Electric Power Systems Research 160 (2018) 151–162

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Small-signal stability improvement of an islanded microgrid with electronically-interfaced distributed energy resources in the presence of parametric uncertainties

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ARTICLE INFO

Article history:
Received 18 September 2017
Received in revised form 12 February 2018
Accepted 14 February 2018

Keywords:
Decentralized droop control
Small signal stability
Parametric uncertainty
Robust control
Microgrids

ABSTRACT

This paper deals with the concept of small signal stability (SSS) issue in an electronically-interfaced microgrid with large penetration of distributed energy resources (DERs) subjected to the parametric uncertainties. Utilizing a method to enhance SSS of the system stemmed from industrial experiences is the first achievement of this study, which is realized by employing two extra feed-forward loops in the power controller section of DER unit. This control structure damps the active and reactive power oscillations by shifting the dominant eigenvalues to the left half-plane (LHP) in case of any changes in the operating point or droop coefficients. For investigating the impacts of parametric uncertainties on the overall stability, the basic theorem of the proposed robust control strategy, frequency-domain modeling of the microgrid, robustness and close-loop stability analyses are outlined. This method shows that improving the power control section topology results in higher stability margins in case of uncertain load perturbations. Furthermore, it demonstrates how much load variations are allowed to preserve SSS of the system in the frequency-domain which is a more convenient approach and takes less time than time-domain simulations. Finally, time-domain simulations conducted in MATLAB/Simulink on the sample test system will show proper results of the frequency-domain findings.

1. Introduction

1.1. Motivation

The necessity of substituting green energy resources with the conventional path for electricity generation is inevitable. To this end, microgrids, thanks to their flexible nature, could fulfill the basic requirements for implementing the concept of clean energy production. Most of the conventional power system studies could be mapped into the microgrids among which, various types of stability analyses have been greatly pronounced [1,2]. In the stability analyses, the impacts of control system architectures are undeniable. These systems within the microgrids can be divided into two distinctive categories. The first one employs a fully centralized control relying on the data summed up in a central controller. This controller performs required calculations and determines control commands for all units at a single point, which in turn needs a communication link between the central controller and local units. The second control approach implements a fully decentralized method representing locally controlled units. These local controllers are not fully aware of system-wide variables and the actions of other controllers.

Implementation of a fully centralized approach is usually problematic due to the need for communication link and computation burden for the interconnected power systems extended over geographic areas [3,4]. On the other hand, a fully decentralized approach is not possible due to a strong coupling between the operations of various units in the system, requiring a minimum level of coordination, which cannot be achieved by using only local variables. A trade-off between fully centralized and fully decentralized control schemes can be achieved by means of a hierarchical control structure consisting of three control levels [5–8]: primary control, secondary control, and tertiary control. Among these levels, the primary and secondary ones act as a pivot on which the autonomous operation of the microgrids is established. The men-

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https://doi.org/10.1016/j.epsr.2018.02.009
0378-7796/

Nomenclature

ω_{sec}	Secondary controller frequency restoration signal
V_{sec}	Secondary controller voltage restoration signal
ω^*	Reference of angular frequency
ω_{rated}	Rated angular frequency
ω_0	DER unit angular frequency
ω_s	Microgrid angular frequency
V^*_{od}	Reference voltage
$V_{od,rated}$	Nominal voltage
δ_0	Voltage angle of DER unit
δ_s	Voltage angle of equivalent microgrid seen from DER unit
δ_i	Parametric uncertainty
$\tilde{\delta}_i$	Normalized parametric uncertainty
$\tilde{\Delta}_s$	Overall uncertainty matrix
N	Lower linear fractional transformation
$W_{mi,ul}$	Weighting factor for i-th uncertain load
n_{ul}	Number of uncertain loads
Z_s	Impedance matrix of source
Y_{cl}	Admittance matrix of certain load
Y_{ul}	Admittance matrix of uncertain load
R_g	Upstream grid resistance
L_g	Upstream grid inductance
f	Microgrid frequency
V_{mg}	Microgrid voltage
C_f	Filter capacitance
L_f	Filter inductance
L_o	Output inductance
r_o	Output resistance
f_s	Switching frequency
F	Feed-forward term
K_{pc}	Proportional gain of current controller
K_{ic}	Integrator gain of current controller
K_{pv}	Proportional gain of voltage controller
K_{iv}	Integrator gain of voltage controller
$K_{i,sec}$	Secondary controller integral term
$K_{p,sec}$	Secondary controller proportional term

tioned hierarchical control is the pillar of each control structure in the electronically-interfaced distributed energy resource (DER) units. Therefore, various aspects of stability analyses in the microgrids need elaborated modeling of each hierarchy.

Each control system architecture within a microgrid should ensure the SSS issue due to erratic pattern of operational point and load perturbations [9]. This type of stability has considerable impacts on the autonomous operation of the microgrid due to low inertia nature of the system; however, its applications in grid-connected operation also have been noticed [10]. In the islanded microgrids, the balance between output power and the load should be maintained by the microgrid itself. Therefore, the SSS can be highly influenced by the interaction between loads and sources [11,12]. The reason for considering this interaction is to design a control system, which is insensitive to the load-source dynamics [13].

1.2. Literature survey

To investigate the effects of load-source interaction on the SSS in the autonomous operation of the microgrids, two main approaches have been proposed. Eigenvalue sensitivity analysis is a common approach, which has been mentioned in the previous works [13–20]. In this method, all equations of the microgrid components are linearized around a stable operating point. Then, the state-space matrices will be formed and employed to evaluate the overall stability of the microgrid. Another class of approaches for evaluating the SSS is the frequency-domain methods [9,21–23]. The main requirements of these methods are the information about amplitude and phase of the network, which could be obtained by the computer simulations or analytical methods [24,25]. Middlebrook criterion is a popular method in this area for analyzing linear, time-invariant, single input single output (SISO) systems [21]. According to this approach, if the total impedance of the source, as the function of the frequency, is less than that of the load impedance for all frequency spectrum, the system is stable [9]. One of the main disadvantages of this method is its conservative nature, which narrows its search domain in order to satisfy the mathematical formulation which in turn leads to the conservative design. Reducing this conservativeness, gain margin and phase margin (GMPM) method has been proposed for SISO systems [26,27]. This approach reduces prohibited region in the Nyquist plane and; therefore, decreases the conservativeness. However, as a negative point, it is difficult to be performed on multi-input multi-output (MIMO) systems. Also, it does not explicitly express the robustness against parameter variation in the system. For improving the damping characteristics of a control system, subroutine library in system and control theory (SLICOT) has been proved to be quite helpful in defining the required amount of damping in a given system. SLICOT is a comprehensive numerical software package for control systems analysis and design which is based on linear algebraic equations of the system. The main requirements for using this package is that the under study system should have full controllability over its states.

An interesting and developing method in the realm of frequency-domain SSS analyses in the microgrids is the robust control theory [28]. This method consists of various approaches to deal with a system subjected to the different types of uncertainties. The H_∞ based design and μ-analysis are two main approaches of this theory. The μ-based control design for mitigating the multiple resonances in the microgrids with power factor correction capacitors has been presented in Ref. [29]. Also, the superiority of μ-based controller over H_∞ controller on the overall robust performance and stability of the multi-loop control system has been noticed. In Ref. [9], SSS of an islanded microgrid consisting electronically-interfaced DER units has been assessed using the μ-analysis. The results of this paper demonstrate that how much *RLC* load variations are allowed to preserve the stability of the system. However, none of the aforementioned studies seek to improve the microgrid stability and verify their results through robust control approaches. Also, the impacts of secondary controller dynamics on the autonomous operation of microgrid have not been considered. A study has been carried out in Ref. [30] to introduce a new decentralized robust strategy for enhancing the small and large signal stability of a hybrid AC/DC microgrid. However, no stability margins in the case of load perturbations have been established in this study.

1.3. Contributions

In this paper, a SSS improvement method is applied to a multi-DER units tests system subjected to the parametric uncertainties. This system is composed of sources, which are assumed to be the droop-controlled electronically interfaced DER units, with the bidirectional power-exchange capability and *RLC* loads. Furthermore, the impacts of distributed secondary controller dynamics are considered in the DER model. This method is analytically verified and the eigenvalue analysis justifies its proper applicability. Also, the stabilizing feature of the proposed control system is performed on the operation point variations. Then, the μ-analysis is applied to verify the appropriate performance of the enhanced method in the presence of parametric uncertainty. This approach not only