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Designing high-order power-source synchronous current converters for islanded and grid-connected microgrids

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HIGHLIGHTS

- The proposed strategy is an integrated controller/synchronizer/load manager.
- It realizes a unified power-source current-controlled microgrid.
- It renders a phase-locked-loop-free synchronization and droop-free power sharing.
- It offers capabilities like fault-ride-through and smooth transition to islanding.
- A general theme for design of high-order filter-based controllers is presented.

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ABSTRACT

This paper deals with development of a versatile and compact control strategy for voltage source converters in grid-connected and islanded microgrids using synchronous current converters technology. The key feature is its new integrated high-order controller/synchronizer with applicability to both operational modes without strategy rearrangement. Using high-order controllers, on the other hand, results in rather complex analysis and design process, therefore this paper aims at providing a general and simple theme for the design and parameter selection. The controller also provides adaptive and automated current-based grid synchronization. Moreover, the controller realizes a power-source current-controlled microgrid with minimum control loops, as compared to widely adopted voltage controlled microgrids in the literature, with advantages such as fault-ride-through and inherent droop-less power sharing capabilities. Adaptive current-based synchronization and smooth switching to islanding mode provides high flexibility, reliability and only-plug operation capability. Extensive simulation and experimental results are presented to demonstrate performance of the proposed control and management strategy.

1. Introduction

The integration of distributed energy resources into power systems is rapidly changing control and operation of the energy sector from a centralized fashion to a decentralized one [1–4]. Fast development of renewable energy resources such as wind turbines and solar cells [5,6] is the main reason of deep penetration and wide application of distributed and decentralized generations. These decentralized smart power grids, as the next generation of power grids, involve a large number of distributed generations (DGs) which a cluster of them are integrated into a utility grid as a microgrid (MG) to make control and management easy and practical [1–4]. Otherwise, distributed nature of generation with scattering over a wide geographical area and intermittent nature of wind and solar sources may cause serious issues in terms of stability and reliability [7,8]. It is widely discussed that maximum benefit of MGs can be exploited if they can work in both grid-connected and islanded modes and also if they provide ancillary service for the grid such as frequency and voltage regulation [1–4,7–9]. In islanding mode, the MG is disconnected from the utility grid and DGs inside the MG supply loads which can significantly improve reliability of the MG [7]. These DGs can be either renewable energy resources or alternative energy generations, and they are commonly integrated by voltage source converters (VSCs) [1–4,7–11]. However, a majority portion of generation units will be conventional electrical-machine

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based ones with basically different characteristics. Beside generation units, it is also expected that most of loads are also connected to the grid by power electronic interfaces [12]. Therefore, the adopted control strategy for VSCs is highly influential on the performance and stability of the MG and also the utility grid. Moreover, it is expected that MGs frequently switch between grid-connected and islanding modes [13–16]. Therefore, unified controllers which are applicable to both grid-connected and islanded modes are acquiring noticeable momentum [1,6–10], in order to use DGs and MGs optimally. Although there are considerable works in the literature (e.g. [17–20]) for designing control and management strategies which can handle smooth switching between two operational modes, most of them still need to detect the utility outage and change the control/management strategy and the associated control parameters subsequent to the islanding. Instabilities due to islanding detection delays and controller reconfiguration are discussed [21,22]. Otherwise, if MGs and generation units within them are able to handle smooth transition to islanding without islanding detection and controller reconfiguration, the MG reliability and stability are significantly enhanced [20], realizing considerable automation and flexibility.

In grid-connected mode, electronically interfaced generations commonly operate as current controlled-VSC (CC-VSC) [22–26] and consequently act as a current source. This is an important factor for stable grid synchronization and also provides great features like current limitation, control and regulation [22–26]. However, they are not suitable for islanded mode as they may cause voltage and frequency excursion [11,25]. The grid forming control strategy is usually adopted for the islanded mode and operates as voltage–controlled VSC (VC-VSC), because of lack of a stiff grid it is necessary that VSCs regulate MG voltage [11,25]. However, VC-VSCs are not good choices for grid-connected mode as they do not provide stable and high-performance grid synchronization [25,27]. Moreover, in an islanded MG it is required that DG units share total MG load demand proportional to their power capacities, preferably without communication links [28–34]. The most adopted method for power sharing in an islanded MG is droop control in which frequencies of VSCs are drooped as functions of their output power [28–33] whereas voltage amplitude droop control is commonly used for reactive power sharing. Nevertheless, permanent frequency and voltage amplitude offset, low stability margin, and rather poor load sharing accuracy are known problems of the conventional droop controls [32–34]. To overcome these difficulties, some new techniques like software defined networking [30] and master–slave [31], and distributed control [35] have been recently developed. However, these techniques may drastically increase computation burden, thus load sharing of islanded MGs still needs more attention.

The power control and management commands in both grid-connected and islanded modes are realized by internal current and voltage controllers. The conventional method for the control of VSCs in the literature is vector control [27]. The main drawbacks related to the vector control are: 1- inefficient use of power capacity of VSC [36–37]. 2- Instabilities and rather poor performance contributed from the PLL, which are widely discussed in the literature [36–38]. This degrades frequency and voltage stability of the smart grids as a result of rather complex frequency dynamics [39–40]. 3- Interactions with conventional electrical machine-based units like synchronous generators (SGs), because of their fundamentally different characteristics [41–47]. Beside rather poor frequency dynamics, VSC dominated MGs suffer from large frequency deviations and lower frequency stability due to elimination of rotating inertia of SGs. Recently, some modern control techniques have been developed to embed virtual inertia into VSCs and emulate SGs, such as virtual synchronous generators (VSGs) [42–45], and synchronous converters [21,46]. However, there are some drawbacks and concerns related to them mandating more work to improve them. For example, VSGs still need internal current and voltage control loops, thus a droop-controlled VSG may require up to four nested loops [45]. Moreover, almost all of them present a first or second order VSG, which restricts their disturbance rejection capability. Transition to islanding may also destabilize internal loops.

Furthermore, although it is widely adopted in the literature to use VC-grid forming strategies to control islanded MGs [11], it is known that these techniques do not have good current control and imitation features [11,19]. In these strategies, references of frequency and amplitude of the voltage are obtained by the conventional droop methods and some internal voltage and current loops must be used to regulate current and voltage [11]. Indeed, the output of power manager/droop control is the voltage command. The internal current and voltage loops may significantly reduce overall system bandwidth and stability margin, and complicate controller design. Also, VC-VSCs have rather poor grid synchronization and they are not commonly used for grid-connected applications. In spite of VC strategies, CC-grid supporting techniques are more compatible with grid codes and present the following advantages [23–26]: direct control of instantaneous currents, overload and peak current protection, high-performance grid synchronization, and compensation of effects due to load parameter change. However, in the islanded mode since VSCs are supposed to support MG voltage and frequency, as there is no main utility grid to do so, conventional CC techniques commonly offer poor performance in the islanding and even may destabilize MG due to frequency and voltage excursion [25]. Actually, CC strategies are commonly supposed to generate preset currents, so they do not have direct control over voltage amplitude and frequency.

Our contributions: The family of synchronous current converters are unified controllers which can realize all the aforementioned requirements. However, this new trend still needs significant improvements and further works. The synchronous converters proposed in [21,41,46], are single-loop second-order controllers which adopt solely power, dc-link voltage or dq-axis current components as feedback signal. In spite of conventional vector controllers, synchronous converters work in polar coordinates and directly control amplitude and angle of VSC output voltage. This allows synchronous converters to present similar characteristics of synchronous machines and introduce some virtual inertia for the grid frequency support. Moreover, they have internal grid synchronization capabilities without the need for an extra synchronization unit like a PLL. However, synchronous converters in [21,41,46] are some basic controllers and suffer from some drawbacks: 1-they are single-loop which control and regulate either power (synchronous power converter [21]) or current (synchronous current converter [21,41]). 2- They are first or second-order controllers, thus this low-order nature restricts their disturbance rejection ability and renders low degree of freedom for a designer to tune controller parameters such that all the control targets are optimally achieved. It is known that low-order controllers cannot realize satisfactory in a wide range of operating conditions particularly for high-order systems [22]. 3- Current limitation and fault-ride-through features and capabilities of the basic synchronous converters have not been investigated yet while their single-loop and low-order nature results in a limited capability in fault current restriction. This is more critical particularly in VSCs with LCL filters. This discussion proves that developing CC-MGs by using advanced high-order power-source synchronous current converter technology is an interesting option.

This paper focuses on the development of CC-MGs by introducing high-order power-source synchronous current converters to integrate aforementioned advantages in one unified controller. In summary, the controller has the following advantages:

- Although there is no explicit droop control, the fourth-order current controller inherently realizes load sharing. In spite of conventional droop-based load sharing methods [11,28,29] or some other modern methods (e.g. [30–32]) in the literature, the proposed controller in this paper uses a high-order band-pass filter for load sharing which is a new trend and technique for load sharing in MGs. In other words, it is a droop-less controller with load sharing capability.

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