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A composable method for real-time control of active distribution networks with explicit power setpoints. Part II: Implementation and validation

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ABSTRACT

In this second part, we evaluate the performances of our control framework by applying it to a case study that contains a minimum set of elements allowing to show its applicability and potentials. We show how the computation of the *PQt* profiles, belief functions, and virtual costs can be synthesized for generic resources (i.e., dispatchable and stochastic generation systems, storage units, loads). The metrics of interest are: quality-of-service of the network represented by voltages magnitudes and lines current magnitudes in comparison with their operational boundaries; state-of-charge of electric and thermal storage devices; proportion of curtailed renewables; and propensity of microgrid collapse in the case of renewables overproduction. We compare our method to two classic ones relying on droop control: the first one with only primary control on both frequency and voltage and the second one with an additional secondary frequency control operated by the slack device. We find that our method is able to indirectly control the reserve of the storage systems connected to the microgrid, thus maximizing the autonomy in the islanded operation and, at the same time, reducing renewables curtailment. Moreover, the proposed control framework keeps the system in feasible operation conditions, better explores the various degrees of freedom of the whole system and connected devices, and prevents its collapse in case of extreme operation of stochastic resources. All of these properties are obtained with a simple and generic control framework that supports aggregation and composability.

1. Introduction

In this second part of the paper, we discuss the implementation aspects and evaluate the performance of the control framework, which we henceforth refer to as *Commelec* (which stands for the joint-operation of Communication and Electricity systems). This assessment is done by using a suitably developed simulation environment. We consider a case study that makes reference to the low voltage microgrid benchmark defined by the CIGRÉ Task Force C6.04.02 [1], connected to a generic medium voltage feeder that contains the minimum number of elements that allow us to show the applicability and potentials of the proposed control framework. In particular, while the formal description of the framework for controlling the grid using power setpoints is presented in Part I, here we show how to specifically implement the request/advertise messages between agents, how we can derive the *PQt* profiles, belief and cost functions of the resources, and how the grid agent computes the resources setpoints and aggregates their internal elements.

The considered case study exhibits the following characteristics: (i) the system is in islanded condition, (ii) the slack bus is provided by the larger storage system (ESS), (iii) storage is distributed in both low and medium voltage, (vi) thermal loads (water boilers) are used as virtual storage, and that (v) the randomness comes from the loads absorption patterns and solar irradiation. For the latter, we used a high time-resolution profile (sampled each 50 ms) obtained from the measurements on solar panels in the authors' laboratory.

A challenge in such a system is that most of the inertia comes from storage and thermal loads rather than rotating machines; it

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Table 1
Electrical parameters of the lines composing the MV and LV lines

Type	MV1	LV1	LV2	LV3	LV4	LV5	LV6
Resistance [Ω/km]	3.938	0.284	0.497	3.690	1.380	0.871	0.822
Reactance [Ω/km]	1.969	0.083	0.086	0.094	0.082	0.081	0.077
Susceptance [μs/km]	2.780	0	0	0	0	0	0
Ampacity [A]	25	170	120	31	60	73	140

is precisely the goal of our real-time control method, to overcome this difficulty in the presence of extremely volatile resources (e.g., PVs).

In order to assess its performance, we used the following metrics: the distances of node voltages and line currents to their operational limits, the state-of-charge of electric and thermal storage devices, the proportion of curtailed renewables, and the robustness against system collapse in case of overproduction from renewables.

We compare our method to two classic ones that rely on droop control: the first only with *primary control* on both frequency and voltage and the second with an additional *secondary frequency control* at the slack device (see, e.g., [2]). We find that our method is able to indirectly control the reserve of the storage systems, thus maximizing the autonomy of the islanded operation. It reduces the curtailment of renewables, compared to the droop based methods, and it is able to implicitly identify local power compensation. Further, it keeps the system in feasible operation conditions and better explores the various degrees of freedom of both network and energy resources. Most importantly, it prevents system collapse in case of overproduction of renewables, in contrast to the droop control strategies.

Further, we show that the properties of Commelec are fundamental in the case of *inertia-less grids* associated with the penetration of energy conversion systems that do not have any rotating mass (e.g., PV plants) or other conversion systems interfaced to the grid with power converters. Indeed, in the cases where these energy conversion systems represent the majority of the electricity supplying means, the control strategies have to be rethought (e.g., [3]). In this respect, as the proposed method does not rely on any shared signals (i.e., frequency), it can inherently account for the control of inertia-less grids.

All of these characteristics are obtained in real-time with a simple and generic framework; the specific properties of electric and thermal resources are known only by their local agents, whereas grid agents are generic and independent of the specific resources they control. As introduced in Part I, a key property is composability: an entire grid can be viewed as a single generic resource, the details of which need not be known by the higher-level grid agent. In this part of the paper, we also evaluate the effect of the simplifications resulting from the aggregation process, and we find that it is essentially negligible.

The structure of this second part is the following. In Section 2, we present the case to be studied, the simulation environment, the related control algorithms, the profiles' data, and the performance metrics. In Section 3, we define the different resource agents and how they manage their exchanged messages. In Section 4, we present the simulation results. A discussion section and a conclusion follow.

2. Case study

In this section, we present a case study where the proposed control framework is implemented. To show the applicability of the proposed framework, we have selected a closed system that contains all types of agents described in Part I. In order to evaluate its performance, we implemented a generic event-driven simulation environment in Matlab®.

2.1. System details

We consider a 0.4 kV LV network that includes (i) distributed generation composed of photovoltaic plants (PV*i*) and a hydraulic microturbine (μH), (ii) a storage system represented by a battery (ESS1), (iii) uncontrollable loads (UL*i*) and (iv) controllable loads (WB*i*) modelled as water boilers all capable of deploying explicit control setpoints. The topology and parameters of this LV grid are taken from [1]. As typically used in a microgrid (MG) setup, we assume that all the generation/storage units connected to the LV MG are interfaced with the grid through power electronic devices [4].

To show the interaction between different grids, the MG is connected to a 20 kV MV distribution system that interconnects (i) a large battery storage system (ESS), (ii) a combined heat and power generator interfaced with the MV grid by means of a synchronous generator (SG) and (iii) an industrial uncontrollable load (UL).

The corresponding electrical diagram for the case study is presented in Fig. 1(a).

To illustrate the mapping between physical subsystems and agents, we consider the hierarchical agents setting shown in Fig. 1(b) where the microgrid agent (LVGA) is in charge of the resources in the LV network, whereas the medium voltage grid agent (MVGA) is in charge of the ones in the MV network and the LVGA. In the terminology of Part I of the paper, the LVGA is an internal GA, while the MVGA is a root GA.

The line parameters used for the network are presented in Table 1.

We use the base system and the voltage bounds presented in Table 2(a), while the parameters of the MV/LV transformer used in our case study are shown in Table 2(b). We use a conventional transformer model as in [5].

2.2. Control methods

We perform a comparison between the following control methods.

(i) The Commelec architecture of Fig. 2(a). We show in the following sections how we implement our framework in this case. In addition, in order to validate the composability property we performed a simulation of the "flat" setting of agents shown in Fig. 2(b).

(ii) The droop control method, with only a *primary control* at each device capable of modifying power setpoints (i.e., all with the exception of ULs). In the slack resource, the output frequency is calculated using the conventional droop control strategy, assuming a null inertia (as it is the case of ESS). This is the

Table 2
System and transformer parameters

MV base	LV base	Base power	V bounds	S_r	V_k	r_k
20 kV	0.4 kV	1 MVA	0.9–1.1 pu	400 kVA	4%	1%