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A unified control strategy for active distribution networks via demand response and distributed energy storage systems[☆]

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ABSTRACT

As part of the transition to a future power grid, distribution systems are undergoing profound changes evolving into Active Distribution Networks (ADNs). The presence of dispersed generation, local storage systems and responsive loads in these systems incurs severe impacts on planning and operational procedures. This paper focuses on the compelling problem of optimal operation and control of ADNs, with particular reference to voltage regulation and lines congestion management. We identify the main challenges and opportunities related to ADNs control and we discuss recent advances in this area. Finally, we describe a broadcast-based unified control algorithm designed to provide ancillary services to the grid by a seamless control of heterogeneous energy resources such as distributed storage systems and demand-responsive loads.

1. Introduction

Increased penetration of decentralized generation, distributed energy storage systems and active participation of end users in the lower level of the electrical infrastructure, intelligently managed to provide support to the grid, define the notion of Active Distribution Networks (ADNs) [1,2].

Within the context of ADNs, application of intelligent control techniques is required in order to achieve specific operation objectives (e.g., [3–8]). In this direction, recently the European Network of Transmission System Operators for Electricity (ENTSO-E) [9] suggested that grid ancillary services,[1] typically employed in the HV transmission networks, should be extended to distribution networks.

On the one hand, recent progress in Information and Communication Technologies (ICT), the introduction of new generation of advanced metering devices such as Phasor Measurement Units (PMUs) (e.g., [10,11]) and the development of real-time state estimation algorithms (e.g., [12]) present new opportunities and will, eventually, allow the deployment of control processes in distribution networks. On the other hand, ADNs exhibit specific peculiarities that render the design of such control processes compelling. In particular, distribution networks are characterized by reduced line lengths with a non-negligible resistance over reactance (R/X) ratio, limited power-flows values and higher dynamics. These characteristics need to be properly taken into account in the design of control algorithms for distribution networks. Additionally, the coordination of large numbers of dispersed energy resources in ADNs, in combination with their small size and heterogeneous nature poses significant technical challenges, and motivates the need for unified scalable control mechanisms.

The goal of this paper is twofold. First, the main challenges and opportunities related to ADNs control are discussed, with particular reference to voltage regulation and lines congestion management. Second, the paper summarizes the main principles and operation of the Grid Explicit Congestion Notification Mechanism (GECN) (proposed in [13,14]), which is a unified control algorithm specifically designed for ADNs. This mechanism acts on a fast time-scale and provides ancillary services to the grid by means of low bit-rate broadcast control signals.

The rest of the paper is organized as follows. Section 2 identifies the challenges and opportunities related to ADNs control. Section 3 summarizes the main principles of the GECN control mechanism. In the same section, an application of GECN to elastic loads and energy storage systems for voltage control purposes is presented. Finally, Section 4 concludes the paper with the main observations on the benefits and the applicability of GECN.

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[1] By "grid ancillary services" we refer to frequency support, voltage support, black start and island operation capabilities, system coordination and operational measurement. See, as a general reference, [9] for further details.

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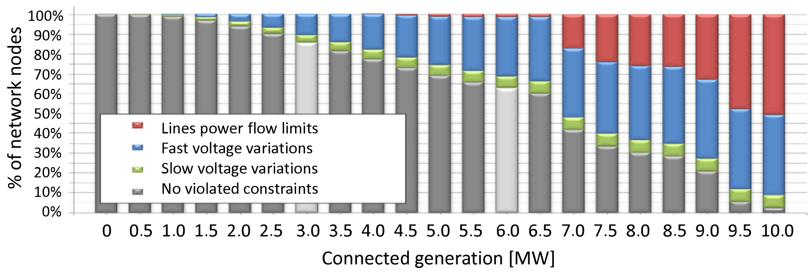

Fig. 1. Number of network nodes exhibiting operational constraints violation as a function of the size of embedded generation.
Source: Adapted from [15].

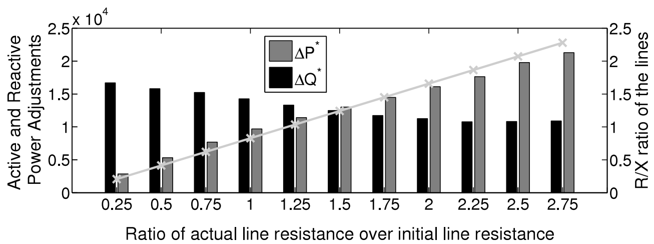

Fig. 2. Optimal active and reactive power adjustments necessary to improve the voltage by 2% as a function of the line parameters.
Source: Adapted from [14].

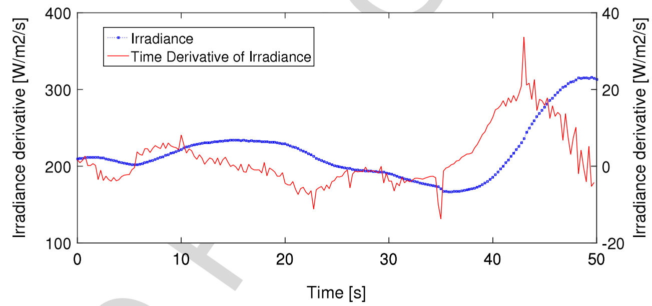

Fig. 3. Example of the highest solar irradiance dynamics measured on March, 24th 2014 at location 46.518397-N, 6.565229-E.
Source: Adapted from [21].

2. ADNs controls: Challenges and opportunities

Several studies of the impact of the embedded generation in distribution systems, essentially composed of non-dispatchable renewable resources, have shown that it leads to frequent violations of operational constraints such as voltage limits and line power flows (e.g., [15,16]) (Fig. 1). As a consequence, it is important to develop optimal control strategies specifically applied to the operation of these networks (e.g., [2,4–7,17]).

One of the most important control functionalities for ADNs is the voltage regulation. This control is a well-known concept in the domain of high voltage (HV) transmission networks where, typically, it is related to reactive power management (e.g., static var compensators) [18]. While this is true in HV transmission networks,[2] such an assumption is no longer valid for distribution networks. Fig. 2 shows the optimal active and reactive power adjustments required to improve the voltage magnitude of a network bus by 2% as a function of the R/X ratio of the network lines. As this ratio increases the active power requirements become, eventually, more important than the reactive power ones. As a consequence, the design of voltage control schemes for ADNs requires the control of both active and reactive power injections, in view of the non-negligible R/X ratio of longitudinal parameters of the medium and low voltage lines (e.g., [19,20]).

Another challenge related to ADNs control is the significant short-term dynamics of the non-dispatchable renewable energy resources. Real measurements of the power production of solar panels found in the literature (e.g., [21]) show that there can be variations in the power profiles of these resources in the order of more than 50% within a few seconds (e.g., Fig. 3). Within this context, the solution of optimal control problems becomes of interest only if it meets the stringent time constraints imposed by the higher dynamics of these networks.

As a potential solution for the design of control algorithms specifically applied to ADNs, several efforts in the literature have proposed to take advantage of the increasing availability of communication technologies, and engage distributed energy resources (e.g., generators, loads, energy storage systems) for providing grid ancillary services. For instance, in [6] voltage control and network losses minimization are provided via the optimal scheduling of distributed generators. Furthermore, the potential of distributed energy storage systems (ESSs) and demand response (DR) has already been investigated for compensating forecast uncertainties and increased volatility in the renewable energy production (e.g., [22,23]). In [24] DR is deployed to mitigate forecast errors due to the integration of renewable resources, whereas in [25] DR is considered in the context of islanded microgrids where it is used as a form of reserve. Furthermore, inspired by traditional frequency droop controls, there has already been an effort to investigate DR schemes for primary and secondary frequency-control. In particular, in [26] frequency-control is provided via the control of electric vehicles, whereas in [27] residential loads are controlled for primary frequency-control purposes and in [28] real-time control of thermostatically controlled loads is deployed to manage frequency and energy imbalances in power systems.

We can envision to adopt such an approach, namely deploying DR and ESSs, also for the case of voltage control and lines congestion management in ADNs. However, most control schemes found in the literature rely on two-way communication between the controllable entity and the distribution network operator (DNO) (e.g., [29,30]), which results in algorithms that cannot scale in the number of network buses and controllable resources. Additionally, completely different architectures are proposed for the control of different energy resources, rendering the problem difficult when heterogeneous energy resources need to be coordinated for the same goal. A possible solution to the aforementioned issues is to keep the system tractable by avoiding individual point-to-point communication from the DNO's controller to every controllable resource and to use broadcast-based control schemes that rely on state estimation for the feedback channel (e.g., [31,32]).

In this direction, in what follows, we describe briefly the principles and operations of the GECN control mechanism, first proposed in [13] and further extended in [14]. This mechanism acts on

[2] In general this holds for networks where the ratio of the longitudinal-line resistance versus reactance is small resulting in the decoupling of the active and reactive power injections on voltage angle differences and magnitudes.

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