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Engineering advance

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.

Contents

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

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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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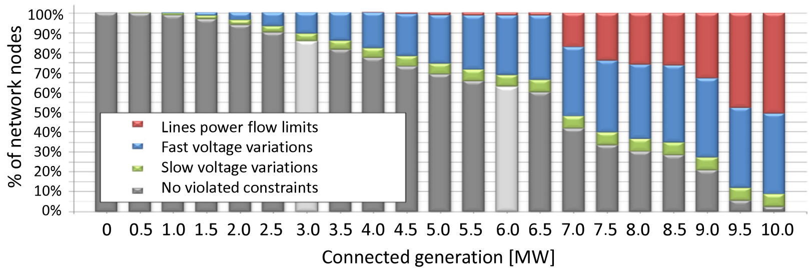


Fig. 1. Number of network nodes exhibiting operational constraints violation as a function of the size of embedded generation.
Source: Adapted from [15].

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.

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]).

[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.

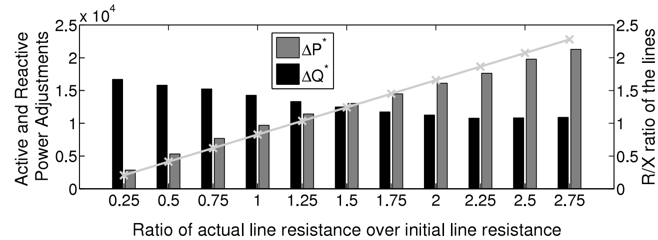


Fig. 2. Optimal active and reactive power adjustments necessary to improve the voltage by 2% as a function of the line parameters.
Source: Adapted from [14].

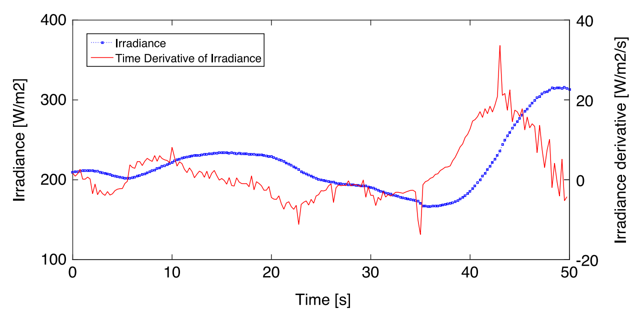


Fig. 3. Example of the highest solar irradiance dynamics measured on March, 24th 2014 at location 46.518397-N, 6.565229-E.
Source: Adapted from [21].

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 a fast time-scale and is designed to provide grid ancillary services by means of low bit-rate broadcast control signals sent to heterogeneous populations of energy resources.

3. Unified broadcast-based ADNs control via demand response and energy storage systems

3.1. Problem statement and hypotheses

We wish to design a scalable control scheme for providing ancillary services to ADNs by managing centralized resources such as transformers' on-load tap changers (OLTC) and, at the same time, nodal power injections of the network buses where a large population of distributed, heterogeneous energy resources is connected. The Grid Explicit Congestion Notification Mechanism [13,14] is conceived for these purposes. GECN is a unified control mechanism inspired by the congestion control mechanism used in the Transmission Control Protocol (TCP) [33] that uses low bit-rate broadcast control signals. The GECN architecture, described in the following section, relies on five main hypotheses:

H1. Knowledge of the network admittance matrix $[\mathbf{Y}]$.

H2. Availability of a monitoring infrastructure and a state estimation process that allows the DNO to observe the network state in each bus i, i.e., voltage phasors $\bar{E}_i(t)$.[3] As known this hypothesis together with H1 allows the computation of the nodal power injections, $P_i(t)$, $Q_i(t)$, as well as the flows of each line k, $\bar{I}_k$.

H3. Solution of an optimization problem to obtain desired power adjustments $(\Delta P_i(t), \Delta Q_i(t))$ in each bus i equipped with controllable resources. The formulation of the optimization problem relies on the linearization of the power flow equations by means of sensitivity coefficients.

H4. One-way communication infrastructure and use of broadcast signals for the control of active and/or reactive nodal power injections.

H5. Development of appropriate smart local controllers tailored to the characteristics of the various controllable resources that receive, interpret the broadcast signals and respond according to each device's capabilities and internal state constraints.

[3] The rated value of the voltage in the network is denoted by E_o.

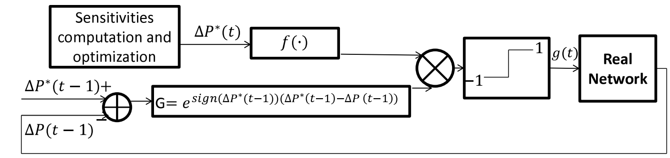


Fig. 4. Control loop for the computation of the GECN signal $\mathbf{g}(t)$ for the control of active power.
Source: Adapted from [13].

3.2. GECN architecture

The architecture of GECN is based on the closed-loop control as shown in Fig. 4.[4] At each time step, the DNO, computes voltage and current sensitivity coefficients for each bus i and line k with respect to absorbed/injected power of a network bus ℓ and transformers' OLTCs positions (n), in order to locally linearize the voltage and current deviations $\Delta|\bar{\mathbf{E}}(t)| = (\Delta|\bar{E}_i(t)|)_i$, $\Delta\bar{\mathbf{I}}(t) = (\Delta\bar{I}_k(t))_k$ (e.g., [19,34]):

$$K_{P,i\ell}(t) := \frac{\partial|\bar{E}_i(t)|}{\partial P_\ell}, \qquad K_{Q,i\ell}(t) := \frac{\partial|\bar{E}_i(t)|}{\partial Q_\ell},$$
$$K_{n,i}(t) := \frac{\partial|\bar{E}_i(t)|}{\partial n}$$
$$H_{P,kl}(t) := \frac{\partial\bar{I}_k(t)}{\partial P_l}, \qquad H_{Q,kl}(t) := \frac{\partial\bar{I}_k(t)}{\partial Q_l}, \qquad H_{n,k}(t) := \frac{\partial\bar{I}_k(t)}{\partial n} \tag{1}$$

$$\Delta|\bar{\mathbf{E}}(t)| \approx \mathbf{K_P}(t)\Delta\mathbf{P}(t) + \mathbf{K_Q}(t)\Delta\mathbf{Q}(t) + \mathbf{K_n}(t)\Delta\mathbf{n}(t).$$
$$\Delta\bar{\mathbf{I}}(t) \approx \mathbf{H_P}(t)\Delta\mathbf{P}(t) + \mathbf{H_Q}(t)\Delta\mathbf{Q}(t) + \mathbf{H_n}(t)\Delta\mathbf{n}(t). \tag{2}$$

The concept of sensitivities is well-established, especially in HV transmission networks (e.g., [35–39]). However, within the context of ADNs, there is a need to increase the computational efficiency of this category of approaches in order to enable its implementation in real-time controllers. To this end, the method in [19] proposes the analytical derivation of node-voltages and line-currents sensitivities as a function of the nodal power injections and transformers OLTC positions by solving a sparse linear system that is proved to admit a unique solution for the case of radial distribution networks.

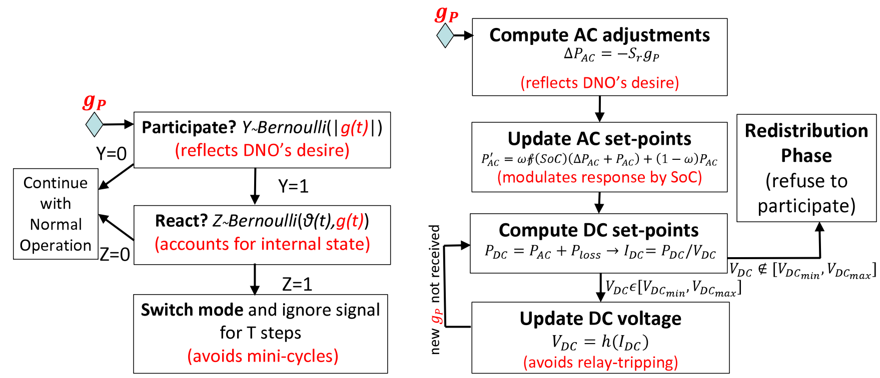
Once the sensitivities are computed, the DNO formulates a constrained optimization problem whose solution is the optimal required nodal power adjustments and OLTC positions $(\Delta\mathbf{P}^*(t), \Delta\mathbf{Q}^*(t), \Delta\mathbf{n}^*(t))$, which lead to the desired operation set-point. For instance when the DNO wishes to match as closely as possible a day-ahead scheduled consumption profile $(P_i^f(t+1), Q_i^f(t+1))$, while maintaining the system within acceptable operating bounds in terms of voltage magnitude $(E_o - \delta \le |\bar{E}_i(t+1)| \le E_o + \delta)$ and lines ampacities[5] $(|\bar{I}_k(t+1)| \le \epsilon)$ the optimization problem is[6]:

$$\min_{\Delta\mathbf{P},\Delta\mathbf{Q},\Delta\mathbf{n}} \sum_i \mu_i \left\{ \left(\Delta P_i(t) - \Delta P_i^f(t)\right)^2 + \left(\Delta Q_i(t) - \Delta Q_i^f(t)\right)^2 \right\}$$
$$+ \sum_i \lambda_i \left[\left(|\bar{E}_i(t)| + \Delta|\bar{E}_i(t)| - E_o\right)^2 - \delta^2 \right]^+$$

[4] Fig. 4 shows the closed-loop control for the active power broadcast signal g_P. A similar feedback control is adopted for the reactive power.

[5] Note that lines congestion management was not included in the initial formulation of [13,14]. However, it can be taken into account in a straightforward manner using the approach in [40].

[6] We consider that, in absence of control, the mismatch in bus i is $\Delta P_i^f(t) := P_i^f(t+1) - P(t)$ and $\Delta Q_i^f(t) := Q_i^f(t+1) - Q(t)$.



(a) TCL local controller design. (b) ESS local controller design.

Fig. 5. Design of local controllers for TCLs and ESSs (detailed functionalities can be found in [13,14]).

$$+\sum_k \rho_k[(|\bar{I}_k + \Delta\bar{I}_k(t)|)^2 - \epsilon^2]^+$$

$$+\psi_1\left(\sum_i \hat{g}_i\right)\psi_2\left(\sum_t |\Delta n(t)|\right)\boldsymbol{\Delta}\mathbf{n}^2$$

$$\text{s.t.:}\quad \gamma_i \leq \cos\varphi_i \leq 1 \quad \text{and} \quad n_{\min} \leq n(t) \leq n_{\max} \tag{3}$$

$$\text{where}\quad \hat{g}_i(t) = \sum_{s=0}^{W-1} k_s g_i(t-s) \quad \text{and}$$

$$n(t) = n(t_0) + \sum_{\tau=t_0}^{t} \Delta n(\tau)$$

γ_i is the constraint on the power factor, $\cos\varphi_i$, on a specific bus i, $n_{\min}$ and $n_{\max}$ are the minimum and maximum OLTC positions allowed, $\hat{g}_i$ is the moving average of the control signal g over a time window of W time steps, and ψ_1 and ψ_2 are penalty functions for altering the OLTC position. The last term of the objective is included only when the DNO wishes to control the centralized OLTC in addition to the distributed resources. Due to their sensitive nature and high cost, the DNO seeks to utilize the OLTC only in periods when demand response cannot provide the desired operating set-points and, even then, in a moderate fashion in order to preserve their limited lifetime. Therefore, the functions ψ_1 and ψ_2 are such that allow OLTC changes only when the GECN signal saturates (i.e., $|\hat{g}| \simeq 1$) and when the number of OLTC operations in a given time window are below an upper-bound.[7]

Next, the resulting optimal power set-points, $(\boldsymbol{\Delta}\mathbf{P}^*(t), \boldsymbol{\Delta}\mathbf{Q}^*(t))$ are mapped to the GECN signal $g(t) = (g_{P,i}(t), g_{Q,i}(t))_i$ with components in the range $[-1, 1]$ corresponding to active and reactive power adjustments in each bus i. For both active and reactive power, when controlling elastic demand, a negative g encourages consumption, a positive g inhibits consumption, and $g = 0$ does not affect the behavior of the controllable resources. Similarly, when controlling ESSs, a negative g encourages charging, a positive g requests discharging, and $g = 0$ has no impact on the ESSs state. At time t, $g_p(t)$ is computed as a function of (i) the optimal set-points at the current time-step and (ii) the mismatch between the optimal and the actual set-points that the DNO observed at the previous time step $t-1$.

Once the GECN signal is broadcasted to the network buses, the local controllers of the various resources in network bus i receive the broadcast signals $(g_{P,i}, g_{Q,i})$ and decide the action to be taken based on the internal state of the resources and on the value of the received signals. Then, the resulting variation of the bus aggregate power provides the DNO with an implicit feedback of the responsiveness of the resources and is used to adjust the control signals at subsequent time steps.

So far we have designed two smart local controllers targeting thermostatically controlled loads (TCLs) and in particular refrigerators, as well as actual ESSs and in particular supercapacitors (SCs). In what follows, we briefly summarize the functionalities of these two local controllers and we elaborate on the main principles on which the design of such local GECN controllers should rely.

3.3. Design of local controllers

The goal of the local controllers of the various energy resources is to interpret the GECN signal and to respond to it by appropriately altering the controllable resources' state without impacting significantly the end-users and the devices' lifetime. Therefore, the first step towards designing a GECN controller for a specific energy resource is to understand the functionalities of the resource under absence of any control and to identify its internal state and constraints.

For example, TCLs operate in an ON–OFF mode in a temperature deadband absorbing active power when ON and, at the same time, a proportional amount of reactive power via a fixed power factor value. Therefore in this case GECN targets only the control of active power injections by requesting the TCLs to switch mode when necessary. It is worth noting that violating the temperature deadband will have a direct impact on the end-users, while abusing the number of ON–OFF mode switches can result in significantly decreasing the TCLs' lifetime. Taking these constraints into account, in [13] a refrigerator controller is designed to react to a g_P signal only if it has not already done so in the near past, at most a predetermined number of time steps ago. This avoids operation in mini-cycles. If this first test is passed, the controller takes the decision of turning ON or OFF the fridge with a certain probability that depends on the received signal and on the TCL's internal temperature.

SCs, and in general electrochemical-based ESSs, operate in a DC voltage deadband and, contrary to TCLs, they can provide both active and reactive power support in a range that is imposed by the capabilities of the AC/DC power converters that interface them with the grid. Therefore, both g_P and g_Q are received by the local controller and they are eventually transformed into DC power requirements and subsequently, in charging/discharging current references. To achieve this, first the controller translates the signals to requested adjustments in the converter's AC-side active and reactive power set-points, while ensuring that the constraints on the PQ capability curve of the converter are respected. Then, the actual AC set-points are computed starting from the previous

[7] See [13,14] for more details.

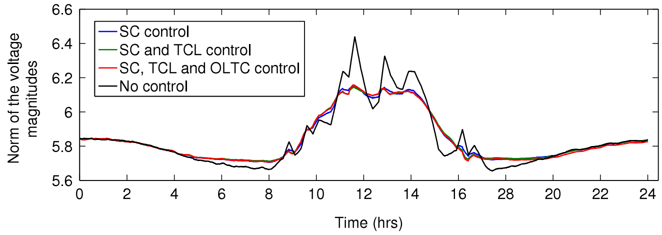


Fig. 6. Norm of the node voltages over a 24 h period when different scenarios of controllable resources are considered.

operating point while taking into account internal DC voltage limits to avoid possible relay tripping of the power electronics. Prior to translating the newly computed AC set-points to DC current references, we filter them by using a function of the state of charge in order to preserve the ESSs lifetime and modulate their response to the GECN signals.

The flow charts describing the various steps taken by these two controllers are shown in Fig. 5.[8] Detailed functionalities of both controllers, as well as a validation of their operation through simulation experiments can be found in [13,14].

3.4. Application example

In what follows, we consider the same network configuration as in [14], as well as 20% of TCLs (see [13]), SC arrays sized as in [14] and OLTCs with limits as in [13]. We apply GECN for primary voltage control considering three distinct scenarios, i.e., only SC control, coordination of SCs and TCLs and finally inclusion of OLTCs in addition to TCL and SC control. Fig. 6 shows the norm of the voltage magnitudes without any control action, as well as the norm of the voltages after the application of GECN for the three distinct scenarios. It is worth observing that the improvement in the network voltage profiles is almost identical under the three scenarios. This indicates that the proposed algorithm is transparent with respect to the adopted set of controllable resources. This provides the DNO with the freedom to define the most suitable set of assets to be allocated to the voltage control functionality.

A more extensive set of simulation experiments has been presented in [13,14] serving as a proof of concept for the application of GECN to primary voltage control. The validation of the algorithm shows that GECN is able to drive the network voltages within acceptable limits, achieving an improvement in the network voltage profiles in the order of 6% or more. Furthermore, evaluating GECN under fast voltage variations, such as a load inrush or volatile PV production, has shown that it can successfully adapt to such conditions and improve successfully the network voltage profile.

4. Conclusion

The continuously increasing penetration of non-dispatchable renewable resources in distribution systems in combination with the peculiarities that characterize ADNs compared to HV networks, call for the development of dedicated control mechanisms. In view of the large number and heterogeneity of the controllable energy resources in ADNs, there is a need for unified control mechanisms that rely on broadcast-signals to keep the system tractable. GECN is such a control mechanism, designed to provide voltage control and lines congestion management in ADNs.

Overall, GECN can be viewed by the DNO as an additional leverage to the available centralized resources, such as the OLTC. The main advantages of this control scheme are that (i) significantly heterogeneous energy resources can be controlled by receiving the same signal; (ii) GECN does not require knowledge of the actual state or nature of each controllable resource, reducing the communication requirements; (iii) controllable resources can join/leave the system dynamically and GECN will continue its operation with a subset of the resources by appropriately adapting the GECN signals.

[8] For the sake of brevity, in the case of ESSs control we only show the flow chart related to g_P. The steps for the reactive power control are similar.

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