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Decentralized Smart Grid Voltage Control by Synchronization of Linear Multiagent Systems in the Presence of Time-Varying Latencies

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Abstract: Modern power distribution systems require reliable, self-organizing and highly scalable voltage control systems, which should be able to promptly compensate the voltage fluctuations induced by intermittent and non-programmable generators. However, their deployment in realistic operation scenarios is still an open issue due, for example, to the presence of non-ideal and unreliable communication systems that allow each component within the power network to share information about its state. Indeed, due to technological constraints, time-delays in data acquisition and transmission are unavoidable and their effects have to be taken into account in the control design phase. To this aim, in this paper, we propose a fully distributed cooperative control protocol allowing the voltage control to be achieved despite the presence of heterogeneous time-varying latencies. The idea is to exploit the distributed intelligence along the network, so that it is possible to bring out an optimal global behavior via cooperative distributed control action that leverages both local and the outdated information shared among the devices within the power network. Detailed simulation results obtained on the realistic case study of the IEEE 30-bus test system are presented and discussed in order to prove the effectiveness of the proposed approach in the task of solving complex voltage control problems. Finally, a robustness analysis with respect to both loads variations and hard communication delays was also carried to disclose the efficiency of the approach.

Keywords: voltage regulation; smart grid; decentralized control architecture; multi-agent dystems; time-varying latencies

1. Introduction

The conceptualization of flexible and reliable architecture for voltage control assumes a key role in modern smart grids (SG) [1], where the solution of the dichotomy between the strictly power quality requirements, and the need for increasing the hosting capacity of renewable power generators represents one of the most relevant issues to address [2]. In particular, it is well known that the increasing penetration of small and dispersed non-programmable generation units into existing electricity distribution grids affects the active and reactive power flows, inducing a number of complex side-effects on the voltage magnitude profiles at the load buses, which could limit the exploitation of renewable energy sources [3–5].

These limitations mainly originate from the so called "passivity hypothesis" [6,7] that has been traditionally assumed when designing power distribution systems, which represents the main application domain of the SGs functions.

The evolution of power distribution systems from passive appendices of transmission systems toward active and self-healing entities [8] asks for new and more effective voltage control systems, which should be able to promptly compensate the voltage fluctuations induced by the randomly changed active power profiles generated by intermittent and non-programmable generators [3,9]. To address this complex problem, different solution techniques have been proposed in the literature. Traditionally, centralized architectures have been proposed [10]. These centralized and hierarchical solutions are based on a central fusion center [11–13], which periodically collects the grid data and identifies the set-points of the available voltage controllers by solving a constrained optimization problem. The latter asks for a preliminary stage aimed at estimating the actual power system state and the network topology, as far as a detailed mathematical model of the analyzed power system, which defines the equality constraints of the optimization problem. Satisfying these requirements for power distribution systems could be very demanding. More specifically, since the control decisions are solely taken by the central intelligence on the basis of global information about the network, such as the status of each agent and how they are being exchanged, computational burden dramatically increase [14]. Indeed, the development of effective algorithms for state and topology estimation in medium-voltage and low-voltage grids is still at its infancy, and more work should be done in order to effectively solve these problems in realistic operation scenarios [11,13,15–18].

The deployment of detailed mathematical models for power distribution systems is another challenging issue to address, due to the intrinsic complexities characterizing these systems, as far as bi-directional power flows, and unbalanced and rapidly changing operating conditions are concerned. All these issues hinder the applications of the conventional power flow equations currently adopted in power transmission voltage control, requiring more sophisticated modeling techniques [6,19]. The limited scalability and adaptivity levels of centralized/hierarchical control paradigms are other severe limitations to address in SG domains, where dispersed generators equipped with proper grid interfaces could be considered distributed sources of reactive power. Although this feature offers additionally flexibility in solving the voltage control problem, it increases the cardinality, and the complexity of the optimization problem, which should be solved in near-real time in order to compensate the rapidly changing dynamics of the dispersed generators [3,12] .

Finally, a reliable, wide-area communication infrastructure covering the entire power system area is required in order to allow the central processing algorithm to have a clear picture of the current SG operation. This could be a limiting issue in several application domains, especially for power distribution systems located in remote or low-urbanized areas [20–24].

All these limitations have stimulated the SG research in conceptualizing and developing new voltage control paradigms, which allow evolving the traditional centralized and hierarchical solutions toward decentralized and self-organizing architectures based on cooperative and adaptive control entities [15,16,25,26].

The most common instance of these architectures is based on multiagent systems (MASs), which have been widely explored in the voltage control literature. Leveraging this framework, all electrical components within the power grids cooperate together in order to reach a collective behavior, as imposed by the control objectives [26]. To that end, each electrical devices embeds wireless communication hardware in order to share information with neighbors and a distributed control module that, leveraging only local and neighboring information, drives its behavior to reach the desired control goal. The idea is to exploit the distributed intelligence along the network, so that it is possible to bring out an optimal global behavior via simple local control actions. Within this framework, the N electrical devices in the grid can be modeled as a network of dynamic agents (MAS), each one regulating the voltage magnitude of its related bus via a cooperative control protocol. In doing so, the controlled SG can be seen as an IoT ecosystem (or cyber-physical System) [1,22,27], where the crucial challenge for the control is to guarantee a desired dynamic behavior for each single node while coordinating at the same time the overall behavior of the ensemble. In particular, [11,13,15,25,26,28] demonstrated that the MASs framework could play a strategic role in SGs voltage control, by promptly adapting the set-points of the distributed voltage controllers according to predefined control objectives. Anyway, selecting the most appropriate processing architecture for a MAS is not an easy task. Indeed, in the SGs domain, the complex economic-driven dynamics of both loads and generators and the severe reliability requirements have been recently orienting research efforts toward the conceptualization of self-organizing and decentralized processing computing paradigms. In this context, one of the most promising enabling methodologies is based on the adoption of decentralized and self-organizing networks of dynamic agents equipped with consensus protocols [17,18,25,29–31]. Although the solutions proposed in these papers allow effectively and reliably solving the voltage control problem, their deployment in realistic operation scenarios is still an open problem, which asks for further investigations. In this context, a formal analysis of the convergence of the controllers network in the presence of non-ideal and unreliable communication system is recognized as a relevant issue to address [17,21,22]. Indeed, in practice, when deploying distributed control strategies, agents share information through dedicated wired or wireless communication networks. Due to technological constraints, time-delays in data acquisition and transmission are unavoidable [29] and their effects on the closed-loop network have to be investigated and prevented, since they may strongly compromise the overall stability performances [32]. To avoid the MAS becoming unstable, and hence, ensure it does not breach the desired behavior, the presence of communication delays has to be taken into account in the control design phase. To compensate the adverse effects of delays, [21] suggests a sliding mode estimation based controller predicting time delays value and grid state in order to reject the disturbance of estimation errors. However, communication delays are assumed to be constant and homogeneous. Again, to counteract homogeneous and constant latencies, [22] proposes a parametric feedback linearization (PLF) control protocol that adapts its structure to the corresponding latency value. This technique requires the knowledge of constant latency characteristics in order to tolerate substantial delays without noticeable performance degradation. However, when treating wireless communication network, based on, for example on the IEEE 802.11 protocol, each communication link that connects a pair of agent is affected by a different variable time-delay whose value depends on actual conditions, or possible impairments, of the communication channel. It follows that the hypothesis commonly made in the technical literature of a unique and constant network delay may be unrealistic. Therefore, delays have to be considered time-varying functions whose actual values depend on the specific communication link under investigation.

To face this issue in this paper we propose a fully distributed and decentralized control architecture (see [25] and references therein for an overview the main advantages of the approach) that allows one to address the voltage regulation problem in a SG despite the presence of time-varying communication latencies. The proposed control architecture is funded on a network of N cooperative smart controllers, each one regulating the voltage magnitude of a specific bus (called a node too). All nodes/controllers are able to share information about their states with their neighbors (within their communication range) so that the control actions can be cooperatively computed by embedding within the online decision making process, not only information coming from local sensing, but the delayed network information about the surroundings. Leveraging the theoretical framework of delayed MAS, we propose for each smart controller a fully distributed cooperative algorithm that, running on the basis of outdated information, ensures that each electrical node converges towards the desired behavior, as imposed by the generators within the power grid, while counteracting the effect of the time-varying communication latencies. Note that, to compute the proper control action, each smart controller does not require the knowledge of global information about the whole electrical grid or global information about the communication network topology. This implies that, according to technical literature, our approach is fully distributed [33,34]. To validate the effectiveness of the proposed approach we consider the well-know benchmark IEEE 30-bus test system [35–37]. Detailed simulation results disclose the effectiveness of the strategy in guaranteeing the voltage regulation for the appraised power network despite the presence of communication latencies. Moreover, to test the robustness of the approach we consider a worst case scenario where both load variations and hard delays are considered. Numerical results further confirm the efficiency of the approach in this critical scenario.

Finally, the paper is organized as follows. In Section 2, the on-line voltage regulation problem is introduced. Section 3 describes the adopted decentralized control architecture, while Section 4 presents the proposed distributed control strategy. In Section 5, the effectiveness and the robustness of the approach is disclosed by considering the exemplary case study of the voltage regulation for the IEEE 30-bus test system. Finally, in Section 6 the conclusions are drawn.

2. On-Line Voltage Regulation Problem

The online voltage regulation as well as the reduction of power losses in a SG is commonly achieved through the optimal coordination of under load tap changing (ULTC) transformers, capacitor banks, flexible AC transmission system (FACTS) devices, a distribution STATCON (D-STATCON) and a power electronic transformer (PET), all combined with the aim of supporting the load bus's voltage magnitude and improving the power quality at the distribution level. However, the overall voltage regulation process in a SG is complex since the network operates in alternating current (AC) mode due to generators drawing energy from renewable sources; hence, not guaranteeing a continuous flow. As a consequence, the voltage regulation requires the adoption of suitable methodology assuring both secure and economic operation of the grid.

In this framework, for each power system state Γ, an online voltage control function identifies a proper set-point y for the grid controllers minimizing an objective function J subject to several equality and inequality constraints, say $g(\Gamma, y)$. In doing so, the general voltage regulation problem can be formulated as:

$$\begin{cases} \min_{y\in\Omega} J(y,\Gamma), \\ g(\Gamma, y) \leq 0, \end{cases} \tag{1}$$

being

$$y = \left[Q_{dg,1}, \ldots, Q_{dg,N_g}, Q_{cap,1}, \ldots, Q_{cap,N_c}, V_{FTS,1}, \ldots V_{FTS,N_f}, m,\right] \tag{2}$$

the target vector embedding the grid controller set-points, where $Q_{dg,i}$ is the reactive power injected by the i-th distributed generator available for the regulation $(i = 1, \ldots, N_g)$; $Q_{cap,j}$ is the vector of the reactive power injected by the j-th capacitor bank $(j = 1, \ldots, N_c)$; $V_{FTS,k}$ is the set-point voltage of the k-th flexible AC transmission systems (FACTS) $(k = 1, \ldots, N_f)$; and m is the tap position of the HV/MV line tap changing transformer. Note that this target vector y takes on value in the solution space Ω:

$$y \in \Omega \iff \begin{cases} tap_{min} \leq m \leq tap_{max}; \\ Q_{dg,min,i} \leq Q_{dg,i} \leq Q_{dg,max,i} & i = 1, \ldots, N_g; \\ Q_{cap,min,j} \leq Q_{cap,j} \leq Q_{cap,max,j} & j = 1, \ldots, N_c; \\ V_{FTS,min,k} \leq V_{FTS,k} \leq V_{FTS,max,k} & k = 1, \ldots, N_f. \end{cases} \tag{3}$$

Moreover, the vector function $g(\Gamma, y)$ in (1) includes the set of technical constraints to be considered in terms of allowable ranges for the bus voltage magnitudes (i.e., $V_{min,q} \leq V_q \leq V_{max,q},\ q = 1, \ldots, N$), and the maximum allowable currents for the n_l power lines (i.e., $I_l \leq I_{max},\ l = 1, \ldots, n_l$). As in [25], the objective function to be minimized takes into account both technical and economic aspects, and it is typically expressed as a weighted sum of O normalized design objectives:

$$J(y,\Gamma) = \alpha_{F_1} \frac{F_1(y,\Gamma)}{\bar{F}_1} + \alpha_{F_2} \frac{F_2(y,\Gamma)}{\bar{F}_2} + \cdots + \alpha_{F_O} \frac{F_O(y,\Gamma)}{\bar{F}_O}. \tag{4}$$

Note that the weights $\alpha_{F1}, \ldots, \alpha_{F0}$ only depend on the objectives the controller designer would reach.

The four typical design objectives (to minimize) are:

- The active power losses:

$$F_1 = P_g - P_l \geq 0, \tag{5}$$

  where P_g and P_l are the total active power generated and absorbed on the network;
- The avarage voltage deviation:

$$F_2 = \frac{\sum_{i=1}^{n} \|V_i - V_i^{\star}\|}{N}, \tag{6}$$

  where V_i and $V_i^{\star}$ are the current and the desired voltage at the node i respectively, and N is the number of nodes;
- The maximum voltage deviation:

$$F_3 = \max_i (\|V_i - V_i^{\star}\|); \tag{7}$$

- The reactive energy cost during regulating period Δt given by [38]:

$$F_4 = (F_1 c_{loss} + c_{dg} Q_{dg} + c_{cap} Q_{cap} + c_{QAT} Q_{AT} + c_{FTS} Q_{FTS}) \Delta t, \tag{8}$$

  where c_{loss} is the real energy price; $Q_{AT}\Delta t$ and c_{QAT} are the reactive energy imported from the HV grid and the corresponding cost; c_{dg} and c_{cap} are the costs of the reactive energy injected by dispatchable generators and capacitor banks, respectively; $Q_{FTS}\Delta t$ and c_{FTS} are the reactive energy injected by the FACTS devices and the corresponding cost.

Since the design objectives are in competition, the voltage regulation problem has no unique solution and a suitable trade-off among objectives has to be identified. In our work we consider the designing objectives function (4) as a linear combination of the functions (5)–(8). Since we are more interested into the technical aspects of the voltage regulation problem rather than the economic ones, we equally weighted the designing objectives (5)–(7) by considering $\alpha_{F1} = \alpha_{F2} = \alpha_{F3} = 1$, while for the energy cost function in (8) we assumed $\alpha_{F4} = 0.5$.

3. Decentralized Control Architecture

In our operating scenario, exploiting the distributed intelligence along the network paradigm, each controller device is equipped with three basic components:

1. A set of *sensors* allowing measuring the set of local electrical variables, such as voltage magnitude, and active and reactive bus power;
2. A control module that computes its action on the basis of predictions from a *dynamic system or agent model*, whose state is initialized by sensor measurements, evolving interactively with the states of nearby controllers according to a *bio-inspired* paradigm. Indeed, each controller evaluates both the local variables characterizing the monitored bus (sensed by in-built sensors) and the shared information over the communication network. Both these pieces of information, if properly processed, allow each controller to: (i) assess the evolution of the objective function describing the voltage regulation objectives; (ii) identify the proper control actions aimed at improving the grid voltage profile and reduce power losses; i.e., minimizing this function.
3. A *wireless interface* ensuring the cooperation among controllers by transmitting the state of the dynamic system and receiving the state transmitted by the other nodes via a communication network.

4. Decentralized Control Module

Consider a power grid made of N_c capacitor banks, N_g generators and $N = N_c + N_g$ buses managed by N cooperative smart controllers. Specifically, if the i-th smart controller is associated with the i-th generation bus of the grid ($i = 1, \ldots, N_g$), then its aim is regulating the bus so to achieve the desired voltage magnitude $V_i^\star$. Conversely, if the j-th smart controller is associated with the j-th capacitor bank bus ($j = 1, \ldots, N_c$), then its aim is controlling bus reactive power generation capability in order to: (a) guarantee that its voltage magnitude achieves the desired optimal voltage value imposed by N_g generators within the grid according to (6) and (7); (b) reduce power losses according to (5)–(8).

Given these goals, in what follows we design each component of the control architecture described in the above section.

4.1. Agent Model

Within our theoretical framework, each smart device j ($j = 1, \ldots, N_c$) associated to the j-th capacitor bank bus of the power grid is described as the following dynamic system:

$$\dot{Q}_j = u_j(t, \tau_{j\rho}(t), \tau_{ji}(t)), \tag{9}$$

where $Q_j(t)$ $[p.u.]$ represents the reactive power of the j-th capacitor bank bus. $u_j(t, \tau_{j\rho}(t), \tau_{ji}(t))$ is the cooperative control protocol that drives the reactive power (i.e., the voltage magnitude) of the electrical node by exploiting both the local measurements and the electrical network information affected by time-varying communication delays depending on the specific link; i.e., $\tau_{j\rho}(t)$ $(j, \rho = 1, \ldots, N_c)$ for $j \neq \rho$ and $\tau_{ji}(t)$ $(i = 1, \ldots, N_g)$. Note that, according to the technical literature on delayed systems [29,39], in what follows, we assume that the functions $\tau_{j\rho}(t)$ and $\tau_{ji}(t)$ are bounded and slowly-varying functions; i.e., $\tau_{j\rho}(t) \in [0, \tau^\star], \dot{\tau}_{j\rho}(t) < 1\ \forall t$ and $\tau_{ji}(t) \in [0, \tau^\star], \dot{\tau}_{ji}(t) < 1\ \forall t$. Finally we remark that, since the capacitor bank is a PQ bus—and hence, it is possible to drive its voltage magnitude only by imposing a variation of reactive power [40]—the dynamic system (9) models this kind of phenomena and allows it to adapt the reactive power of the capacitor bank so as to guarantee the voltage regulation.

Conversely, we assume that each smart device i ($i = 1, \ldots, N_g$) associated to the i-th generator bus within the electrical grid is described as [25]:

$$\dot{V}_i(t) = u_i(t), \tag{10}$$

where $V_i(t)$ $[p.u.]$ represents the voltage magnitude of the i-th generator; $u_i(t)$ is the control action that drives the voltage magnitude of the electrical node so to achieve the desired voltage $V_i^\star$. Note that generators provide the leading behavior for the whole smart grid by forcing the voltage magnitude $V_i(t)$ that needs to be imposed on the capacitor bank buses.

4.2. Communication Topology

The communication topology describing the connections among the N smart devices ($N = N_c + N_g$) can be modeled according to the graph theory. Namely, the topology of the N_c cooperative smart controller for the capacitor banks buses can be represented as a directed graph (digraph) $\mathcal{G}_{N_c} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ of order N_c characterized by the set of nodes $\mathcal{V} = \{1, \ldots, N_c\}$ and the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. To the graph $\mathcal{G}_{N_c}$ it is associated the adjacency matrix with non-negative elements $\mathcal{A} = [\alpha_{j\rho}]_{N_c \times N_c}$, being $\rho = 1, \ldots, N_c$. In what follows, we assume $\alpha_{j\rho} = 1$ in the presence of a communication link from the device j to device ρ; otherwise, $\alpha_{j\rho} = 0$. Moreover, $\alpha_{jj} = 0$; i.e., self-edges (j, j) are not allowed. The presence/absence of connections among the N_c cooperative smart controller and the N_g smart controller for the generation, buses are instead described by the graph $\mathcal{G}_N$ and the relative adjacency matrix $\mathcal{A}_1 = [\alpha_{ji}]_{N_c \times N_g}$, whose elements are equal to one ($\alpha_{ji} = 1$) in the presence of a communication link among the smart device j and the device i; otherwise, they are set to zero ($\alpha_{ji} = 0$). Moreover, we assume that pairs (j, ρ) and (j, i) ($\rho = 1, \ldots, N_c$, $i = 1, \ldots, N_g$ being $\rho \neq j$) communicate only if there exists a sufficiently powerful transmission line among them.

Finally, we assume that communication network topology is such that information sent by generators, that impose the desired voltage magnitude for the entire power networks, are globally reachable. Note that, this is not a restrictive assumption since it means, in other words, that every capacitor bank can obtain information from, at least, one generator (directly or indirectly) if there exists a path in the communication graph $\mathcal{G}_N$ from every capacitor bank to the generator itself, which is a prerequisite to guarantee the internal stability of the multiagent System [41].

4.3. Control Design

The solution of the voltage regulation problem for a power grid requires the achievement of the following control goals:

(1) To design the control action, based on local measurements, $u_i(t)$ in (10) regulating the voltage magnitude of the bus i so to reach and maintain the desired reference voltage value $V_i^\star$; i.e.,

$$\lim_{t\to\infty} \|V_i(t) - V_i^\star\| = 0, \; i = 1, \ldots, N_g, \tag{11}$$

being $V_i(t)$ the voltage magnitude of the i-th electrical node;

(2) To design a fully distributed cooperative control protocol, based on both local measures and network information, $u_j(t, \tau_{j\rho}, \tau_{jk})$ in (9) for opportunely driving the reactive power of the bus j updating its voltage magnitude V_j until it reaches the desired reference behavior as imposed by the i generators ($i = 1, \cdots, N_g$) of the smart grid; i.e.,

$$\lim_{t\to\infty} \| \sum_{i=1}^{N_g} \alpha_{ji}(V_j(t - \tau_{jk}(t)) - V_i(t - \tau_{ji})))\| \to 0, \tag{12a}$$

$$\lim_{t\to\infty} \| \sum_{\rho=1}^{N_c} \alpha_{j\rho}(V_j(t - \tau_{j\rho}(t)) - V_\rho(t - \tau_{j\rho}(t)))\| \to 0, \tag{12b}$$

where V_i is the voltage magnitude of the i-th generation bus and V_ρ is the voltage magnitude of the neighboring smart controllers ρ ($\rho = 1, \ldots, N_c$, with $j \neq \rho$).

Now, in order to fulfill the control objective in (11), we use, for each electric node i, the following proportional action based on the error with respect to the desired voltage value $V_i^\star$:

$$u_i(t) = k_i\big(V_i(t) - V_i^\star\big), \tag{13}$$

being $k_i \in R^+$ control gains to be properly tuned ($i = 1, \ldots, N_g$).

Conversely, to fulfill the control goals in (12a) and (12b), we propose for each electrical node j the following consensus-based control protocol that leverages both local and networked information:

$$u_j(t, \tau_{j\rho}(t), \tau_{ji}(t)) = k_j \textstyle\sum_{\rho=1}^{N_c} \alpha_{j\rho}\big(V_j(t - \tau_{j\rho}) - V_\rho(t - \tau_{j\rho}(t))\big) + b_j \sum_{i=1}^{N_g} \alpha_{ji}\big(V_j(t - \tau_{ji}(t)) - V_i(t - \tau_{ji}(t))\big), \tag{14}$$

where $\alpha_{j\rho}$ models the presence/absence of a communication link among the bus j and the bus ρ; α_{ji} models the presence/absence of communication link among the bus j and the generator bus i; $\tau_{ji}(t)$ and $\tau_{j\rho}$ model the communication latencies arising from the information exchange among the smart controllers; k_j and b_j are control gains that to be tuned in order to guarantee that the reactive power of the bus j does not exceed a prefixed operating range $[Q_{j,min}; Q_{j,max}]$.

5. Case Study

In this section the effectiveness of the control approach is verified for the exemplar case of the voltage regulation problem in the IEEE 30-bus test system depicted in Figure 1. The aim of the analysis is to show how the fully distributed control solution, despite the presence of communication time delays, can ensure a desired optimal voltage magnitude for the whole grid with reduced power losses. The power grid is made of $N_g = 6$ generators (namely, nodes 1,2,5,8,11, and13) and $N_c = 24$ capacitor banks with $N = 30$ buses and $n_l = 41$ lines. Information about load, line impedance and reactive power limits were provided according to [37]. The numerical analysis was carried out by exploiting the MATLAB/Simulink © platform, where the time-varying communication delays $\tau_{j\rho}(t)$ $\tau_{ji}(t)$ were emulated as random variables uniformly distributed in [0, 0.1] [s], with an upper bound that was one order of magnitude greater than the average end-to-end communication delay typical of the IEEE 802.11.(which is of the order of few hundredths of a second [42]) so as to provide delay margins. Initial conditions for the N cooperative agents within the grid and the values of the control gains are listed in Table 1. Note that the initial conditions for each agent are randomly chosen by selecting their values within their acceptable ranges. At the same time, control gains are selected so as to avoid reactive power exceeding its maximum/minimum allowable values.

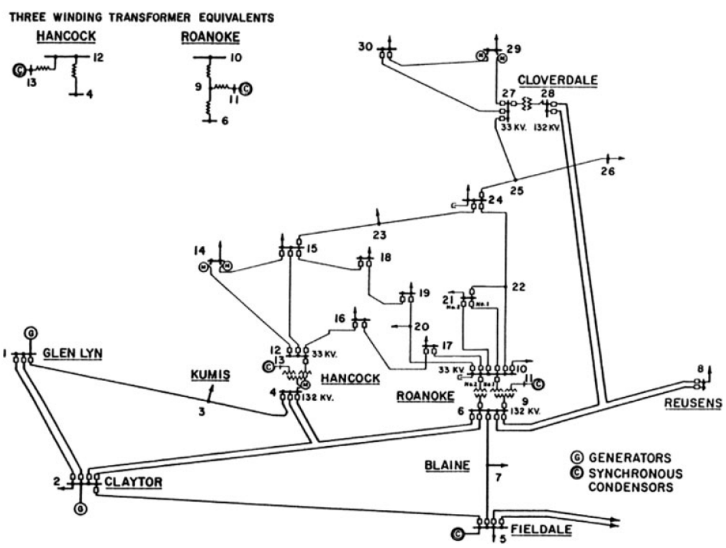

Figure 1. The IEEE 30-bus test system.

Table 1. IEEE 30-bus test: parameters values.

	Initial Conditions
Voltage magnitude of generator bus i $[p.u.]$	$V_1(0) = 1.02$; $V_2(0) = 1.0.1$; $V_5(0) = 1.03$; $V_8(0) = 1.04$; $V_{11}(0) = 1.01$; $V_{13}(0) = 1.03$
Reactive power of capacitor bank bus j $[p.u.]$	$Q_3(0) = -0.012$;$Q_4(0) = -0.016$; $Q_6(0) = -0.005$; $Q_7(0) = -0.109$; $Q_9(0) = -0.005$; $Q_{10}(0) = -0.02$; $Q_{12}(0) = -0.075$; $Q_{14}(0) = -0.016$; $Q_{15}(0) = -0.025$; $Q_{16}(0) = -0.018$; $Q_{17}(0) = -0.058$; $Q_{18}(0) = -0.009$; $Q_{19}(0) = -0.034$; $Q_{20}(0) = -0.007$; $Q_{21}(0) = -0.112$; $Q_{22}(0) = -0.005$; $Q_{23}(0) = -0.016$; $Q_{24}(0) = -0.067$; $Q_{25}(0) = -0.005$; $Q_{26}(0) = -0.023$; $Q_{27}(0) = -0.005$; $Q_{28}(0) = -0.005$; $Q_{29}(0) = -0.009$; $Q_{30}(0) = -0.019$;

Table 1. *Cont.*

	Control Gains
Control gains k_i	$k_i = 5 \quad i = 1, 2, 5, 8, 11, 13$
Control gains k_j	$k_j = 6 \quad \forall j \in N_c$
Control gains b_j	$b_j = 20 \quad \forall j \in N_c$

As exemplary information communication topology, we chose the one described by the power transmission lines' electrical topology, which satisfies the assumption of generators being globally reachable. However, if other communication topologies satisfying this assumption were considered, our approach would be still able to guarantee the voltage regulation of the whole power network. Indeed, our proposed strategy is flexible to all the communication topologies for which generators are globally reachable. Finally, the desired voltage values $V_i^\star$ for the generation buses N_g were selected as follows: $[V_1^\star, V_2^\star, V_5^\star, V_8^\star, V_{11}^\star, V_{13}^\star] = [1.05, 1.02, 1.05, 1.03, 1.05, 1.02][p.u.]$.

5.1. Nominal Operational Scenario

Results in Figure 2 confirm that under the action of the control $u_i(t)$ in (13) the first control goal (11) is fulfilled. Indeed, the smart controllers for the generation buses ensure that the corresponding voltage magnitude converges to the desired value ($V_i^\star, i = 1, \ldots, N_g$) in $1[s]$.

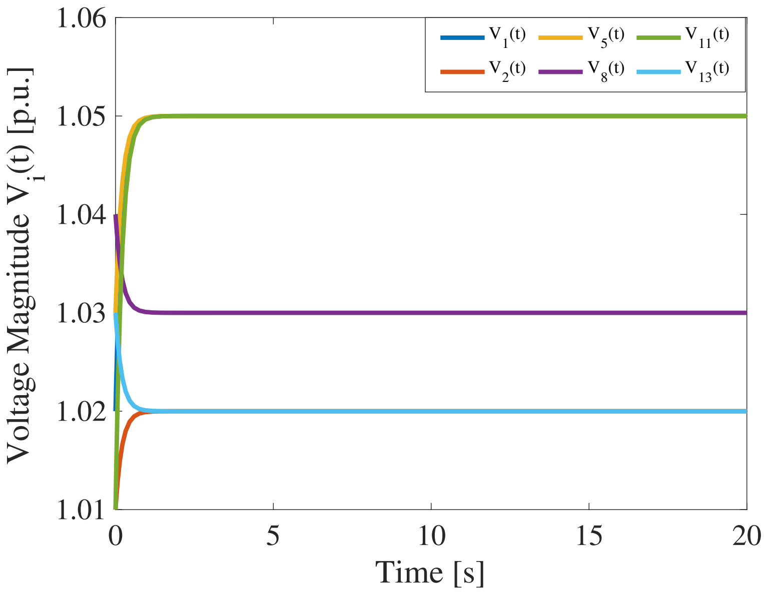

Figure 2. Time history of the voltage magnitude $V_i(t)[p.u.]$ for $i \in N_g$.

As a consequence, the cooperative control protocol $u_j(t, \tau_{j\rho}(t), \tau_{jk}(t))$ in (14) drives the reactive power generation capability of each capacitor bank j ($j = 1, \ldots, N_c$) so that it properly produces or absorbs the necessary bus reactive power allowing the voltage magnitude to reach an optimal value within the range spanned by the generators; i.e., within [1.02; 1.05] [p.u.] (see results depicted in Figures 3 and 4). In so doing, the control objective (12a) is satisfied and accordingly, the control goal (12b) is also achieved, since the mean grid voltage of the each of the N_c electrical nodes converges to the average voltage imposed by the N_g generators $V_{mean} = 1.03$ $[p.u.]$. Therefore, the control architecture is able to self-adapt so that the overall electrical grid synchronizes to the reference behavior imposed by generators.

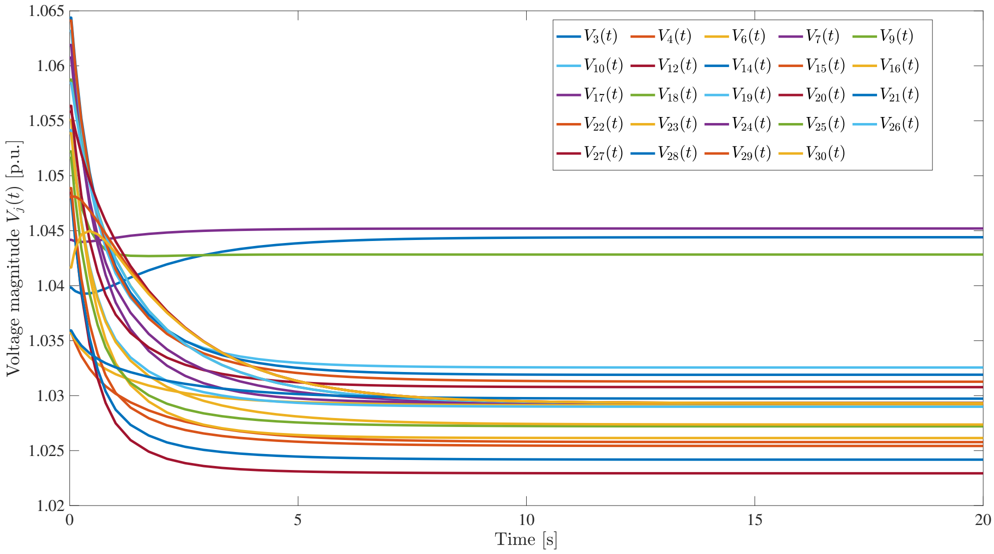

Figure 3. Time history of the voltage magnitude $V_j(t)[p.u.]$ for $j \in N_c$.

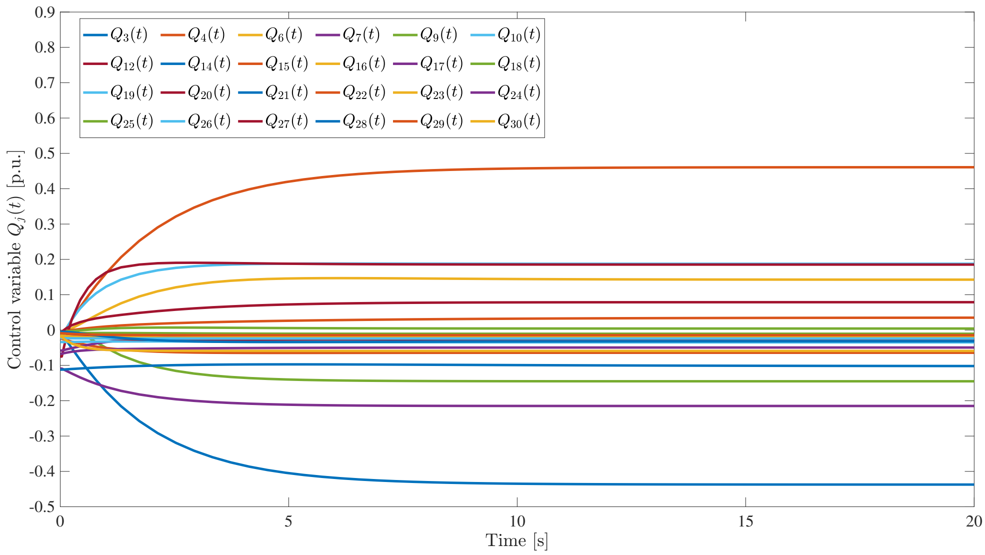

Figure 4. Time history of the reactive power $Q_j(t)[p.u.]$ for $j \in N_c$.

5.2. Robustness Analysis

In this section, the robustness analysis with respect to both loads variations and hard communication impairments is described.

5.2.1. Load Changing

In a power grid, according to the specific and practical requirement, load demand is subject to frequent changes. Thus, the evaluation of robustness with respect to load variations is a crucial aspect to be investigated for assessing the performance of the controlled grid. To that end, we considered the variable load profile $L(t)$ depicted in Figure 5 (where a maximum load variation of $\pm 50\%$ can be observed).

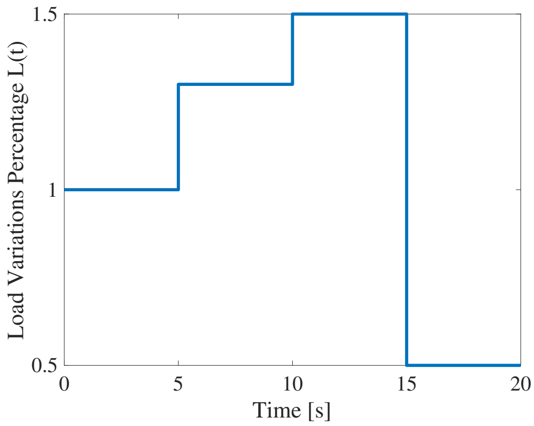

Figure 5. Time history of the variable load profile $L(t)$. Percentage variation with respect to the nominal value.

Results in Figures 6 and 7 show that the proposed approach is able to effectively counteract the sudden variations in the load request, recovering the desired optimal voltage intensity imposed by the N_g generators. Namely, the distributed control actions react to the increase of load of 30% at time instant $t = 5$ s, inducing a variation in the production/absorption rate of the reactive power (as shown in Figure 6) and promptly restoring the average voltage at the required level $V_{mean} = 1.03$ $[p.u.]$. The same good performance can be observed at the next time instants within the time interval $10 \leq t < 15$ when variations of 50% occur, and in the time interval $15 \leq t < 20$ for variations of -50% (see Figure 6).

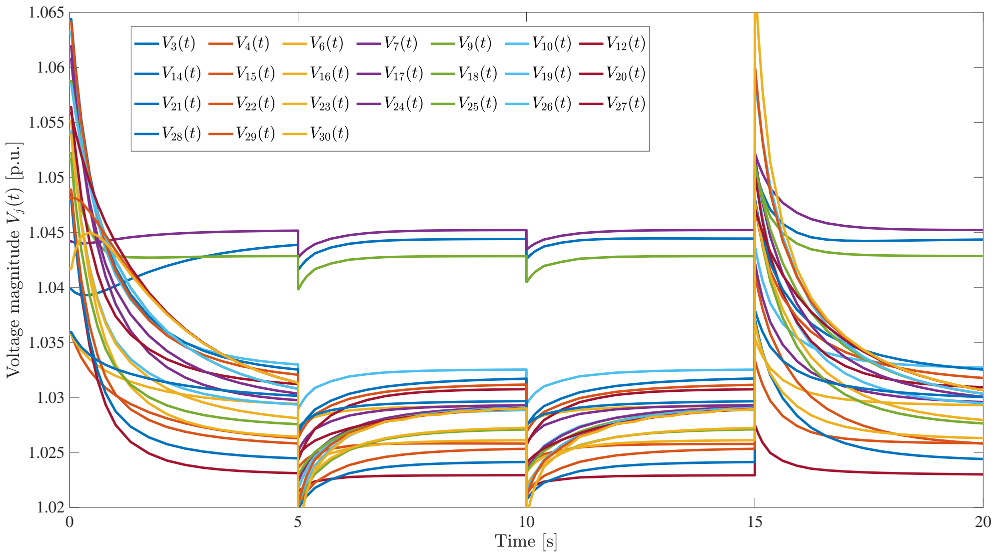

Figure 6. Robustness with respect to variable loads: time history of the voltage magnitude $V_j(t)[p.u.]$ for $j \in N_c$.

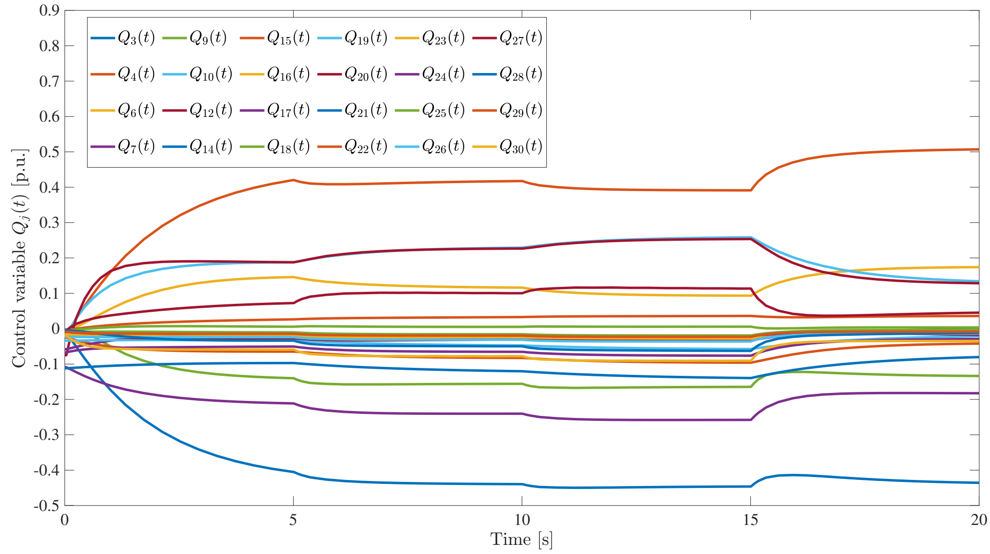

Figure 7. Robustness with respect to variable loads: time history of the reactive power $Q_j(t)[p.u.]$ for $j \in N_c$.

5.2.2. Hard Delay

Robustness has been also assessed with respect to hard delay. Namely, in this subsection we consider the worst case analysis when all communication time-delays are always equal to the maximum (i.e., they have been forced to $\tau^\star = 0.1$ [s]) above the typical value observed for wi-fi networks in real scenarios. Again, the results shown in Figures 8 and 9, disclose the robustness of the decentralized architecture in dealing with these hard delay conditions and confirm that control performance is preserved also in this worst-case scenario.

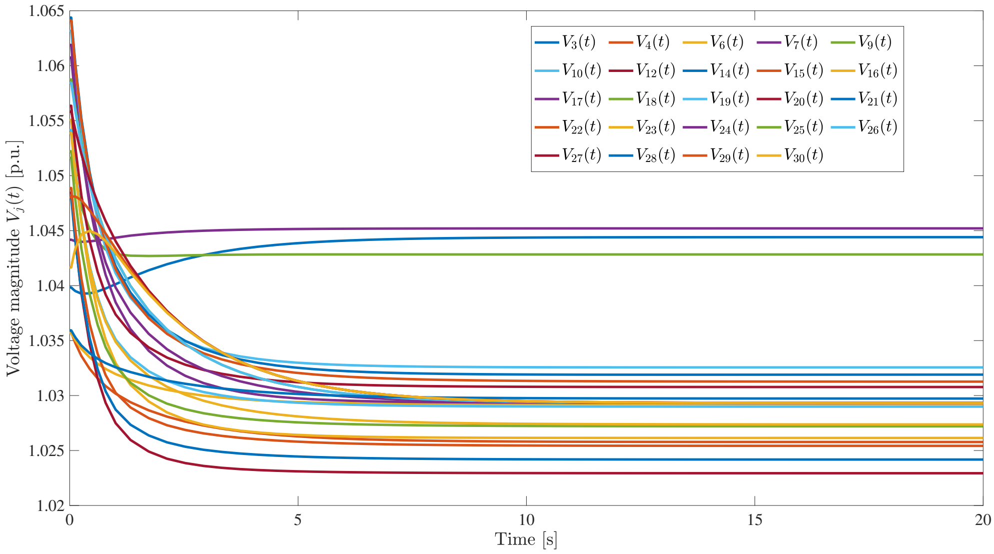

Figure 8. Worst case analysis in the the presence of a hard communication time-delay of $\tau^\star = 0.1$ [s]: time history of the voltage magnitude $V_j(t)[p.u.]$ for $j \in N_c$.

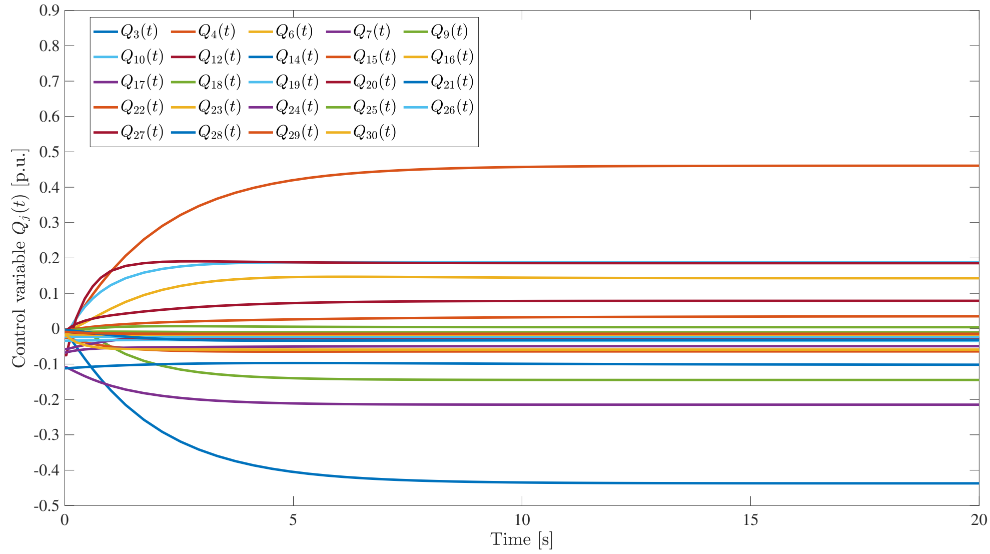

Figure 9. Worst case analysis in the the presence of a hard communication time-delay of $\tau^\star = 0.1$ [s]: time history of the reactive power $Q_j(t)[p.u.]$ for $j \in N_c$.

Finally, we consider a simulation scenario where both load variations and hard delays are considered simultaneously. Simulation results, depicted in Figures 10 and 11, further confirm the effectiveness and the robustness of the proposed approach in this case. Indeed, despite the simultaneous presence of both load variations and hard delays, the proposed control strategy is able to promptly restore the average voltage at the required level $V_{mean} = 1.03$ $[p.u.]$.

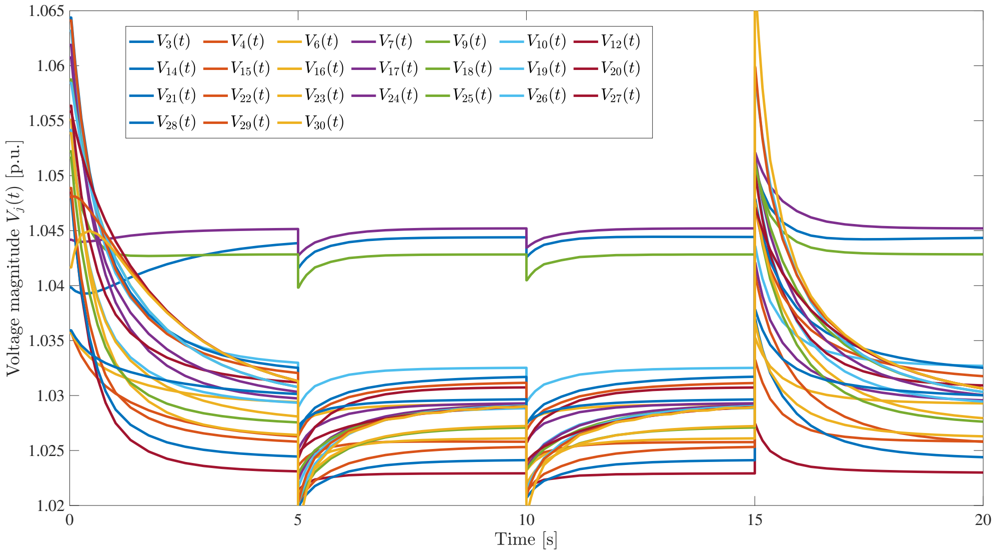

Figure 10. Worst case analysis in the presence of both a hard communication time-delay of $\tau^\star = 0.1$ [s] and load variations: time history of the reactive power $V_j(t)[p.u.]$ for $j \in N_c$.

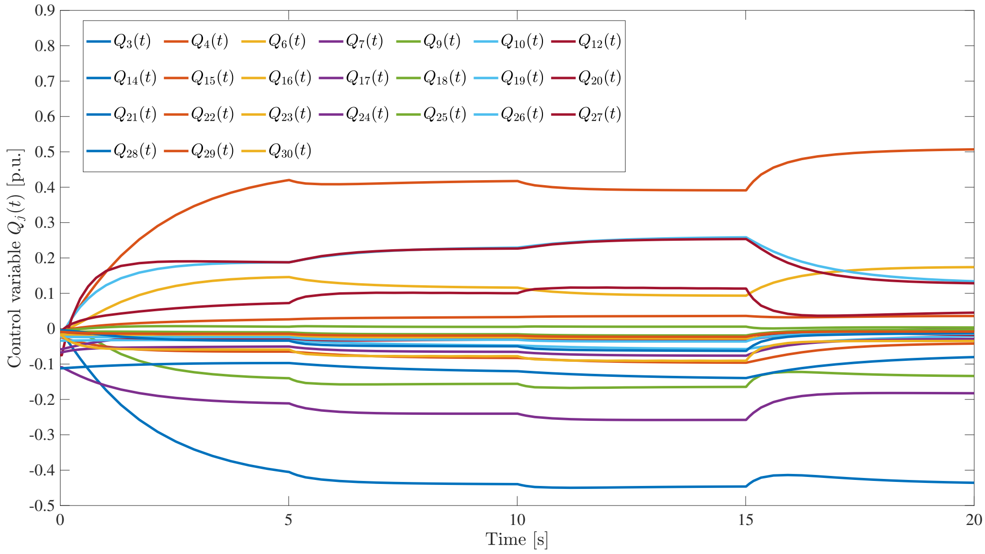

Figure 11. Worst case analysis in the presence of both a hard communication time-delay of $\tau^\star = 0.1$ [s] and load variations: time history of the reactive power $Q_j(t)[p.u.]$ for $j \in N_c$.

6. Conclusions

In this paper a fully distributed and decentralized architecture has been proposed to solve the voltage control problem in a smart grid domain. The proposed control architecture funds on a network of cooperative smart controllers, each one regulating the voltage magnitude of a specific bus, and sharing information about their state only with their neighbors. Thanks to these features, the controlled smart grid can be considered a cyber-physical power system, where the crucial challenge for the control is to guarantee a desired dynamic behavior for each single node while coordinating, at the same time, the overall behavior of the ensemble.

The results obtained demonstrated the effectiveness of the proposed control architecture in the task of solving complex voltage control problems by a fully distributed, cooperative control paradigm, which was able to achieve the optimal energy management of the whole power grid while counteracting the effect of the time-varying communication latencies.

Detailed simulation analysis, carried out both in nominal and uncertain scenarios, have disclosed the effectiveness of the proposed architecture.

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