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A distributed non-Lipschitz control framework for self-organizing microgrids with uncooperative and renewable generations

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ABSTRACT

This paper investigates the design of robust distributed voltage and frequency control for a self-organized microgrid. A multiagent distributed secondary hierarchy is proposed using control Lyapunov function. Power resources are categorized as controllable and uncontrollable distributed generations (DG). Controllable DGs are exchanging information with neighbor DGs through agents at communication layer. The agents communicate to restore the voltage and frequency to their nominal references. Furthermore, the proposed scheme is robust against the insufficient data from uncontrollable DGs, since it provides an improved and stable operation even when there is no communication with uncontrollable DGs and loads. It can actively compensate for the random unknown demand and generation, by sharing the power mismatch in distributed droop architecture. It is shown that the suggested controller is capable of stabilizing an uncooperative microgrid in which not all DGs are cooperating. Also, the convergence speed of the system is improved using the finite-time controller. The performance and finite-time stability of a microgrid with partially-cooperative DGs is proved using Lyapunov theorem and is validated through numerical simulation. The results show improved transients, accurate steady state values for voltage and frequency control of a microgrid, and robustness against communication architecture variations. The impact of communication delays, the uncertainty in coupling gains of the communication links, and the time-interval between updating the controller and the states through communication are investigated.

1. Introduction

High penetration of the distributed generation (DG) including the renewables on the distribution grid, provides diverse advantages including reduced pollutions. Though, unsupervised operation of DGs may degrades the power quality provided to the consumer and can cause voltage/frequency instability. Supervised integration of DGs under the concept of microgrids has recently been widely accepted as the main solution [1,2]. Generally, a microgrid is defined as a group of distributed energy resources (DERs) including DGs, distributed storage, active loads, as well as measurements, control devices, and management algorithms, which are mainly conducted in a cooperative approach. Microgrids can be utilized in grid-connected and islanded modes of operation [3] and can switch between them, seamlessly [4].

In grid-connected mode, the voltage and frequency of the microgrid is dominated by the main grid. However, the voltage profile can be enhanced by reactive power contribution from the DGs. A microgrid can be exploited in islanded mode after unprepared disturbances as well as an arbitrary schedule. Islanded mode is motivating in rural remote regions and islands where the main grid is unavailable.

Nonetheless, high penetration of DERs, and the islanding may causes large variations and instability in microgrid voltage and frequency due to its low equivalent inertia compared to the grid-connected mode. This requires additional compensating control loops. Designing a proper control scheme for a microgrid has recently been an interesting field of research [5]. The two- and three-level hierarchical control scheme [6–8] is the most common methods with diverse advantages and high robustness. The primary control level consists the independent local control loops of the devices to track the references. Usually, this level is decentralized and the adopted control strategies consists droop, real/reactive power (PQ), and voltage/frequency (VF) control. The droop-based primary control level requires variation of the microgrid's voltage and frequency from its nominal references for independent stable operation. Therefore, the secondary control level is adopted

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to compensate the deviations. This control level may have centralized, decentralized, and distributed architecture.

In centralized control architecture, the local controller of the devices and resources in the microgrid communicates with a fusion center as the control center to report the states and the measurements and to receive the control signals. Clearly central architecture can provide some advantages such as comprehensive and optimal decision-making for microgrid operation. Yet, the operation and stability of the microgrid would be highly dependent on the performance of the control center. Failures of the control center and communication structure results in low reliability and can cause instability [8,9]. Besides, large-scale computational requirements as well as the complexity and cost of the communication structure are some other burdens of centralized architecture for high number of DERs in a microgrid [8]. Decentralized and distributed control architectures eliminate the dependence of the microgrid on a control center while a distributed control scheme also exploits the advantages of communications between the agents.

Consequently, the control decisions are made based on the local data and limited communication with the neighbors [9–12]. Also, the computations and data analysis are manipulated in a distributed approach.

Various advantages of distributed control systems and communication architectures inspire its application in microgrids [13–26]. A distributed secondary with primary droop control was presented by [13] for a microgrid. Impact of communication delay and data loss was studied by [13]. Decentralized optimal *PQ* control in a microgrid was investigated using the Lagrangian relaxation technique [14]. A distributed control for DGs of an islanded microgrid was demonstrated in [15,16] and local controllers were designed using the approach presented in [17]. Moreover, cooperative control was investigated for power management of a microgrid [27–29]. In [27,28], output power of DGs was regulated cooperatively after clustering the DGs, in which each cluster has some specific tasks. In [18,19], distributed cooperative control with optimum power dispatch was applied to a microgrid.

Application of multiagent systems (MAS) in management of a microgrid has also studied by the literature [21–26,30–33] and was used for distributed/decentralized control of the DERs, optimal active and reactive power dispatch, voltage profile regulation, and energy management issues. MAS was used to control the frequency of a microgrid in islanded mode by [22], in which DGs was able to communicate locally. An MAS-based secondary control of an islanded microgrid is investigated in [23] using a two-layer scheme to balance the power of the microgrid by measuring the loads and the generations. For constructing a communication network, a design approach is provided. However, the control law has to be redesigned for a new configuration of the communication network (CNet). Also, all loads and DGs have to be connected to an agent and the CNet in order to gain stability and power balance. The number of DGs and loads are equal, and the stability of the microgrid is degraded if the V/F DG is not ready for service. Further, an MAS-based DCS has been used for a system of multiple microgrids [24] in which the microgrids and the transmission lines were equipped with individual agents.

A finite-time secondary frequency controller was designed using the hard-switching discontinuous sign function in which the control output switches between two bounds [34]. This approach may result in the high frequency fluctuations as chattering, due to its bang-bang output.

Combining the cooperative DCS with MASs, a secondary voltage control was developed in [25] using feedback linearization design technique and optimal state-feedback control. Also, a MAS-DCS leader-following management framework is designed for voltage/frequency and power control of voltage-source and current-source converters respectively [26]. A cooperative MAS-DCS is proposed in [30] using a leader-follower architecture to regulate the voltage and frequency, and to share the power mismatch in a distributed manner [31,32].

A secondary control scheme with finite-time frequency regulation and asymptotic voltage regulation using a distributed voltage observer was developed [31]. This enables the control designs to be separated for the voltage and frequency [31]. The input-bounded finite-time controller was constructed adopting the fractional powers, the discontinuous sign function, and the saturation constraints.

Furthermore, the sufficient conditions for stability of the pinning-based voltage/frequency controller and the consensus-based power controller was presented in [32] assuming a time-varying CNet with non-uniform delays. The maximum delay for asymptotic stability of the distributed voltage observer, and then for the microgrid with the proposed controller was derived [32]. Furthermore, the conventional voltage control is incapable of sharing the reactive power demand, due to effect of the line impedance. Accurate sharing of the reactive power was proposed in [31,32] in addition to regulating the weighted average voltage of DGs, which accounts for the effect of the line impedances.

The secondary controller schemes presented in [25,26,30–33] are the fully-distributed MAS-based approaches in which the all-to-all communication is not necessary as well as the fusion center. Furthermore, the establishment of an intermittent sparse CNet containing a spanning tree is sufficient for stable operation of the microgrid with the distributed secondary control methods [25,26,30–33] which confirms these methods are fully distributed approaches.

Considering the conventional synchronous generators and the inverter-interfaced DERs in an ac microgrid, a control hierarchy was implemented to replicate the functions of the optimal dispatch [35,36] at the third control layer in a distributed architecture, as well as the frequency regulation at the second control layer [36,37]. The optimal dispatch was developed in an event-triggered scheme to eliminate the unnecessary control efforts. The optimal dispatch and the frequency regulation was implemented in a distributed fashion using a ratio-consensus algorithm to update the output active power of the *i*th distributed resource, proportional to the difference between the incremental minimum and maximum power output of that resource [36]. Although the same approach can be utilized for reactive power dispatch, voltage regulation and reactive power control is not discussed by [35–37]. Besides, the ratio-consensus yields asymptotic frequency control whereas the convergence time is greater than the finite-time controllers.

In this paper, a robust secondary controller is designed to regulate the voltage and frequency of an islanded microgrid. The control scheme has a hierarchical decentralized architecture with cooperative secondary and droop-shaped primary. However, the uncontrollable and uncooperative DERs are also considered in this study to realize a partially-cooperative microgrid which is more demanding and realistic compared to current studies. Moreover, essence of a management center is eliminated by pinning the reference. Each agent can play the coordinator role by pinning the reference. This provides high reliability and robustness against DG outage and communication failures.

In the proposed distributed leader-following scheme, the DGs are connected with its neighbor DGs through the CNet and updates its output with respect to state of the neighbors. For stable operation of the microgrid, it is required the CNet implies a digraph containing a spanning tree, and there exist at least one virtual leader connected to the CNet which cannot receive information from all