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Fixed-order decentralized/distributed control of islanded inverter-interfaced microgrids

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ABSTRACT

This paper focuses on the problem of voltage control of islanded inverter-interfaced microgrids consisting of several distributed generation (DG) units with radial structure. The main objectives are to (i) design a decentralized/distributed voltage controller with minimum information exchange between DG units and their local controllers (ii) design a fixed-/low-order dynamic output feedback controller which ensures stability as well as desired performance of the microgrid system in spite of load parameter uncertainties. To this end, the problem is formulated as an optimization problem which is the minimization of the cardinality of a pattern matrix subject to an H_∞ performance constraint. Since the problem is intrinsically non-convex, a convex optimization-based design procedure for the controller synthesis is proposed in this paper. The effectiveness of the proposed controller is evaluated through simulation studies and Hardware-In-the-Loop (HIL) verifications. The simulation and experimental results demonstrate the effectiveness of the proposed control strategy.

1. Introduction

Nowadays the growth of electricity demand, the critical shortages of fossil fuels, and global warming caused by greenhouse-gas-effect have negatively impacted on conventional power systems. The problems have been tackled alternatively through an efficacious integration and coordination of distributed generation (DG) units such as photovoltaics (PV), and wind power.

Reliable integration of DG units into power systems can be achieved by means of microgrids which are small electrical networks heterogeneously composed of DG units, loads, and energy storage systems (Olivares et al., 2014). Renewable energy sources are normally interfaced to the microgrid through power electronic converters acting as voltage sources (Guerrero, Chandorkar, Lee, & Loh, 2013).

Microgrids normally operate in grid-connected mode where they are connected to the main grid at Point of Common Coupling (PCC). Under this connection scheme, the microgrid voltage and frequency are predominantly determined by the main grid while the microgrid control system accurately shares active and reactive power among DG units and controls the power exchange between the microgrid and the main grid. Due to intentional (scheduled)/unintentional reasons, the microgrids can experience islanding conditions where they are disconnected from the main grid (Yazdanian & Mehrizi-Sani, 2014). In this case, due to the power mismatch between the DGs and the loads, voltage and frequency of the loads deviate from their rated values and the islanded microgrid eventually becomes unstable. This operation mode of microgrids is more challenging than the grid-connected mode because accurate load sharing mechanisms are required to balance the power mismatch (Olivares et al., 2014). Therefore, upon the islanding condition, a new microgrid control strategy must come into service in order to provide voltage and frequency stability as well as a proper power sharing among DG units (Bidram, Lewis, & Davoudi, 2014).

A control strategy ubiquitously used for the control of microgrids is droop control which relies on the principle of power balance of a classical synchronous generator in conventional power networks (see, e.g., Guerrero, Chandorkar et al., 2013; Guerrero, Loh, Lee, & Chandorkar, 2013, Guerrero, Vasquez, Matas, Castilla, & de Vicuna, 2009; Guerrero, Vasquez, Matas, de Vicuna, & Castilla, 2011; Majumder, Ledwich, Ghosh, Chakrabarti, & Zare, 2010; Lee, Chu, & Cheng, 2013; Lopes, Moreira, & Madureira, 2006; Piagi & Lasseter, 2006; Savaghebi,

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Jalilian, Vasquez, & Guerrero, 2013; Vasquez, Guerrero, Luna, Rodriguez, & Teodorescu, 2009; Vasquez, Mastromauro, Guerrero & Liserre 2009). In the power systems based on rotating generators, frequency (rotor speed) is dependent on active power balance, i.e. the frequency is dropped when the demanded active power increases (Kundur, Balu, & Lauby, 1994). The idea of the so-called "droop" controllers has been developed by Chandorkar, Divan, and Adapa (1993). From a control point of view, droop control is a decentralized proportional controller maintaining the voltage and frequency stability of the microgrids (Schiffer, Ortega, Astolfi, Raisch, & Sezi, 2014). The main advantage of droop-based control is the elimination of the communication links among DG local controllers. Nonetheless, the droop-based approaches suffer from several drawbacks including (i) poor transient performance, (ii) poor performance for mixed-line microgrids with resistive–inductive line conditions, and (iii) coupled dynamics between active and reactive power.

In addition to the droop-based control strategies, non-droop-based approaches for voltage and frequency control of the islanded microgrids have also been developed, e.g. Pogaku, Prodanovic, and Green (2007), Karimi, Nikkhajoei, and Iravani (2008), Karimi, Davison, and Iravani (2010), Karimi, Yazdani, and Iravani (2011), Moradi, Karimi, and Karimi-Ghartemani (2010), Etemadi, Davison, and Iravani (2012, 2014), Bahrani, Saeedifard, Karimi, and Rufer (2013), and Babazadeh and Karimi (2013). The proposed methods regulate the voltage of single-DG-unit (Bahrani et al., 2013; Babazadeh & Karimi, 2013; Karimi et al., 2008, 2010; Moradi et al., 2010) and/or multi-DG-unit microgrids (Etemadi et al., 2012, 2014). In these methods, the frequency of each DG unit is controlled through an internal oscillator in the open-loop manner with $\omega_0 = 2\pi f_0$, where f_0 is the nominal system frequency. All oscillators are synchronized by a common time reference signal according to a global positioning system (GPS) (Etemadi et al., 2014).

Although extensive research has been carried out on the development of non-droop-based control of microgrids, they suffer from one or more of the following drawbacks: (i) inability to guarantee robust stability and/or robust performance with respect to load parameter variations (Bahrani et al., 2013; Etemadi et al., 2012; Karimi et al., 2010). (ii) inapplicability to multiple-DG microgrids, e.g. Bahrani et al. (2013) and Karimi et al. (2010), (iii) high-order controllers, e.g. Moradi et al. (2010) and Babazadeh and Karimi (2013), and (iv) centralized control strategy, e.g. Pogaku et al. (2007).

To overcome the disadvantages of the existing microgrid control approaches, various challenges associated with robustness to load parametric uncertainties, design of decentralized or distributed controllers with minimum communication links among DGs, and low-complexity of the local controllers must be addressed. Therefore, the problem of microgrid control is translated into fixed-/low-order decentalized/distributed controller design of interconnected systems with parameter uncertainties.

In the distributed control strategy, there exist several communication links between the local controllers and the subsystems according to the control structure. Most of the available distributed control approaches assume that the control structure is given *a priori* (Skogestad & Postlethwaite, 1996). However, it is possible that the assumed control structure is not the best one which can be taken into consideration. Moreover, it is generally difficult to select the structure of the controller in advance. Therefore, the question arises is that in an interconnected system, what is the best control structure, in terms of the connections between the local controllers and the subsystems, to satisfy the given control objectives?

This question has been recently addressed by some researchers in Schuler, Gruhler, Münz, and Allgöwer (2011), Fardad, Lin, and Jovanovic (2011), Lin, Fardad, and Jovanovic (2013), Schuler, Münz, and Allgöwer (2012), and Schuler, Li, Lam, and Allgöwer (2011). They have focused on the problem of sparse static output/state feedback controller design where the gain between the subsystems' inputs and outputs/states is sparsified (Fardad et al., 2011; Lin et al., 2013; Schuler et al., 2012, 2011). In this way, the amount of information exchange between subsystems and the controller is reduced. The results of Schuler et al. (2011) are extended to sparse dynamic output control design by Schuler et al. (2011). However, in Schuler et al. (2011) some parts of the controller structure, i.e. the structure of matrices A_c, B_c, and C_c, have been specified *a priori*. In all these approaches, the sparsity is formulated in terms of the cardinality of the gain matrix defined as the number of its non-zero elements. The communication links between the local controllers have not been considered in these approaches. Moreover, the robustness of the controller to system parameter uncertainties is another important issue which has not been taken into consideration. In an uncertain interconnected system, the control structure and the control parameters have to be designed for a prescribed family of models.

In this paper, a new LMI-based approach to the problem of fixed-order decentralized and/or distributed H_∞ control of interconnected systems subject to polytopic uncertainty is proposed. In this approach, the controller structure as well as the controller parameters are simultaneously designed. The objectives are achieved by transforming the problem into a non-convex optimization problem in which the number of non-zero elements (cardinality) of a pattern matrix is minimized subject to an H_∞ performance constraint. The non-convex cardinality of the pattern matrix is relaxed by a weighted ℓ_1 norm (Candes, Wakin, & Boyd, 2008) and an inner convex approximation of fixed-order H_∞ controllers for polytopic systems is then given. Therefore, the problem of fixed-order decentralized/distributed H_∞ controller design can be solved by finding a feasible solution of an iterative convex optimization problem. Then, the proposed robust fixed-order decentalized/distributed control strategy is applied to an LTI model of a microgrid in a rotating reference frame (*dq*-reference frame). The designed controller is able to overcome the limitations of the existing droop-based controllers which are only appropriate for microgrids with dominantly inductive and/or resistive power lines. Furthermore, opposed to most non-droop-based control methods, the controller guarantees the robust stability and robust performance against the load parameter changes. Simulation studies in MATLAB and experimental results using real-time hardware-in-the-loop (HIL) environment demonstrate the effectiveness of the designed controllers.

The organization of the paper is as follows. The problem formulation is presented in Section 2. A convex solution to the problem of fixed-order decentralized/distributed control of polytopic systems with guaranteed H_∞ performance is provided in Section 3. Section 4 is devoted to the design of robust fixed-order voltage controllers for islanded inverter-interfaced microgrids. Section 5 concludes the paper.

Throughout the paper, matrices I and 0 are the identity matrix and the zero matrix of appropriate dimensions, respectively. The symbols T and $\star$ denote the matrix transpose and symmetric blocks, respectively. For symmetric matrices, $P > 0$ ($P < 0$) indicates the positive-definiteness (negative-definiteness).