



A generalized descriptor-system robust H_∞ control of autonomous microgrids to improve small and large signal stability considering communication delays and load nonlinearities

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ABSTRACT

This paper presents a descriptor system H_∞ approach to enhance performance of robust H_∞ controller and previously-reported decentralized robust servo-mechanism (DRSM) control scheme for autonomous voltage sourced converter (VSC)-based microgrids including multiple distributed energy resources (DERs). The power management system specifies voltage set points for local controllers and the frequency of each DER unit is specified by a hierarchical droop-based control structure. A descriptor system H_∞ robust controller is designed based on a closed-loop representation of microgrid either with H_∞ or DRSM controller for set point tracking, disturbance rejection and improving performance of microgrid for small/large-signal disturbances and nonlinear loads. Here, unlike some of the previous researches, the load current is modeled as disturbance and also communication time-delay is considered. The theoretical concepts of proposed control strategy, including mathematical modeling of microgrid, basic theorems, and design procedure are outlined. Then, design problem is formulated by a set of linear/bilinear matrix inequalities and then solved using a new iterative algorithm in the form of convex optimization problem. To demonstrate effectiveness of the proposed control scheme, offline time-domain simulation studies are performed on a multi-DER microgrid in MATLAB/Simulink environment and also the results are experimentally verified by OPAL-RT real time digital simulator.

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1. Introduction

1.1. Motivation and incitement

Due to technical, environmental, and economic reasons, an increasing interest is shown by energy sector in adopting micro and smart grid technologies, such as novel control and protection techniques and advanced communications to enhance the efficiency and reliability of future electricity grids [1–3]. Microgrid is a small-scale power grid in the low voltage that must be able to locally solve energy issues and enhance the flexibility and can operate either in grid-connected or islanded (autonomous) mode of operation [4–7]. Particularly, the DER units are forming building blocks for the smart microgrids that can include renewable energy sources (REs) and energy storage systems (ESS) [8–10]. However, severe concerns over stability, control, and efficiency of microgrids have been raised with the coexistence of multiple DER units with different dynamic features [10,11]. In this regard, several issues

regarding microgrid resiliency are concerned such as fault ride through (FRT) capability, inclusion of nonlinear and unbalanced loads, communication time-delay (CTD), power sharing and advanced microgrid power-flow methods [6–7,10–12].

1.2. Literature review

Several strategies have been reported to control the VSCs in the microgrids [6–7,10–24]. Droop-control method uses small-signal modeling, works mainly based on local measurements and almost obviates need for high-bandwidth communication [4,6,7,10–23]. However, it has several limitations such as lack of stability when load dynamics are considered, weak transient performance, and lack of black start capability [11,18,24]. Centralized control demands high-bandwidth communication and thus, failure in communication system lead to system collapse [25,26]. Also, Master-Slave control strategy has been reported which is flexible for connection/disconnection of DER units; but, it requires dominant DER unit for suitable operation [27,28]. Robust servomechanism and multivariable controllers provides some improvements for robustness against microgrid uncertainties.

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However, it still depends on dominant DER unit and still cannot be used practically [28]. In the decentralized control that is preferred over the centralized one from reliability and redundancy points of view, each DER unit has its own local controller (LC), which is not necessarily aware of the whole microgrid system. Hierarchical control is a tradeoff between centralized and decentralized control methods. The hierarchical droop-based control (HDRC) scheme of microgrid is overallly organized in primary, secondary and tertiary levels [6,7,11,13,14]. The primary control level exploits the droop control to provide power sharing between DERs and regulate voltage and frequency deviations according to the load demand. In the secondary control, the frequency and amplitude deviations are restored. The tertiary control performs power management between microgrid and upstream grid and regulates the power sharing between the microgrid and main grid at the point of common coupling (PCC) [6,7,11,13,14,24]. The secondary control can perform cooperative characteristics to restore the microgrid voltage and frequency, so that each DER unit acts as an agent, which operates together with other agents to achieve a common goal [13–15,29]. When the communication latencies are considered, the distributed secondary control performs better in contrast with the conventional central one [30,31]. The impact of CTD on secondary frequency control in a proportional integral (PI)-based centralized control structure has been studied [21]. Also, a centralized robust secondary control scheme has been developed for frequency restoration, considering variable and unknown CTD and using a phase-locked loop (PLL) to obtain frequency at bus loading [22]. Later, a distributed control structure, including primary and secondary control levels, has presented based on small-signal modeling of islanded microgrid using delay differential equations (DDEs), and by applying consensus algorithm for secondary level that exploits a data network to present CTD based on graph theory [23]. Also, by combining decentralized droop-based PI control with distributed averaging, a distributed averaging proportional integral (DAPI) controller has been proposed for secondary frequency and voltage control in islanded microgrids [32]. In the reported literature, microgrids have been studied based on small-signal modeling for normal condition or small-signal events; however, no solution has been presented to maintain the stability of the system in large-signal disturbances. Moreover, in the electrical distribution systems and especially in microgrids, load is parametrically uncertain and topologically unknown and so, it is a source of dynamics that cannot be modeled exactly [27]. However, it is assumed that load current is measurable and bounded. More importantly, in most of the reported researches [15,17,18,27,28], the communication time delay (CTD) has been ignored or at least have not been discussed in detailed. Practically, the microgrid stability margins are decreased by CTD which may lead to instability [27,33].

1.3. Contribution and paper structure

This paper presents a new add-on feature for two kinds of robust control schemes namely H_∞ controller and the previously-reported DRSM controller based on a new descriptor-system H_∞ approach not only with considering CTD, but also by modeling the load current as disturbance (unlike the previous methods that easily modeled a constant RLC load [18]). The presented control scheme aims to enhance microgrid dynamic performance for small and large-signal disturbances, improve FRT capability and guarantee the desired power sharing, under unbalanced and nonlinear load conditions. Also, unlike [18] that uses an open-loop frequency control and synchronization scheme, here, for all LCs of DER units, a HDRC scheme provides amplitude and frequency of the sinusoidal reference signal to provide desired proper power sharing. The controller design problem based on descriptor-system H_∞ approach is expressed based on a delay-dependent bounded real

lemma (BRL) and then, the basic theorem is outlined to express the design problem as a bilinear matrix inequality (BMI). After that, a new iterative algorithm is proposed based on convex optimization to convert the BMI problem to a linear matrix inequality (LMI) for the sake of finding controller parameters. Finally, the effectiveness of the proposed control scheme is evaluated by off-line time-domain simulation studies performed in MATLAB/SIMULINK environment and experimental real-time verification by OPAL-RT real time digital simulator (RTDS).

The rest of this paper is organized as follows. Section 2 describes the structures of the microgrid, proposed control strategy and power management system (PMS). Dynamic model of the microgrid is presented in Section 3. Section 4 elaborates on the proposed controller based on the descriptor-system H_∞ control of microgrid system with robust H_∞ and modified DRSM control schemes considering CTD and presents basic lemma, controller design procedure, theorems for closed loop stability analysis of multi-DER robust H_∞ -controlled and DRSM-controlled microgrids. Verification of the performance and viability of the proposed method, based on offline time-domain simulations and experimental real-time verifications, are presented in Section 5. Finally, conclusions and discussions are stated in Sections 6 and 7, respectively.

2. Study system

In [18], a control strategy has been proposed for a typical multi-DER radial microgrid system, including a general PMS, DRSM-based LC and frequency control/synchronization scheme. The independent oscillator of LC controls the microgrid frequency in an open-loop manner and all oscillators are synchronized by a common time-reference signal based on global positioning system (GPS). However, using GPS-based synchronization/frequency controller is sometimes impossible or at least cumbersome. Moreover, decentralized HDRC schemes can resolve previously drawbacks of the centralized control and conventional droop-based controllers and require only a low-bandwidth communication system. Anyway, the CTD may result in microgrid instability. Even though the open loop frequency control and synchronization scheme of [18] is used, the effect of CTD is considerable.

2.1. Structure of proposed control strategy

Fig. 1 illustrates the structure of the proposed control strategy. The author aim to design controller $K(s)$ (that is derived from robust H_∞ -based and DRSM-based controllers of [27,33] and [18], respectively) to achieve to the desired performance, enhance system stability and moreover, minimize the effect of disturbance on the output voltages considering the effect of CTD. In [27], a two-degree of freedom (2DOF) control scheme has been presented with two different controllers for plants G and G_d while in this paper, the goal is to realize the abovementioned objectives with one controller shown in Fig. 1(a), based on a descriptor system H_∞ controller for an autonomous multi-DER microgrid. Here, the problem is to propose a descriptor-system H_∞ solution for robust H_∞ and DRSM controllers considering CTD, not only for robust stabilization and disturbance attenuation, but also for reference tracking and improve microgrid performance for small and large-signal disturbances and nonlinear loads. The proposed descriptor-system H_∞ controller is used in the inner control loop of HDRC structure to enhance the stability and track the references values (Fig. 1(b)) [11,24]. More details for the HDRC structure and its parameters are provided in [6,7,11,24]. As shown in Fig. 1(b), active and reactive powers of DER unit are passed through low-pass filters (LPFs) with cut off frequency of 10 Hz to suppress high frequency ripples.

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