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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.

In this complex framework, the AGC function can be related to the control architecture of a multi-area system, properly scaled to

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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]
$\Delta\mathrm{CLR1}_{\mathrm{bid}}$	contracted regulation band for controllable loads inside the smart user grid [MW]
$\Delta\mathrm{CLR2}_{\mathrm{bid}}$	contracted regulation band for controllable loads outside the smart user grid [MW]
$\Delta\mathrm{EVS}_{\mathrm{bid}}$	contracted regulation band for the electric vehicle station [MW]
$\Delta\mathrm{GRID}_{\mathrm{bid}}$	contracted regulation band for generation outside the smart user grid [MW]
ΔP^{*}	requested amount of regulation [MW]
$L_{\mathrm{CLR1}}^{\mathrm{sch}}$	scheduled power demand from controllable loads inside the smart user grid [MW]
$L_{\mathrm{CLR2}}^{\mathrm{sch}}$	scheduled power demand from controllable loads outside the smart user grid [MW]
L_{cr}	critical (uncontrollable) loads [MW]
$L_{\mathrm{EVS}}^{\mathrm{sch}}$	scheduled electric vehicle charging [MW]
P_{BM}	scheduled power production from the biomass power plant [MW]
$L_{\mathrm{GRID}}^{\mathrm{sch}}$	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]

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.