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Research Article

A robust nonlinear stabilizer as a controller for improving transient stability in micro-grids

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ABSTRACT

This paper proposes a parametric-Lyapunov approach to the design of a stabilizer aimed at improving the transient stability of micro-grids (MGs). This strategy is applied to electronically-interfaced distributed resources (EI-DRs) operating with a unified control configuration applicable to all operational modes (i.e. grid-connected mode, islanded mode, and mode transitions). The proposed approach employs a simple structure compared with other nonlinear controllers, allowing ready implementation of the stabilizer. A new parametric-Lyapunov function is proposed rendering the proposed stabilizer more effective in damping system transition transients. The robustness of the proposed stabilizer is also verified based on both time-domain simulations and mathematical proofs, and an ultimate bound has been derived for the frequency transition transients. The proposed stabilizer operates by deploying solely local information and there are no needs for communication links. The deteriorating effects of the primary resource delays on the transient stability are also treated analytically. Finally, the effectiveness of the proposed stabilizer is evaluated through time-domain simulations and compared with the recently-developed stabilizers performed on a multi-resource MG.

1. Introduction

Development of new micro-grids (MGs) incorporating various electronically interfaced distributed resources (EI-DRs) renders the control of the MGs more and more challenging [1]. The primary energy of some of the EI-DRs is green resources. Delay in energy generation by the primary resource of EI-DRs is known as the primary resource dynamics, which lead to a deterioration of the transient stability [2]. Furthermore, the EI-DRs often employ dissimilar control strategies for each mode of operation. These issues have been partially addressed by the multi-mode control strategies implementing a unified control topology in all functional modes of the MG. The leading obstacle involves maintaining transient stability during mode transition transients, especially, when the primary resources are different [3,4]. Robust nonlinear control strategies have been advanced to cope with the interactions of the control modules with the rest of the control system, and the uncertainties in the system parameters [5–8].

A number of investigations have been carried out concerning different types of stabilizers for EI-DRs. The first stabilizer for the EI-DRs has been introduced in [9], where a supplementary control signal is generated through an additional control loop in parallel with the traditional droop loop. This controller, which has been designed based on a linear, small-signal approach is intended solely for the islanded mode, and its operation is similar to power system stabilizers (PSSs). Thus, it is not able to handle large transients in the voltage and the frequency occurring during the mode transitions in MGs. Although stabilizers of this type have been designed based on a linearized model around the equilibrium point, during large transition transients the equilibrium point of the system changes and, as a result, the transient stability cannot be achieved in this class of stabilizer. A nonlinear stabilizer has been presented in [8] which deploys an adaptive back-stepping technique. Nonlinear controllers are useful when the transient stability is the main objective in the control system. These stabilizers, however, fail to take the dynamics of the primary resources into account. In addition, the designed control signal is extracted by a relatively nonlinear complex expression leading to an increase in the calculations and the number of the parameters. Furthermore, the total external disturbances have been considered as a constant parameter estimated by an adaptation law. In reality, the external disturbances cannot be modeled by a constant value and therefore, may not be estimated by a first-order adaptive law. Moreover, the dynamics of the adaptation law render the transient operation of the controller inefficient. The introduced stabilizer in [8] has been implemented in [10,11], however, the primary

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resource dynamics as well as the robustness of the stabilizer have not been taken into consideration in the design procedure. This issue will directly influence the transient stability as will be proved analytically in Section 3. The other disadvantage relates to their implementation and their relative complexity in adjusting the controller parameters, which poses a particular challenge, when the number of EI-DRs increases. Thus, these strategies exhibit limitations in achieving transient stability especially when the primary resource dynamics are considered. A novel control strategy has been introduced in [12] which applies a nonlinear control strategy based on a fractional order active sliding mode. This controller, which is less sensitive to the variation of the interface impedance is, however, solely intended for the grid-connected mode and has been validated on a single EI-DR connected to the main utility. Moreover, the primary resource dynamics and the robustness of the controller in the presence of the bounded disturbances have not been evaluated. Therefore, this idea is not capable of coping with large signal transition transients appearing during the mode transitions in a MG containing a set of EI-DRs with different primary resource dynamics. In addition, the reported control strategy in [12] is based on a single mode operation, namely the grid-connected mode, while in a unified operational scheme the control system must be adapted to both operational modes. A new modified sliding mode control strategy leading to improved voltage and frequency dynamics in the EI-DRs in the grid-connected mode has been developed in [13]. However, this controller does not support unified control strategies and has been introduced specifically for the grid-connected mode. The robustness analysis and issues related to the primary resource dynamics do not fall under the scope of this study.

The idea of incorporating a multi-purpose droop controller with a decentralized stabilizer for the seamless operation of EI-DRs has been reported in [14]. The designed stabilizer has been developed using the passivity-based control approach (PBC) which enhances the transient stability in a unified control scheme using a simple feedback controller. However, the robustness analysis of the proposed strategy in the presence of the bounded-disturbances have not been evaluated analytically. Moreover, the stabilizer reported in [14] guarantees asymptotic stability when the system experiences large frequency and voltage transients. Nevertheless, if the exponential stability is provided by the controller, the transition transients are suppressed more effectively compared with cases in which asymptotic stability can be achieved. Asymptotically stable systems have lower convergence order near the equilibrium point in comparison with exponentially stable systems. Higher convergence order not only can result in faster convergence but also can provide more robustness for the system. In addition, as opposed to asymptotic stability, exponential stability can provide a lower ultimate bound in the presence of non-vanishing perturbations. In addition, the control parameters identified in [14] have to be selected using evolutionary optimization programs, such as those reported in [8,11], which complicates the design procedure. This issue will become more challenging as the number of resources increases. The steady-state operation and the power management in MGs have been addressed in [15] using the droop control strategy. Since, the conventional droop controllers have been designed under steady-state conditions, they lack the ability to damp large voltage and frequency transients [14]. A novel robust control strategy for the voltage source inverters (VSIs) has been presented in [16]. The reported control framework has been implemented in a single VSI operating in the grid-connected mode. However, the operation of a number of VSIs with different primary resource dynamics in the islanded mode and during mode transition transients do not fall in the scope of this work. The robustness of the control system in the presence of the uncertainty and disturbances have been addressed in different literatures [17–19]. A novel control strategy has been introduced for the precision control of piezoelectric ultrasonic motors in which a sliding mode control law is included in the main feedback control signal to deal with system uncertainties [17]. The conventional disturbance observers are deployed to cope with this problem in some control applications. However, inclusion of these observers require the availability of the exact system information which may not always be at hand. Furthermore, the bandwidth of the conventional disturbance observer is limited due to the use of the low-pass filters. This problem is addressed in recently-published literature by implementation of an advanced disturbance observer which does not requires exact system information [18]. In [19], a robust output feedback control strategy incorporating a model-based high-gain disturbance observer is developed to provide a stable estimation of states associated with tracking error when the exact system information is not available. The complexity of the observer structure along with the complex structure of multi-resource MGs render the applications of this approach in MGs more challenging. Recently, decentralized controllers have received considerable attentions [6,8,14] as compared with conventional centralized controllers [20], since they do not require a communication link. This leads to an increase in the reliability and the security of the control system as well as a significant decrease in the overall costs. On the other hand, the cooperative control strategy [21], which combines the centralized and the decentralized strategies, transmits the control signals using communication links between the adjacent distributed generators. The associated obstacles related to the communication links, however, continue to persist in this strategy.

In the literature, a number of the recently-presented solutions with regard to the development of the controllers as stabilizers in the MGs have been reviewed. From this discussion, it is obvious that the robustness of the stabilizer in relation to the bounded-disturbances have not been widely taken into account in the MGs. In some of the recently-developed stabilizers [8,10,11], the effects of the bounded-disturbances have been represented by a constant term which has been estimated in order to eliminate the effect of the disturbance on the control system. However, since these disturbances are nonlinear, the representation of these bounded-disturbances with a constant term is not more applicable. Moreover, some additional dynamics must be added to the control system to estimate this term resulting in an associated delays to the control system while the speed of the controller in the transients is of high importance [10,11]. The primary resource delays in power generation and the effects of this phenomenon on the transient stability are also of high interest. Additionally, the number and diversity of the resources in the MGs complicate the design and tuning of the stabilizers, thereby motivating adoption of simpler topologies. Some strategies present controllers with a large number of parameters requiring tuning, which renders the design procedure increasingly challenging and time consuming [8,11]. Provision of the exponential stability as opposed to the asymptotic stability could enhance the performance of the stabilizer in suppressing the power angle and frequency transition transients [24]. In the presence of the bounded-disturbances, the states must be remained ultimately bounded, nevertheless, the systems which guarantee exponential stability in the nominal form are able to cope with disturbances more effectively [24]. This issue has not been taken into account in the recently-presented studies. Some previously-suggested controllers have been designed and implemented for a single operational mode of the MGs and a significant reconfiguration is required to adapt these controllers for different modes.

In light of the aforementioned literature review, this paper proposes a decentralized stabilizer operating as a nonlinear robust controller with the following unique features:

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