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Conditions for stability of droop-controlled inverter-based microgrids[☆]

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ABSTRACT

We consider the problem of stability analysis for droop-controlled inverter-based microgrids with meshed topologies. The inverter models include variable frequencies as well as voltage amplitudes. Conditions on the tuning gains and setpoints for frequency and voltage stability, together with desired active power sharing, are derived in the paper. First, we prove that for all practical choices of these parameters global boundedness of trajectories is ensured. Subsequently, assuming the microgrid is lossless, a port-Hamiltonian description is derived, from which sufficient conditions for stability are given. Finally, we propose for generic lossy microgrids a design criterion for the controller gains and setpoints such that a desired steady-state active power distribution is achieved. The analysis is validated via simulation on a microgrid based on the CIGRE (Conseil International des Grands Réseaux Electriques) benchmark medium voltage distribution network.

1. Introduction

Motivated by environmental, economic and technological aspects, the penetration of renewable energy sources into the electrical networks is increasing worldwide. Most of these sources are small-scale distributed generation (DG) units connected at the low voltage (LV) and medium voltage (MV) levels via alternating current (AC) inverters. As a consequence, the power generation structure is moving from purely large, centralized plants to a mixed generation pool consisting of conventional large plants and smaller distributed generation units. Since, in addition, the physical characteristics of inverters largely differ from the characteristics of conventional electrical generators (*i.e.*, synchronous generators (SGs)), new concepts and strategies to operate the electric power system that ensure a reliable and stable operation are needed.

The microgrid concept represents one promising solution to address these issues by facilitating local integration of renewable energy sources (Hatziargyriou, Asano, Iravani, & Marnay, 2007; Lasseter, 2002). In general, a microgrid gathers a combination of generation units, loads and energy storage elements at distribution level into a locally controllable system, which can be operated in a decentralized and completely isolated manner from the main transmission system. An autonomous or islanded microgrid is operated in such mode. The microgrid concept has been identified as a key component in future electrical networks (Farhangi, 2010). Furthermore, it is envisioned to greatly contribute to the implementation of numerous smart grid functions (Lasseter, 2011).

In this work we consider three important problems in such networks: frequency stability, voltage stability and power sharing. Power sharing is understood as the ability of the local controllers of the individual generation sources to achieve a desired steady-state

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distribution of their power outputs *relative* to each other, while satisfying the load demand in the network. The relevance of this control objective lies within the fact that it allows to prespecify the utilization of the generation units in operation.

A control technique widely used to address the problem of active power sharing in large power systems is droop control, also referred to as power–speed characteristic (Kundur, 1994). In droop control the current value of the rotational speed of each SG in the network is monitored locally to derive how much mechanical power each SG needs to provide. From a control perspective, droop control is a decentralized proportional controller where the control gain (known as droop gain) specifies the steady-state power distribution in the network. Since performance under droop control is satisfactory for large SG-based systems, this technique has been adapted to inverter-based grids (Barklund, Pogaku, Prodanovic, Hernandez-Aramburo, & Green, 2008; Chandorkar, Divan, & Adapa, 1993; Coelho, Cortizo, & Garcia, 2002; Soultanis, Papathanasiou, & Hatziargyriou, 2007).

In large SG-based transmission systems droop control is usually only applied to obtain a desired active power distribution, while the voltage amplitude at a generator bus is regulated to a nominal voltage setpoint via an automatic voltage regulator (AVR) acting on the excitation system of the SG. In microgrids the power lines are typically relatively short. Then, the AVR employed at the transmission level is, in general, not appropriate because slight differences in voltage amplitudes can cause high reactive power flows. As a consequence, the reactive power sharing among generation units cannot be ensured. Therefore, droop control is typically applied in microgrids to achieve also a desired reactive power distribution. The most common approach is to control the voltage amplitude with a proportional control, the feedback signal of which is the reactive power generation relative to a reference setpoint (Chandorkar et al., 1993; Coelho et al., 2002). See the recent survey (Guerrero, Loh, Chandorkar, & Lee, 2013) for further details.

The paper is devoted to the stability analysis of droop-controlled microgrids operated with the control laws given in Chandorkar et al. (1993). These droop control laws are heuristic control laws derived under the assumption of a dominantly inductive network, *i.e.,* for power lines with small R/X ratios, and they are (by far) the most commonly used ones in this scenario. If the network lines possess large resistive components, the standard droop control exhibits limitations (Guerrero et al., 2013). In this case, several modified droop controls (De Brabandere et al., 2007; Guerrero, Matas, de Vicuna, Castilla, & Miret, 2007; Zhong, 2013) have been proposed. Even in the presence of non-negligible line resistances the application of the droop controls of Chandorkar et al. (1993) and Coelho et al. (2002) can be justified, on one hand, via the virtual impedance approach (Guerrero, Garcia de Vicuna, Matas, Castilla, & Miret, 2005) while, on the other hand, invoking their analogy to conventional droop control (Engler, 2005) of SG-based grids.

As in any conventional power system, stability is understood in the sense of achieving asymptotic synchronization of the frequencies of all DG units, with the angle differences not exceeding $|\frac{\pi}{2}|$ and constant generated voltages (Kundur et al., 2004). Since the synchronization frequency is the same for all DG units and their dynamics depend on the angle differences, it is possible to translate – via a time-dependent coordinate shift – the synchronization objective into a (standard) equilibrium stabilization problem, which is the approach adopted in the paper.

Stability analysis of droop-controlled microgrids has traditionally been carried out by means of detailed numerical small-signal analysis as well as extensive simulations and experimental studies aiming to characterize a range for the droop gains guaranteeing system stability (Barklund et al., 2008; Coelho et al., 2002; Pogaku, Prodanovic, & Green, 2007; Soultanis et al., 2007). As pointed out in Guerrero et al. (2013), most work on microgrid stability has so far focused on radial microgrids, while stability of microgrids with meshed topologies and decentralized controlled units is still an open research area. For radial lossless microgrids, and under the assumption of constant voltage amplitudes, analytic conditions for proportional power sharing and synchronization of lossless microgrids with first-order inverter models have been recently derived – applying results of the theory of coupled oscillators – in Simpson-Porco, Dörfler, and Bullo (2013a). Conditions for voltage stability for a lossless parallel microgrid with one common load have been derived in Simpson-Porco, Dörfler, and Bullo (2013b).

For general meshed networks, with the aim to schedule the droop coefficients under the consideration of frequency droop, an iterative procedure based on bifurcation theory has been proposed in Diaz, Gonzalez-Moran, Gomez-Aleixandre, and Diez (2010). Under the assumption of constant voltage amplitudes, analytic synchronization conditions for a lossy meshed microgrid with distributed rotational and electronic generation are derived in Schiffer, Goldin, Raisch, and Sezi (2013) using ideas from second order consensus algorithms. A decentralized LMI-based control design for lossy meshed inverter-based networks guaranteeing overall network stability for a nonlinear model considering variable voltage amplitudes and phase angles, while accounting for power sharing, is provided in Schiffer, Anta, Trung, Raisch, and Sezi (2012).

The main contribution of the present paper is to give conditions on the droop gains to ensure stability of droop-controlled inverter-based microgrids with general meshed topology and inverter models with variable frequencies as well as variable voltage amplitudes. In contrast to Schiffer et al. (2013) and Simpson-Porco et al. (2013a,b), no assumptions of constant voltage amplitudes or small phase angle differences are made. In this more general scenario, the graph theoretic methods employed in the aforementioned papers are not directly applicable. Instead, we adopt a classical Lyapunov-like approach for analysis of stability of equilibria and boundedness of trajectories. Following the interconnection and damping assignment passivity-based control approach (Ortega, van der Schaft, Maschke, & Escobar, 2002; Schiffer, Ortega, Astolfi, Raisch, & Sezi, 2014), we represent the lossless microgrid system in port-Hamiltonian form (van der Schaft, 2000) to identify the energy-Lyapunov function and give conditions for stability of the frequency synchronization equilibrium state.

The present work extends our results in Schiffer et al. (2014) in several regards: first, conditions for global boundedness are given for lossy microgrids; second, we relate the spectral properties of the local network couplings between the phase angles and the active power flows of the microgrid in port-Hamiltonian form (which has a reduced state vector in relative coordinates) to those of the microgrid in absolute coordinates; third, making use of the global boundedness result, a relaxed stability condition for a lossless microgrid under a specific parameter selection of the controller gains and setpoints of the frequency droop control is derived; finally, the theoretical analysis is illustrated via detailed simulation scenarios.

The remainder of the paper is organized as follows. The network model is presented in Section 2. In Section 3 we give the model of the inverter and the droop control. Section 4 presents conditions for global boundedness of trajectories. Sufficient conditions for stability for lossless microgrids are established in Section 5. In Section 6 we propose a selection of the droop gains and setpoints, similar to the one given in Simpson-Porco et al. (2013a), that ensures the DG units share (in steady-state) the active power according to a specified pattern. Compared to Simpson-Porco et al. (2013a), we extend the proof to lossy networks, *i.e.,* networks with nonzero conductances. Our analysis is validated in Section 7 with