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Robust multiobjective control method for power sharing among distributed energy resources in islanded microgrids with unbalanced and nonlinear loads

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ABSTRACT

This paper proposes a robust control method for power sharing among dispatchable electronically-coupled distributed energy resources (DERs) in an autonomous microgrid. The DER units operate in parallel to meet the total aggregated load demand. The aggregated load is assumed to be uncertain, unbalanced and/or nonlinear, thus it is considered as a source of unmodeled dynamics. The main objective of this paper is to design an H_∞ robust controller to enable tracking reference commands of the voltages at the output of the DERs in the presence of unmodeled dynamics. In addition, the H_∞ control design problem is combined with other control methods, such as constrained optimal control and regional pole placement, to achieve an optimal control objective, and to improve transient response. The optimal controller is achieved by minimizing an upper bound on H_2 performance. The regional pole placement is achieved by defining a linear matrix inequalities (LMI) region. This multiobjective H_2/H_∞ problem, combined with regional pole placement are expressed as a set of LMIs, and solved by using standard convex optimization algorithms. To show the effectiveness of the proposed method in maintaining the desired voltage at the DER outputs, in presence of unbalanced and nonlinear loads, simulation results are provided for a single DER unit, and the performance of the proposed control strategy is compared with three different controller strategies. Power sharing among multi DER units in autonomous networks is then demonstrated through digital time-domain simulation studies using MATLAB/SimPowerSystems Toolbox.

1. Introduction

Autonomous power grids are viable means of electrifying remote communities due to the infeasible interconnection with the main power network and/or economic reasons. The common choice for supply of electricity in these remote communities has been fossil-fuel generation [1]. Recently, integration of renewable generation technologies has become a preferred option for economical, technical, and environmental reasons. An acceptable alternative for integrating distributed energy resources (DERs) are microgrids [2].

A microgrid can be defined as a cluster of DER units, energy storage units and (local) loads that can be controlled as a single integrated control system. A microgrid may operate in grid-connected or islanded modes [3]. Most modern DER units use voltage source converters (VSCs), which acts as an interface between the energy source and AC grid, and hence a substantial amount of research has been alloted to control of converter-based DER units, in particular control of islanded-mode microgrids [4–11].

It is well-known that converter dynamics are highly nonlinear, due to switching action (and also due to possible saturation of pulse width modulation (PWM) signals), however, the model usually used to design control strategies is a linearized model about an operating point. Linearized models allow for simpler and lower cost linear controllers compared to nonlinear models. Linear models commonly neglect high frequency ripples (which is valid because the switching frequency is relatively much higher than the system dynamics [12]). Regardless of the type of model used, in most cases, a load connected to a DER system might be topologically unknown or structurally uncertain. Although the load current can be measured, the load dynamics may be nonlinear and in some cases (e.g. a rectifier unit) difficult to model. In order to take into account the overall system uncertainties or unmodeled nonlinearities, robust control of electronically-coupled DER units has been investigated [11,13–16].

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The robust control objective, or H_∞ performance, such as disturbance attenuation [4] and loop shaping [6], may be designed in frequency domain. However, design of H_∞ controller in frequency domain provides little control over assigning closed-loop poles location (region), and thus the transient response behavior may not be able to be shaped [17]. Transient response behavior can usually be achieved by forcing the poles of a closed-loop system to lie in certain region of s-plane. In addition, it may be also desirable to place a bound on the energy of the input signal to avoid actuator saturation; this is achieved in this paper by considering H_2 performance. It is important to note that a special case of H_2 synthesis is the very well-known LQR problem [18], which, unlike H_∞ synthesis, cannot cope with system uncertainty. To solve a control problem which embodies a multi objective H_∞ and H_2 problem with pole placement constraints, LMI (linear matrix inequalities [19]) synthesis is used in this paper. Using LMIs, a multiobjective problem of minimizing H_2 performance at a specified H_∞ performance, and regional pole location can be formulated and solved. In this paper, we solve the set of LMIs by using MATLAB, which employs efficient interior-point optimization algorithm [20]. The outcome of the LMI synthesis in this paper is state-feedback controllers for islanded dispatchable DERs that robustly satisfy the following objectives:

- Stability.
- Attaining H_∞ disturbance rejection, at a desired level.
- Placing the closed-loop poles into a suitable region in the left-half s-plane for satisfactory time response.
- Reducing the control effort by minimizing the H_2 norm.

The results of this paper draw from the advances in the area of robust and multiobjective control via LMI optimization [17,21–23]. This paper makes contributions in the area of robust control design for dispatchable DER units operating in autonomous (islanded) mode. It systematically formulates the problem of robust state-feedback H_2/H_∞ controller synthesis with the regional pole placement technique reported in [17] suitable for a class of systems with converter-based DER units and unknown load dynamics. The aforementioned objectives are crucial for reliable operation of DERs in islanded microgrid where the local loads may not be necessarily three-phase balanced loads. Thus, the control strategy proposed in this paper guarantees satisfactory performance in presence of *unbalanced* and *harmonically polluted* loads. This is a significant contribution because without dealing with load dynamics adequately, the output voltages of the DERs become polluted with harmonics, thus the power quality deteriorates. The contribution of the paper can now be summarized as follows:

1. The proposed control strategy in this paper is specifically designed to mitigate the effect of *unbalanced* or *harmonically polluted* loads. This is the main contribution of this paper, and the proposed controller can be used for electronically-coupled DERs in islanded microgrids, where the aggregated local loads may not be balanced. This is made possible by the robust H_∞ control design proposed in this paper, which can minimize the adverse impacts of the harmonics caused by *unbalanced* and *harmonically polluted* loads.
2. The designed H_2 controller guarantees that the control inputs do not violate the PWM saturation limits.
3. Using this method, a satisfactory *transient response* for the DER unit can be obtained by bounding the rise time, settling time and maximum overshoot.
4. This paper proposes a frequency control strategy, which together with conventional frequency/power droop control is able to control parallel multi-DER units in an islanded microgrid reliably and efficiently.
5. Comprehensive comparative results are provided in this paper to demonstrate the advantages of the multiobjective control strategy used in this paper in terms of reduction in total harmonic distortion (THD), negative to positive sequence ratio and improving the transient response of DER output voltage.

The rest of the paper is organized as follows. The existing related literature is discussed in Section 2. The electronically interfaced DER system dynamical equations are presented in Section 3. Section 4 focuses on control objectives and introducing the problem formulation. The LMI formulation for this problem is presented Section 5 and the controller gains are computed in Section 6. Simulation results are provided in Sections 7, wherein comparative results are presented for different control strategies. The controllers are tested on a benchmark system consisting of nonlinear loads, and detailed switch model of converters. To further validate the proposed approach experimental results are provided in Section 8. Finally, conclusions are drawn in Section 9.

2. Related works

A survey on control of distributed generators for microgrid applications is carried out in [24]. In reference [4] the electromagnetic transients of a microgrid caused by grid connected switching to islanding mode are demonstrated. Several issues such as development of control strategies are highlighted in this reference for further investigation. Control objectives that enable a microgrid to operate autonomously and stably are defined in [5]. One of the earliest works in control of islanded microgrids is reported in [25], where the control strategy is carried out in *abc*-frame but for balanced loads only. In this reference power sharing among the DER units is achieved by introducing fictitious real power-frequency droop characteristics into the DER controllers. A control scheme that exploits the controllability of inverters in the islanded operation of a microgrid is reported in [26], where limitations of control bandwidth and communication are discussed. A proportional resonance controller in $\alpha\beta$-frame is designed in [9]. However, the effectiveness of the controller in attenuating distortion of nonlinear load currents caused by higher order harmonics is not demonstrated.

In [27] a state-space dynamic model for an islanded DER electronically coupled to an *RLC* network is developed, and a linear quadratic Gaussian controller is designed. This design methodology is used for voltage control of an islanded single DER unit microgrid. The control strategies proposed in [28] for a single DER unit, and proposed in [29] for multi DER units are designed based on the *dq* model of balanced and linear load circuit configurations. In [30] balanced loads are considered, with the flexibility of being reconfigurable (linear or nonlinear). Similar reconfigurable balanced load scenario is considered in [31,32], where sliding-mode controllers are used to control the microgrid's converters. An overview of recently used control strategies for voltage source inverters is given in [33]. However the surveyed references, deal with balanced loads. Therefore, in practice, the methods proposed in the surveyed references may not necessarily guarantee robustness, especially when the loads are single phase, unbalance, and/or harmonically polluted.

Robust controller for a grid-connected microgrid under unbalanced conditions is proposed in [34]. The problem of designing a *robust* controller for islanded microgrid with single DER units [11] and with multi DER units [13] has been studied. However, frequency control, which is essentially important in islanded microgrids, is not discussed in these references. Furthermore, other objectives such as transient behavior and energy input are not taken into account. A robust control method is proposed in [35],