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A composable method for real-time control of active distribution networks with explicit power setpoints. Part I: Framework

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ABSTRACT

The conventional approach for the control of distribution networks, in the presence of active generation and/or controllable loads and storage, involves a combination of both frequency and voltage regulation at different time scales. With the increased penetration of stochastic resources, distributed generation and demand response, this approach shows severe limitations in both the optimal and feasible operation of these networks, as well as in the aggregation of the network resources for upper-layer power systems. An alternative approach is to directly control the targeted grid by defining explicit and real-time setpoints for active/reactive power absorptions/injections defined by a solution of a specific optimization problem; but this quickly becomes intractable when systems get large or diverse. In this paper, we address this problem and propose a method for the explicit control of the grid status, based on a common abstract model characterized by the main property of being *composable*. That is to say, subsystems can be aggregated into virtual devices that hide their internal complexity. Thus the proposed method can easily cope with systems of any size or complexity. The framework is presented in this Part I, whilst in Part II we illustrate its application to a CIGRÉ low voltage benchmark microgrid. In particular, we provide implementation examples with respect to typical devices connected to distribution networks and evaluate of the performance and benefits of the proposed control framework.

1. Introduction

The modern and future electrical infrastructure has to satisfy two main conflicting requirements: (i) provide reliable and secure supply to an increasing number of customers, and (ii) take into account the rational use of energy and the protection of the environment. This last requirement drives major changes in power systems, where the most evident result is an almost quadratic increase of the connection of renewable energy sources [1]. It is generally admitted that these sources need to be massive and distributed, in order to provide a significant part of the consumed electrical energy (e.g. [2]). However, the increased penetration of renewable energy-resources in medium and low-voltage networks is such that, in several countries, operational constraints have already been attained. This calls for a radical re-engineering of the entire electrical infrastructure. Conventional approaches are unable to scale to such an increase in complexity.

As known, the main controls of an interconnected power system are essentially concerned with (i) maintaining the power balance and (ii) maintaining the voltage levels close to the rated values, both performed at various time scales. These two basic controls are the building blocks used by other more sophisticated regulators responsible for hierarchically superior actions (e.g., angular and voltage stability assessment, congestions in main transmission corridors, etc.). As well known, the control of (i) is based on the link between the power imbalance and the network frequency (that constitutes the control variable) and it is usually deployed in three main time-frame controls that belongs to primary, secondary and tertiary frequency controls. There are essentially two main drawbacks to this control philosophy: First, there is a monotonous increasing dependency between the primary/secondary frequency-control reserves and the errors associated with the forecasts of increasing renewable production (especially when distributed in small dispersed units). Second, the definition of the primary/secondary frequency-control reserves is centralized; hence, distributed control mechanisms, to be deployed

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Nomenclature

$u = (P_1, Q_1, P_2, Q_2, \ldots, P_n, Q_n)$ control (target) setpoints
$x = (P'_1, Q'_1, P'_2, Q'_2, \ldots, P'_n, Q'_n)$ implemented (actual) setpoints
$\hat{x}$ current (estimated) setpoints
$\mathcal{A}_i$ *PQt* profile of follower i (set of possible target values for (P_i, Q_i))
$C_i(P_i, Q_i)$ virtual cost of follower i
$BF_i(P_i, Q_i)$ belief function of follower i (set of possible (P'_i, Q'_i) when (P_i, Q_i) is requested)
$\mathcal{A} \triangleq \mathcal{A}_1 \times \mathcal{A}_2 \times \cdots, \times \mathcal{A}_n$ joint *PQt* profile (set of possible values for u)
$\widetilde{\mathcal{A}}_0$ exact aggregated *PQt* profile (set of possible values for (P_0, Q_0) power at PCC)
$\widetilde{\mathcal{A}}_0^*$ approximate aggregated *PQt* profile
$BF(u) = BF_1(P_1, Q_1) \times \cdots \times BF_n(P_n, Q_n)$ joint belief function (set of possible x when u is targeted)
$\widetilde{BF}_0(P_0, Q_0)$ exact aggregated belief function (set of possible (P'_0, Q'_0) when (P_0, Q_0) is targeted)
$\widetilde{BF}_0^*(P_0, Q_0)$ approximate aggregated belief function
$\mathcal{U}$ set of admissible setpoints u
J penalty for electrical state feasibility
J_0 penalty for power flow deviation at the PCC

in distribution networks with active resources, cannot be easily implemented. These mechanisms will require increasing reserve scheduling in order to keep acceptable margins and to maintain the grid vulnerability at acceptable levels (e.g. [3]). An example of such a principle is described in [4].

As for the control of (ii), which requires maintaining the voltage deviations within predetermined limits (e.g., [5]), it is implemented at various levels and with different strategies that mainly control reactive-power injections. However, network voltages fluctuate as a function of various quantities such as the local and overall network load, generation schedule, power system topology changes and contingencies. The typical approach for voltage-control divides (still into primary, secondary and tertiary controls) the control actions as a function of their dynamics and their area of influence. The major advantage of such an approach is that it enables a decoupling of the controllers as a function of their area of influence. However, it is not easily down-scalable to distribution networks because, similarly to the frequency control, it was conceived for interconnected power systems, where the control resources are limited in number, large in size, and centrally controlled.

In general, if we base the equilibrium of the grid in terms of purely power injections, there is always the need to assess adequate reserves in order to guarantee the power balance (both active and reactive) of the system. In agreement with this approach, the European Network Transmission Systems Operator (ENTSO-E) attempts to extend to distribution the network codes that set up a common framework for network connection agreements between network operators and demand/producers owners [5]. This specific network code requires the distribution networks to provide the same frequency/voltage support provided by other centralized resources (i.e., power plants) directly connected to transmission networks. Such an approach, however, has many drawbacks in systems characterized by dominant non-dispatchable stochastic renewable energy resources where, to balance the power, the non-desirable use of traditional power plants (usually gas-fired power plants e.g. [6] or, when available, hydro power plants) is necessary. In contrast, if in distribution networks it is possible to expose to a *grid controller* the state of each energy resource (i.e., generation, storage, and loads) in a scalable way, then it is possible, in principle, to always find an admissible and stable system-equilibrium point with small or negligible power-balancing support from the external grid. This feature will enable the graceful operation of each local distribution network in both islanded and grid-connected operation modes, thus allowing, for this last one, the possibility of quantifying the amount of the microgrid's ancillary services to the upper power network (i.e., primary and secondary frequency control support, as well as voltage compensation). Directly controlling every resource however is clearly too complex when resources are numerous and diverse. This is the challenge we propose to tackle.

Our goal is therefore to define a *scalable* method for the direct and explicit control of real-time nodal power injections/absorptions. We use software agents, which are responsible for subsystems and resources, and we communicate with other agents in order to define real-time setpoints. To make our method scalable, we use the following features:

(a) *Abstract framework*. It applies to all electrical subsystems and specifies their capabilities, expected behavior, and a simplified view of their internal state. A subsystem advertizes its internal state by using *PQt profiles*, *virtual costs* and *belief functions*, which are expressed using a common device-independent language (Section 4).

The existence of a common abstract framework is an essential step for scalability and composability. It was applied, for example, to the control of very large and heterogeneous communication networks in [7].

(b) *Composition of subsystems*. It is possible to aggregate a set of interconnected elements into a single entity. A local grid with several generation sources, storage facilities and loads can be viewed by the rest of the network as a single resource.

(c) *Separation of concern*. Agents that are responsible for grids (henceforth called "Grid Agents") manipulate only data expressed by means of the abstract framework and do not need to know the specific nature of the resources in their grid; in particular, there is only one grid agent software for all instances of grid agents. In contrast, resource agents (which are responsible for specific resources) are specific, but their function is simpler, as it is limited to (i) mapping the internal state of the resource and expressing it in the proposed abstract framework and (ii) implementing the power setpoints received from the grid agent with which they communicate. In other words, agents that need to know details of diverse systems are simple-minded, whereas agents that need to take intelligent decisions have an abstract, simple view of the grid and of their resources.

In view of the complexity of the proposed approach, the paper has been divided into two parts. In Part I, we give the formal description of the proposed method. In Part II, we present the detailed application with the reference to actual resources connected to active distribution networks and evaluate the performance of the proposed method in a CIGRÉ low voltage benchmark microgrid. The structure of this first part is the following. In Section 2, we discuss the state of the art. In Section 3, we present the definition of agents and their interaction and give a global overview of our method. The abstract framework is described in Section 4 (*PQt* profiles, virtual cost, and belief functions). In Section 5, we present the details of the decision process performed in the grid agent. In Section 6, we discuss the composability property and propose methods for aggregation of subsystems. Finally, we close this part with concluding remarks in Section 7.

2. State of the art

The literature on the real-time control of microgrids in the presence of stochastic generation tackles the problem by using two