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A distributed secondary scheme with terminal sliding mode controller for energy storages in an islanded microgrid

Amin Mohammadpour Shotorbani [a,*], Saeid Ghassem-Zadeh [a], Behnam Mohammadi-Ivatloo [a], Seyed Hossein Hosseini [a,b]

[a] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Engineering Faculty, Near East University, Nicosia, North Cyprus, Mersin 10, Turkey

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ABSTRACT

Different levels of the stored energy is the main challenge in control of the distributed energy storages (DESs) in an islanded microgrid. The conventional power-droop and the secondary distributed controllers of distributed generators (DGs) does not consider the long time-span dynamics of state of charge (SoC) of the DESs. Subsequently, the DESs with lower initial SoCs are discharged before other DESs. Besides, the SoC-droop primary control results in further deviation of the frequency of the microgrid. In this paper, the secondary control scheme is employed to share the power mismatch, match the SoCs of the DESs, and regulate the frequency and voltage of the microgrid. The proposed scheme has distributed cooperative architecture, and employs distributed terminal sliding mode controller (DTSMC) for the state regulators, and proportional controller for distributed power-sharing and SoC-matching. The proposed scheme organizes the controllable DGs, the DESs with limited SoCs, and the uncooperative DGs with unknown generation, through communicating between the neighbor cooperative DGs and DESs. Performance of the designed DTSMC is verified for the changes of communication topology, time-delays, data drop-outs, load variations, and external disturbances. DTSMC provides finite-time convergence, fast transients, and improved robustness.

1. Introduction

The expanding utilization of distributed generation (DG) and renewable DGs entails employment of distributed energy storage (DES) systems, for economic compensation of the renewable generation and variable demand. The concept of microgrid has recently been introduced as the main solution for establishing the requirements to organize the DGs and the DESs [1]. A microgrid replicates a scaled-down power system, which can further disconnect from the main grid to operate in islanded mode and synchronize with the main grid to reconnect [2].

Besides, DES systems are progressively implemented in many aspects of microgrids utilizing sustainable and renewable energy [3]. DESs are flexible elements to improve the quality and reliability of microgrids through uninterruptable supply of loads [4]. DES provides a fundamental back-up in grid forming generation and black start, in addition to the merits of peak shaving, smoothing the renewable generation, improving the grid efficiency and reliability, and congestion management [5,6].

To extend the life cycle of the costly DES, its operation requires further considerations, especially the SoC level of the DES unit, to avoid deterioration of the battery life during different modes. Maintaining the SoC of the DES unit within a safe range (e.g. between 10% and 90% or 20% and 80%), ensures its state of health and high efficiency [5,6]. The certain range is determined based on the production technology, and operation history [6].

The DES units with SoCs tending beyond the allowable safe range are forced to disconnect, to avoid the consequent damages. Matching the SoC level of multiple DESs during the course of the operation, avert the charging and discharging of specific DESs more than the others. Accordingly, the SoC-balancing consistently maximizes the power capacity of DESs, and establishes contribution of all DESs during the operation.

Sharing the power demand between DESs of a microgrid, results in early discharge of the energy of certain DERs [5–7]. With standard power droop control, the energy of the DESs with lower initial SoC is discharged earlier than the DES with higher initial SoC, and thus cannot contribute in power-sharing any longer. Besides,

* Corresponding author.
E-mail address: a.m.shotorbani@tabrizu.ac.ir (A.M. Shotorbani).

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operation of the DESs at a low SoC degrade the lifespan service and efficiency of the DES [8]. SoC of a DES is also influenced by the remaining expiration duration, the environment temperature, operational efficiencies for the charging and discharging of the DES.

In an islanded microgrid, high penetration of distributed energy resources (DERs) necessitates supplementary control loops to compensate for its low equivalent inertia and improve the stability of the microgrid. Different control schemes has recently been introduced to enhance the stability and improve the power quality of an islanded microgrid [9]. The decentralized architectures with hierarchical control schemes exploit the diverse advantages of the microgrid, provide scalability, and improve the stability and reliability of the microgrid both in islanded and grid-connected mode [10]. In hierarchical control of the microgrid, the primary level consists the droop control to share the power mismatch in a decentralized scheme, whereas the secondary level can be used to compensate for the deviations in frequency and voltage caused by the primary power-droop control. The implementation of the secondary level can employ centralized, distributed and cooperative, and decentralized architectures.

Using a centralized architecture [11], the robust H-infinity controller design for the DERs in a microgrid was investigated, where the conventional droop was utilized for the frequency control loop, and the power management system and the power flow analysis was employed to design the DG output voltage references. Employing a full linearized state-space model of the microgrid, a centralized controller was proposed [12] to provide small signal stability, utilized by an optimal Kalman estimator. Genetic algorithm was used to optimize the proposed linear quadratic centralized controller. A cooperative control of DESs was proposed employing a SoC-droop and centralized PI control during discharging and charging modes, respectively. SoC-droop avoids prompt depletion of an individual DES, and PI control limits the power absorption to provide power balance. Reactive power sharing is achieved using virtual impedance method [13]. In a centralized architecture [14], the current error was directly added to each DER converter in order to eliminate the output current error by modifying the voltage reference. However, centralized architecture restricts the scalability, system expansion and redundancy of the microgrid. Stability of microgrid with centralized control is highly dependent on the CSN limitations and failure of the control center. Likewise, the centralized SoC-matching methods are inappropriate for the microgrids with high penetration of DERs, due to the limitations in scalability and CSN costs. The necessity to employ the detailed global microgrid model to design the local controllers in [15], reduces the plug-n-play capability of the DERs and restricts the scalability of the microgrid.

Distributed architecture with cooperative scheme has been widely investigated for power management of a microgrid. Reduction in communication costs for high penetration of DERs, unchallenging scalability, and improved reliability are some advantages to inspire the application of distributed architectures at the secondary control level [16]. Multi-agent system (MASs) could be a valuable asset in control of a microgrid, using a distributed architecture. The DGs in a microgrid can be considered as agents of an MAS, due to their attributes, such as: limited functionality for global achievements, reactivity in satisfying local objectives, proactivity toward universal goals, and the capability of interacting with other agents. In view of MASs, the secondary controllers for microgrid frequency and voltage regulation and the power-sharing can be modeled as tracking synchronization problem between the agents, since all agents are aimed to synchronize to a leader using local communications with neighbor agents [17–19].

Through offline clustering of the photovoltaic DGs in a microgrid [20], the output power of DGs was controlled to regulate the voltage profile and optimize the reactive power demand from the main utility. In this scheme, the photovoltaic DGs of each cluster have a predefined task and a leader DG.

The exact regulation of voltage in a microgrid, disturbs the droop-based reactive power-sharing, due to impact of line impedances on the power flow. In order to share the reactive power demand and restore the voltage deviation, a consensus-based approach was proposed to regulate the average weighted voltage of the DERs [21–24], instead of regulating the exact voltage magnitude. These schemes share the reactive power mismatch accurately, and regulate the average voltage, using a distributed architecture.

Employing a distributed voltage observer, a voltage controller with asymptotic convergence was designed to regulate the microgrid average voltage [21]. Moreover, frequency and voltage control loops was decoupled using finite-time and asymptotic control schemes for frequency and voltage regulation, respectively [21]. The suggested finite-time controller takes an input-bounded and saturation-based scheme. Supposing a time-varying CSN and communication time-delays, the sufficient stability conditions for the pinning control of voltage and frequency, and the consensus-based control of power was discussed for the designed controller [22]. The unallowable delay in CSN of the distributed voltage observer was calculated considering asymptotic stability of the suggested voltage control loop [22]. Using the conventional PI control, a distributed controller with asymptotic convergence was designed [23]. In this scheme, it is required to communicate the average frequency, voltage, and reactive power of all the DGs in the microgrid to each DG through the CSN [23]. The secondary frequency regulation and the average voltage control with the distributed architecture proposed in [24] both yield asymptotic convergence of the system states, with a large settling time, compared to finite-time controllers.

Besides, instead of the conventional $E-Q$ droop, the $E-\int Qdt$ droop was designed at the primary control level, to eliminate the error in sharing the reactive power demand [25].

For secondary regulation of the microgrid voltage, the MAS was adopted and a cooperative distributed scheme was proposed [17]. A distributed optimal state-feedback controller was designed based on the feedback linearization technique, which converts the voltage regulation to a tracking synchronization problem [17]. MAS-based average consensus was established to estimate the active power mismatch in an islanded microgrid [18]. Then the frequency controller was designed regarding the power mismatch and considering the constraints of the communication system network (CSN) [18]. Using a directed CSN and a leader-follower architecture, a distributed secondary controller was developed [19,26] using proportional control scheme, to regulate the frequency and voltage of a microgrid and share the active power demand, with asymptotic [19] and finite-time convergence [26]. In [27], a robust discrete-time controller was investigated to compensate for the time-varying couplings and uncertainty of the CSN links. In [28], a ratio-consensus distributed algorithm was developed to regulate the frequency of ac microgrids, considering the inverter-based DGs as well as the synchronous generators. In this approach, the output active power of each DER is proportional to its incremental bound [28].

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