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Research Article

Multi-purpose droop controllers incorporating a passivity-based stabilizer for unified control of electronically interfaced distributed generators including primary source dynamics

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ABSTRACT

This paper presents multi-purpose droop controllers for electronically-interfaced distributed generators (EI-DGs). These controllers allow the micro-grids to operate in grid-connected mode, islanded mode and mode transition transients with a unique control configuration. The active and reactive-power sharing among EI-DGs are satisfied by the proposed droop controllers in islanded mode. On the other hand, in the grid-connected mode, the droop controllers adjust the output active and reactive-powers of EI-DGs at the pre-programmed constant levels. The provision of sufficient damping capability and maintenance of the transient stability in all operational modes of EI-DGs are warranted by the suggested stabilizer. This stabilizer, which is designed using the passivity-based control (PBC) approach, is incorporated in the droop controllers to dampen power-angle, frequency and voltage deviations during large transients using solely local information. The primary source dynamics of EI-DGs are also considered. It is analytically proven that the presence of the primary source dynamics leads to attenuation of the damping capability of EI-DGs in transients. To compensate the adverse effect of the primary source dynamics during transients a novel compensator is inserted in the frequency-droop loop. Finally, time-domain simulations are performed on a multi-resources MG to verify the analytical results compared to those obtained, based on a recently-developed strategy.

1. Introduction

Due to the rapid growth of micro-grids (MGs) in recent years and the importance of security and reliability issues, the control and stability of MGs have raised a major concern [1,2]. Micro-grids can operate in two separate operational modes, namely the grid-connected mode and the islanded mode. Droop controllers are deployed in the islanded mode to share the total, demanded powers among distributed generators, whereas in the grid-connected mode these controllers must be replaced by constant-power controllers. In other words, the control strategy has to be changed depending on the operational mode of MGs. This mode change relies on the islanding detection signal sent from the central control system via specific communication infrastructure, implemented using different technologies [3,4]. Any type of error in the islanding detection can interfere with the proper operation of MGs. In this stage, the control system remains in its previous configuration while the operational mode of the MG has changed. Lack of coordination between the control system in electronically distributed generators (EI-DGs) and the operational mode in MGs can drive the system into faulty operation and instability [4]. Applying a unified control strategy to all operational modes of the MGs in distributed generators (DGs) deploying only local information can eliminate the need for a central islanding detection system and central controllers [4,5]. However, the control framework must be applicable to the grid-connected mode, the islanded mode and the mode transition transients with a unique control topology.

Provision of the stability during mode transition transients will be the main challenge, particularly when the MG contains only EI-DGs [6]. It will be shown that incorporating the primary source dynamics in the control system will increase the transition transients. These conditions highlight the importance of maintaining the transient stability when mode transition transients occur in a unified control method. The steady state operation of MGs has been addressed using newly-developed methods [7]. The finding of this work can be applied to controllers operating under steady state conditions wherein transient reactions have diminished.

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Hence, this approach is inapplicable to the seamless operation of MGs experiencing large mode transition transients. However, few studies have addressed the unified operation of MGs under the aforementioned conditions. A control strategy for DGs in grid-connected mode and islanded mode has been developed in [8]. This method has been verified for a single EI-DG connected to the main grid without regard to the active and reactive-power sharing among EI-DGs. This scheme, however, needs to be significantly reconfigured when the operational mode of MG changes. A new control approach has been developed in [9] allowing design of a nonlinear controller based on fractional order active sliding mode approach. While this controller is less sensitive to variations of the interfacing impedance, it has been designed only in the grid-connected mode and simulated on a single distributed generator connected to the main utility. In [10] and [11], a novel strategy known as synchronverter allowing control of EI-DGs as synchronous generators (SGs) has been introduced. Nevertheless, this model does not consider the seamless operation of MGs. In this model, the voltage generation principle is similar to rotational back electro-motive force (back-EMF) generation in typical SGs. The generated voltage will, therefore, be a function of the virtual flux from the voltage droop loop and the frequency specified by the frequency droop loop. This relation links voltage and frequency loops to one another, which, in essence, amplifies mode transition transients. However, this approach allows efficient control of EI-DGs such as SGs. Seamless formation and robust control of EI-DGs in MGs have been addressed in [4]. However, this study has proposed two control strategies in the voltage loop, namely constant-voltage and constant-reactive-power strategies. Thus, EI-DGs can not participate in reactive-power sharing in islanding mode. The primary source dynamic of EI-DGs and their associated problems during transients were not taken into account. The application of stabilizers in EI-DGs was first introduced in [12]. Specifically, a supplementary loop was placed in parallel with the conventional droop controllers in EI-DGs to stabilize the system while using high angle droop gains. Nevertheless, this stabilizer is similar to those employed in conventional power systems and is, therefore, suitable for maintaining small-signal stability in EI-DGs operating in the islanded mode. However, due to presence of large transients, this approach is not suitable for unified operation of MGs. Some developed stabilizers are centralized requiring communication infrastructure to receive information and transmit control commands to DGs [5,13]. Due to their dependency on communication infrastructure, these kinds of strategies are not popular for unified control of MGs. In addition, the security, stability and the economic issues associated with this strategy have limited its popularity in comparison to decentralized strategies. The idea of deploying decentralized nonlinear stabilizers handling large transients during mode transitions of MGs, has been advanced in [14]. This study has implemented adaptive back-stepping to design the stabilizer, which was introduced in [15]. The given stabilizer requires power-angle reference to provide the control signal. This approach, though efficient, has a drawback in that the information about the power-angle reference is not readily available and must be calculated. In addition, the primary source dynamics of EI-DGs are not considered in the design of the nonlinear stabilizer. The control signal employed in this study is expressed by a relatively complex expression leading to an increase in the number and complexity of calculations. A combination of angle and frequency droop control strategies has been suggested in [16], which provides damping and synchronizing torque in EI-DGs in the same manner as SGs. One issue associated with this work is that, similar to the work presented in [14], the outer loop serving as the angle-droop loop must receive angle reference information, acquisition of which may be difficult. This problem will be highlighted when the operational mode of MG changes. Moreover, no specific consideration is given to the primary source dynamics of EI-DGs in the design of the stabilizer and the reactive-power sharing is not taken into account. The need for power-angle reference in the control loop has been removed in [17], by introducing a novel structure for the droop controllers. However, reactive-power sharing in the islanded mode and the problems associated with the primary source dynamics in transition transients have not been taken into consideration. The strategies developed in the recently-reported literature rely on complex methods requiring a large number of controller parameters. The values of these parameters have to be extracted based on optimization approaches such as those introduced in [18,19]. The voltage transients during the mode transition have not been considered in the recently-reported literature, even though attention to these transients in the process of controller design may enhance the performance of the system in a unified control strategy. To make the operation of EI-DGs more feasible in MGs it is better to control EI-DGs such as SGs [10]. The idea of designing droop-based controllers in terms of second order dynamics of the SGs has been introduced in [20], and can be potentially applied to the unified control of MGs. However, this approach has been examined only in frequency droop controllers, and has not been applied to the seamless operation of MGs.

In unified control of MGs, we must pay specific attention to the performance of the phase-locked loop (PLL). In the grid connected mode, the EI-DGs need the conventional PLLs for detecting the voltage phase angle of the grid during grid restoration. On the other hand, the dynamics of the PLLs can cause instability following the mode transition transients [21,22]. In [21], the concept of power-synchronization has been presented. This idea, which has been implemented widely in the recently-reported seamless control strategies, eliminates the need for PLL in the EI-DGs. This approach, however, is not effective during severe transients in the voltage and the frequency causing a backup PLL to be required for these situations [23]. This problem is also addressed in [24], by instantaneous tracking of the voltage phase angle, thereby eliminating the PLL requirement.

Having reviewed different studies in unified control of MGs, we can bold the following topics.

Previous studies mainly focus only on one operational mode, namely either the grid-connected or the islanded mode. In other words, the control system must be reconfigured completely in each state of operation based on islanding detection commands which have a significant dependence on the communication infrastructure. This problem will increase costs while decreasing the security of the system. The voltage and frequency quality during transients as well as active and reactive-power sharing are also of high interest in a unified control strategy. The voltage quality and its associated problems, in particular, have not received due consideration in unified control strategies. To date, the strategies suggested for unified control are strongly nonlinear and requiring experimental implementation of advanced digital signal processors (DSPs). Furthermore, in the recently-developed strategies the primary source dynamics and its effects on transient stability have not been taken into consideration. This problem can be addressed based on theoretical analysis and simulations. In this paper, multi-purpose droop controllers are proposed allowing unified control of EI-DGs. This strategy facilitates seamless operation of MGs and incorporates the following enhanced characteristics:

(1) The proposed droop controllers are applicable in grid-connected mode, islanded mode and mode transition transients with a unique control configuration as shown in Fig. 1.
(2) The proposed droop controllers have been equipped with decentralized stabilizers which have been designed using the