Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Distributed stabilizing modular control for stand-alone microgrids

Despoina I. Makrygiorgou, Antonio T. Alexandridis*

The Department of Electrical and Computer Engineering, University of Patras, Rion 26504, Greece

HIGHLIGHTS

- An ac microgrid operating in stand-alone mode is investigated in view of stability.
- A suitable model deployment on a module form is proposed.
- The control scheme involves the droop-based with the cascaded-mode PI controllers.
- A Lyapunov-based analysis is applied to evaluate the microgrid system stability.
- Stability is ensured regardless from the number of DERs or the network topology.

ARTICLE INFO

Keywords:
AC microgrids
Frequency control
Voltage control
Droop-controller
Stability
Lyapunov techniques

ABSTRACT

A model-based decentralized control design and analysis is presented for varying topology ac autonomous microgrids. Particularly, the proposed method is developed on a modular form by considering local control schemes for each distributed generation (DG) region as it is formulated by a distributed energy resource (DER) among with its controlled power electronic interface and a local load. Each DG region is driven locally by a droop-based outer-loop slow control scheme in cascaded-mode with inner-loop fast current controllers. The proposed inner-loop current controllers are of simple proportional-integral (PI) type and do not involve the standard used parameter-depended decoupling terms. A general method of integrating the different DG regions, with their inner-loop fast controllers involved, is deployed to include any distribution network connecting the DG regions to each other and to external loads. To confront the challenging issue of proving stability and convergence to the desired equilibrium of such a complex, decentralized controlled microgrid, an advanced Lyapunov-based technique is effectively applied on the model constructed. Hence, the main novelty of the present approach is that it can be used as a flexible general tool, independently from the system scaling, parameters, operating conditions and the intermittent nature of the different DERs, since the modular and open model-based analysis enables expandability to any microgrid structure instead of considering all the DG units being connected in parallel or in a common bus. The overall scheme is evaluated by examining a typical stand-alone microgrid and the results verify the theoretical analysis indicating stability and smooth system performance without adverse impacts between the different parts.

1. Introduction

In recent decades, large-scale renewable energy resources (RES) have been widely penetrated into power distribution systems [1,2] in order to handle the increasing electric power demands and carbon emissions worldwide [3,4]. Therefore, in modern power systems, the influence of active loads in distribution significantly changes the structure, operation, and system performance [5]. In this frame, distributed generation (DG), mainly based on controllable RES and new local grid structures at the distribution side, such as microgrids, play a key role in the electricity grid deployment [6]. Distribution has become an active network required to operate in grid connected or stand-alone modes, whereas microgrids have immense potential in boosting sustainable growth [7] as a suitable, reliable, and clean solution [8]. A microgrid is a low-voltage distribution system consisting of DG units, energy storage devices, and loads [9], that can interchange power between the different distributed energy resources (DERs) and the utility grid. Furthermore, microgrid integration on a smart grid is the key for the beneficial use of widespread DERs and it can exploit new technologies in communications, computing, and control [10,11]. Owing to the intermittent nature of most DERs, the development of practical, cost-effective, and simple control strategies is obligatory [12,13]. Many

* Corresponding author.
E-mail addresses: dmakrygiorgou@ece.upatras.gr (D.I. Makrygiorgou), a.t.alexandridis@ece.upatras.gr (A.T. Alexandridis).

http://dx.doi.org/10.1016/j.apenergy.2017.07.085
Received 7 April 2017; Received in revised form 21 July 2017; Accepted 22 July 2017
0306-2619/

control structures based on hierarchical control levels, which are suitable for DG systems, have been proposed at the primary and secondary levels [12,14,15], and at upper levels where day-ahead scheduling and operation management are applied [6,16,17]. Nevertheless, since all the management decisions and tasks are eventually executed by the DGs in real-time, the importance of power electronic interfaces of the DG units [18] for the microgrid control and analysis becomes evident.

Power electronic devices offer a critical opportunity for controlling the power transferred through them, since they realize the smart grid supervisory commands at the power grid level [19]. The aim is to create a structure wherein, on one hand, each DG unit region can operate in a self-controlled mode, whereas on the other hand, a completely reliable co-operation can be guaranteed between the different DG units installed in a microgrid. Especially, in the case of autonomous operation, this is very essential and the key issue is to determine a suitable design that ensures the overall system stability and the avoidance of adverse impact between the units. An adequate study may include different DG units, which are usually represented as dc sources connected via a voltage source inverter (VSI), into a common local grid where varying loads are fed. Therefore, VSI is a crucial component of a microgrid, since it acts as an interface between the DG unit, load, and grid [9]. Moreover, the controls should be applied on each VSI such that the ac frequency and voltage of the microgrid are regulated quickly and smoothly, and several control techniques have been proposed for the proper operation of the parallel-connected VSIs in a microgrid structure [9,20,21].

In the stand-alone mode of operation, microgrids can provide electricity to rural areas or remote island communities [22,23] with low cost and minimum power losses. There are many cases where large-scale distribution networks are required to operate in the stand-alone mode with the power injected mainly from RES (and perhaps other production units) e.g. when large islands or other isolated areas are disconnected from the main grid for any reason. In these situations, it is important for a high performance distributed control to act locally on the power electronic interfaces of the DGs in an efficient and stable manner. Since the voltage and frequency regulation and the power sharing between the VSIs of the different generators are important issues for stand-alone operation, different control strategies have been investigated [13]. In the stand-alone mode, the VSI does not have externally provided reference signals, as in the grid-connected mode, and therefore, it is necessary for the VSI to generate the frequency and voltage nominal references by itself [24,25]. Nevertheless, both these references usually are not directly applied as command inputs. The intermediate actions of droop-based controllers provide the final command inputs, which are slightly modified from their nominal reference values. Droop control is widely accepted and commonly used [9], owing to its simplicity to realize the physical behavior of a synchronous generator [25–27]; it is simply designed to provide small negative or positive deviations on the frequency and voltage command inputs, when the active and reactive power increases or decreases, respectively [19,24]. Notably, each DG unit region frequency is practically created by a standard phase-locked loop (PLL) circuit, which responds very quickly to follow the common microgrid frequency, as this is determined by the droop characteristics and the alignment of the local ac voltage.

The standard methods used so far for frequency and voltage control are deployed in the cascaded-mode [28,29]. The cascaded-mode control consists of an inner-loop proportional-integral (PI) current fast controller, which regulates the output VSI current at its reference value in accordance with the main control tasks, as they are realized by the slower outer-loop controllers. The basic notion that allows the design of cascaded-mode controllers is founded on the time-scale separation principle. According to this principle, the outer-loop controllers do not immediately affect the system response and therefore can be neglected from the system dynamics. In contrast, the inner-loop fast controller influence should be taken into account in the analysis [30]. In analysis, the model and the controller deployment are better expressed in terms of mathematical equations at the synchronously rotating d-q reference frame via the d-q Park transformation [29]. The basic advantage of this representation is that the state variables of the system are transformed from sinusoidal to constant quantities at steady state, which facilitates the effective design of PI form controllers.

In autonomous microgrid operation, control and stability are crucial for the system performance and these issues have been investigated by many researchers. In the studies in [31,32], an overview of the microgrid structures with the power electronic devices and their control are presented, whereas in the study in [33] different kinds of DERs are heuristically examined; moreover, in the study in [34] a heuristic analysis is presented with simulations on MATLAB environment. More accurate approaches use a linear system formulation with uncertainties for the design of stable controls that satisfy the robustness criterion [35], whereas the small-signal technique is applied in the study in [36,37] for studying stability. Recently in this field, based on small signal analysis [38,39], impedance-based approaches [40] have been successfully proposed for modeling, control, and stability studies [41,42]. Stability is mainly investigated by applying the Nyquist criterion on the basis of a model obtained either in the sequence domain using symmetric components or by simply applying the synchronously rotating d-q reference frame. Although the method is very satisfactory for investigating instabilities and resonance problems, it is inherently limited to simple or simplified system models suitable for frequency domain techniques [43,44].

In this study, the analysis and design of effective distributed control schemes in modular form are addressed for each DG region that involves the local RES unit among with its VSI and local load; the aim is to guarantee no adverse impacts between the different DG units when are integrated to any arbitrary microgrid structure and to ensure overall system smooth performance and stability. Accordingly, by adopting the distributed cascaded PI control scheme for each DG unit region, a DG modular system description is first obtained. The control method is based on the design of simple PI local controllers, familiar to the power engineers, which do not involve the standard used parameter-dependent decoupling terms [29,45]. Furthermore, the model considers the fast inner-loop PI current controllers, as they are driven by their local command inputs created from the slower outer-loop/droop-based frequency/voltage regulators [35]. Hence, the proposed controllers are developed on a typical DG region module to ensure a fully decentralized design and expandability to different topologies. In the second stage, the different DG region modules are connected to each other via a local power network and are integrated to completely form the microgrid structure. The proposed modular deployment of the entire set of DG unit regions/inner-loop controllers is combined with the microgrid network to allow a novel open-form stability analysis to be formulated by using a suitable Lyapunov approach. The analysis is contacted under the reasonable assumption that the DG system frequency can be considered as a time function and therefore, the full system model becomes a linear time-varying model. The latter assumption, among with some observability properties imposed by the network deployment, enables the stability and convergence to the equilibrium to be established. This facilitates the easy study of a microgrid with a variety of DG units since the analysis presented can be effective for any local distribution network, instead of considering all the DG units being connected in parallel or in a common bus.

Hence, the main novelty with respect to other research approaches is that the present analysis can be used as a general tool, since its modular and model-based nature guarantees expandability to any microgrid structure and control designs, independently from the system scaling, parameters, operating conditions and the intermittent nature of the different DERs. Another aim of the analysis is to demonstrate that the stability of the system is ensured and improved under the action of the inner-loop current controllers, which is necessary for the successful integration of the droop-based controllers in a microgrid operation. This is very critical since, as it has been extensively analyzed [46], strict