and load are provided in Table 1 [25,38,40,41], whereas the assumed unitary AGC costs are shown in Fig. 2 [42,43].

4.2.1. Main grid

The DSO can sell energy services depending on demand and trading. Aggregated generation from distributed thermal resources is assumed, whereas the CLRs (CLR2) are characterized with typical aggregated profiles for flexible thermal loads [41].

4.2.2. Microgrid

PV and BM power plants are characterized with typical aggregated hourly production profiles derived on a statistical basis. Although a certain level of uncertainty is associated to such aggregated profiles, since this work does not aim either to address the problem of power forecasting or to propose modeling improvements of the generation, the uncertainty is neglected in the case study without loss of generality. In this respect, the aggregated profiles used for these DGRs are obtained by re-elaboration of data from a generalized scheme already adopted in [25]. It is important to highlight that the availability of power generation from these resources in the specific case study serves for ensuring the SUG autonomous supply at all times.

As for the load, an aggregated 24-h profile is considered for critical loads, such as lighting, electronic devices, security systems.

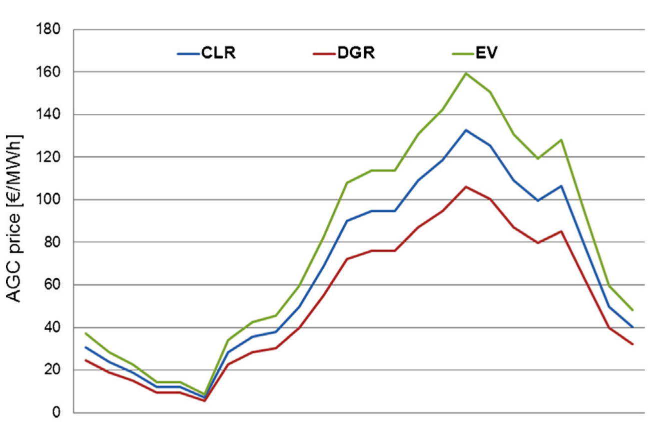


Fig. 2. Unitary AGC pricing.

4.2.3. Controllable loads managed by the SUG operator

The considered CLRs (CLR1) are represented by an aggregation of thermal loads for commercial buildings such as heating and cooling systems.

4.2.4. Electric vehicle charging/swapping station

The EVS is configured as an agglomeration of several distributed parking sites within a large area, with a total number of 1700 parking spaces. The station is equipped with two charging platforms – 400 V/32 A–24 kW-3 phase for normal (2 h) charging, and 400 V/63 A–43 kW-3 phase for fast (30 min) charging. Furthermore, a sufficient number of batteries are available for swapping service in order to supply the entire fleet of hosted EVs, if needed. EV charging profiles are modeled considering on average 60 EVs per hour, equally sharing normal and fast charging, based on a pre-established DRP between EVA and EVCs.

4.2.5. Costs and contracted bands

The values of unitary AGC costs are assumed based on a dynamic pricing structure, referring to an indicative typical average day. Costs for main grid's generation correspond to 2013s levelized energy prices, whereas costs associated with AGC from CLRs and EVs are considered slightly higher, discretionally related to the resources' size and features [42,43].

As for the contracted bands, they are hierarchically assigned according to the "load-based" AGC implementation criteria described in Sections 2.3 and 3.1–3.3. Specifically, the contracted bands are assigned, with respect to the expected power production/demand programs, equal to: 0.25 for all generating units; 0.30 for all CLRs; 0.50 for EVs. The higher value of the EV contracted band complies with the structural and organizational architecture of the EVS, which is provided with swapping facilities that can guarantee

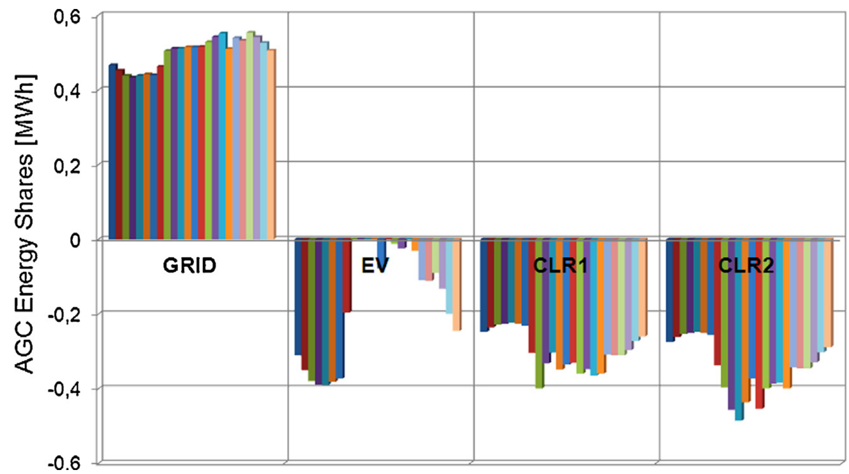


Fig. 3. Results – resources' share of AGC in the 24 scenarios for case 1.

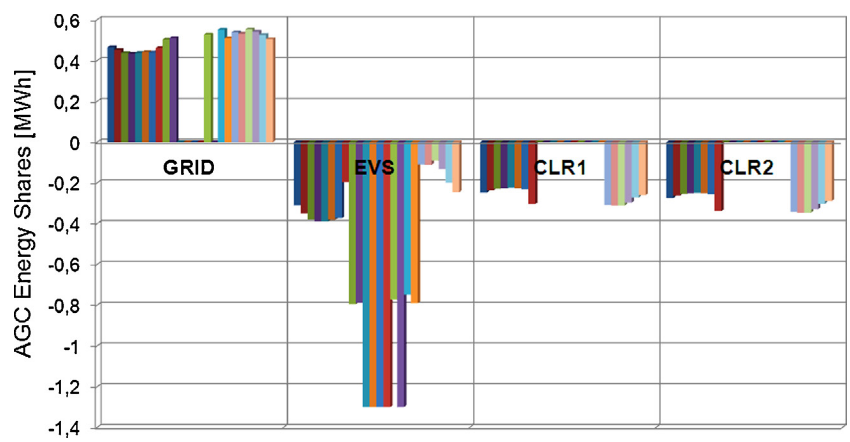


Fig. 4. Results – resources' share of AGC in the 24 scenarios for case 2.

to EVs the availability of batteries to switch to in case the charging cannot be accomplished.

4.3. Case 1: base case

Considering an AGC signal of 1.3 MW, the SUG-AGC MM is used to assess the possible AGC response of the SUG and external resources in 24 different scenarios, each corresponding to the imbalance occurring at a different fraction (order of seconds) of hour, within the referred day. The problem is then solved 24 times using the CPLEX solver [44], and in each scenario the solution is achieved in less than 7 s.

The results obtained from the simulations are shown in Fig. 3, where the depicted plots represent the adjustment of generation and load resources due to AGC requirements. Note in particular that the higher pricing of AGC provision from controllable EVs substantially affects their contribution. In fact, the EVs contribution is significant if the AGC signal occurs in a fraction of off-peak hours, whereas it is zero(despite the greater regulation availability, with $\Delta\text{EVS(bid)} = 0.50 \cdot L_{\text{EVS}}^{\text{sch}}$) if the AGC signal occurs during the daytime. Such an outcome suggests that it could be more profitable and reliable for the SUG operator to further invest in AGC provision from the EVS, so that this resource becomes more competitive than the CLRs in supporting the grid for the AGC service. This would be particularly convenient also from the technical point of view, as EVs represent a more flexible resource compared to thermal loads. Such a possibility is investigated next, through a parametric analysis.

4.4. Case 2: parametric analysis

Based on the outcomes of the base case, and in order to investigate the possibility of making the EVS more competitive in the AGC provision, the same case study is addressed reducing the pricing of the AGC service from EVs during the day, with the aim of analyzing the sensitivity of the outcomes to the costs of AGC from EVs. In particular, during the day these costs are reduced by 15%. Note, however, that this reduction does not alter the general structure of the EV pricing, which follows the trend shown in Fig. 2.

The results obtained from the analyses are provided in Fig. 4, where the plots represent the new adjustments of generation and load due to AGC requirements. It can be observed that the price reduction yields a substantial EVS contribution to the AGC service in every scenario, and especially if the imbalance occurs in daytime. On the other hand, although being cheaper, the CLRs dispatch less regulation. Figs. 5 and 6 show the final energy profiles of generation and load in the parametric analysis, for comparison with the base case results.

Fig. 7 depicts the trend of the optimal costs over the scenarios, before (case 1) and after reducing the daytime EV AGC price (case 2). The results clearly show that in case 2, the daytime AGC costs are significantly smaller than those resulting in the base case. This outcome, which turns out to be particularly convenient for the DSO, is associated to a greater profitability and availability of the AGC service for the SUG, and –at a global level – to better operating conditions of the system as a whole.

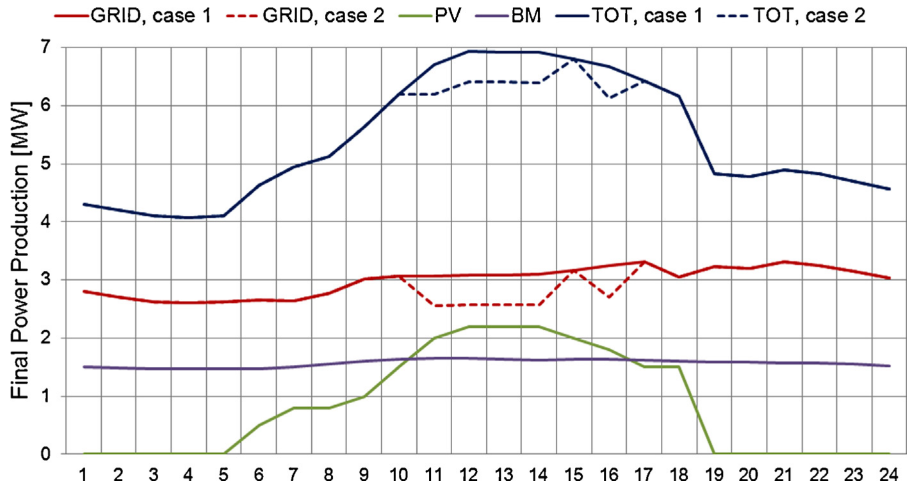


Fig. 5. Results – comparison of final power production.

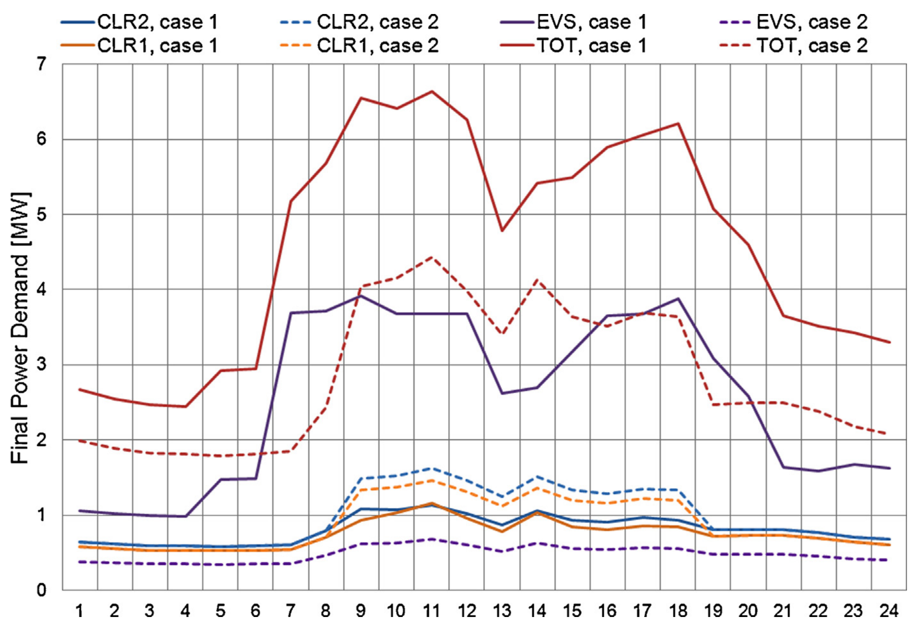
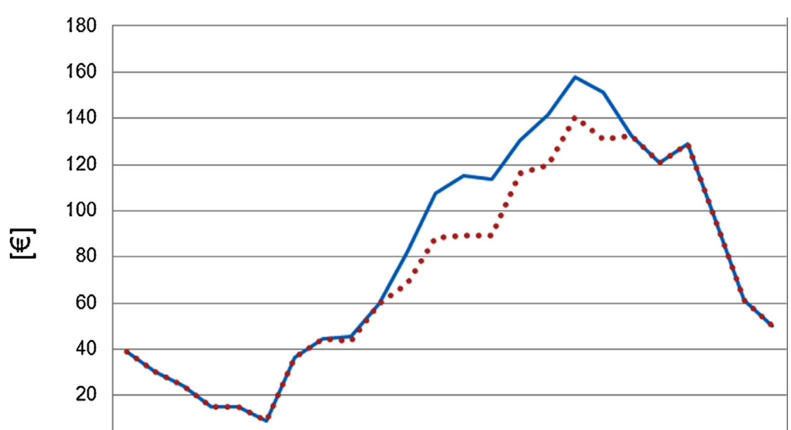


Fig. 6. Results – comparison of final power demand.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
AGC costs - Case 1	39	30	24	15	15	9,2	37	44	45	60	82	108	115	113	130	142	158	151	132	121	129	95	61	50
AGC costs - Case 2	39	30	24	15	15	9,2	37	44	44	60	68	88	89	89	116	120	140	131	132	121	129	95	61	50
Costs reduction [€]	0	0	0	0	0	0	0	0	-2	-0	-14	-19	-26	-24	-14	-22	-18	-20	0	0	0	0	0	0

Fig. 7. Results – comparison of AGC costs.

5. Conclusions

In the context of DRPs applied to end-users of the energy service, this paper presents an analysis and systemization of AGC in DNs with high penetration of distributed resources, including EVs. The reference framework is that of a smart energy user grid where the aggregator of the local resources is characterized as a physical entity that represents the actual interface to the DSO in the market trading for the AGC service. From the proposed systemization a methodology is derived for designing the AGC service, where the DSO, the SUG operator and the AGC resources are properly characterized and modeled. An optimization model is also developed to assess the potential of AGC provision from EVs, which is suited for integration in the energy management system of DN operators.

The realistic case study demonstrates the implementation criteria and the effectiveness of the proposed model. The generality and flexibility of this model makes it suitable for implementation into more complex contexts, with greater SUG configurations and more differentiated types of participants. In this respect, though some computational hurdle could be faced in planning the AGC services for complex distribution areas, no difficulties should be expected in case of AGC management and operation.

The applicative results show how the proposed model represents an efficient tool for the operator to get information on how adjusting the planned AGC service strategy in order to enhance the economic value of this service as well as its security and flexibility.

Future work will regard the implementation of proposed approach and model on real-world larger-scale cases, introducing operational aspects related to SG-oriented implementation of organizational models for DNs. Such studies also envision the modeling of uncertainties via statistical/probabilistic techniques, as well as the use of specific techniques for managing the computational bottlenecks that could result from higher models dimension and complexity.

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