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Sliding mode voltage control of boost converters in DC microgrids☆

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ABSTRACT

This paper deals with the design of a robust decentralized control scheme for voltage regulation in boost-based DC microgrids. The proposed solution consists of the design of a suitable manifold on which voltage regulation is achieved even in presence of unknown load demand and modeling uncertainties. A second order sliding mode control is used to constrain the state of the microgrid to this manifold by generating continuous control inputs that can be used as duty cycles of the power converters. The proposed control scheme has been theoretically analyzed and validated through experiments on a real DC microgrid.

1. Introduction

Nowadays, due to economical, technological and environmental reasons, the most relevant challenge in power grids deals with the transition of the traditional power generation and transmission systems towards the large scale introduction of smaller Distributed Generation units (DGus) (Ackermann, Andersson, & Söder, 2001; Guerrero et al., 2010; Lopes, Hatziargyriou, Mutale, Djapic, & Jenkins, 2007; Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005). Moreover, due to the ever-increasing energy demand and the public concern about global warming and climate change, much effort has been focused on the diffusion of environmentally friendly Renewable Energy Sources (RES) (Panwar, Kaushik, & Kothari, 2011). However, it is well known that when several DGus are interconnected to each other, issues such as voltage and frequency deviations arise together with protections problems (Pepermans et al., 2005; Wang & Wang, 2008). In this context, in order to integrate different types of RES and, in addition, electrify remote areas, the so-called *microgrids* have been proposed as a new concept of electric power systems (Carrasco et al., 2006; Kanase-Patil, Saini, & Sharma, 2010; Liserre, Sauter, & Hung, 2010). Microgrids are electrical distribution networks, composed of clusters of DGus, loads, energy storage systems and energy conversion devices interconnected through power distribution lines and able to operate in islanded and grid-connected modes (Hatziargyriou, Asano, Iravani, & Marnay, 2007; Katiraei, Iravani, & Lehn, 2005; Lasseter, 2002; Lasseter & Paigi, 2004).

Since electrical Alternating Current (AC) has been widely used in most industrial, commercial and residential applications, AC microgrids have attracted the attention of many control system researchers as well as power electronics and electrical engineers (Cucuzzella, Incremona, & Ferrara, 2015, 2017; De Persis & Monshizadeh, 2018; Sadabadi, Shafiee, & Karimi, 2017; Schiffer, Ortega, Astolfi, Raisch, & Sezi, 2014; Simpson-Porco, Dörfler, & Bullo, 2013; Trip, Bürger, & De Persis, 2014). However, several advantages of DC microgrids with respect to AC microgrids are well known (Dragicevic, Vasquez, Guerrero, & Skrlec, 2014; Justo, Mwasilu, Lee, & Jung, 2013). The most important advantage relies on the natural interface of many types of RES, energy storage systems and loads (e.g. photovoltaic panels, batteries, electronic appliances and electric vehicles) with DC network, through DC–DC power converters. For this reason, lossy conversion stages are reduced and consequently DC microgrids are more efficient than AC microgrids. Furthermore, control systems for a DC microgrid are less complex than the ones required for an AC microgrid, where several issues such as synchronization, frequency regulation, reactive power flows, harmonics and unbalanced loads need to be addressed.

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DC microgrids can operate in the so-called islanded operation mode to supply an isolated area or can be connected to existing AC networks (e.g. an AC microgrid or the main grid) through a DC–AC bidirectional converter, forming a so-called hybrid microgrid (Guerrero, Loh, Lee, & Chandorkar, 2013; Liu, Wang, & Loh, 2011), ensuring a high power quality level. Moreover, the growing need of interconnecting remote power networks (e.g. off-shore wind farms) has encouraged the use of High Voltage Direct Current (HVDC) technology, which is advantageous not only for long distances, but also for underwater cables, asynchronous networks and grids running at different frequencies (Flourentzou, Agelidis, & Demetriades, 2009). Different control approaches have been investigated in the literature (see for instance Andreasson, Wiget, Dimarogonas, Johansson, & Andersson, 2017, Benedito, del Puerto-Flores, Dòria-Cerezo, van der Feltz, & Scherpen, 2016, Zonetti, Ortega, & Schiffer, 2018 and the references therein). Finally, DC microgrids are widely deployed in avionics, data centers, traction power systems, manufacturing industries, and recently used in modern design for ships and large charging facilities for electric vehicles. For all these reasons, DC microgrids are attracting growing interest and receive much attention from the research community.

Two main control objectives in DC microgrids are voltage regulation and current or power sharing. Regulating the voltages is required to ensure a proper operation of connected loads, whereas current or power sharing prevents the overstressing of any source. Typically, both objectives are simultaneously achieved by designing hierarchical control schemes. In the literature, these control problems have been addressed by different approaches (see for instance Anand, Fernandes, & Guerrero, 2013, Cucuzzella, Rosti, Cavallo, & Ferrara, 2017, Cucuzzella, Trip, De Persis, Ferrara, & van der Schaft, 2017, De Persis, Weitenberg, & Dörfler, 2016, Hamzeh, Ghazanfari, Mohamed, & Karimi, 2015, Guerrero, Vasquez, Matas, de Vicuna, & Castilla, 2011; Han et al., 2017, Nasirian, Moayedi, Davoudi, & Lewis, 2015, Tucci, Meng, Guerrero, & Ferrari-Trecate, 2016, Zhao & Dörfler, 2015 and the references there in). All these works deal with DC–DC buck converters or do not take into account the model of the power converter. However, in many battery-powered applications such as hybrid electric vehicles and lighting systems, DC–DC boost converters can be used in order to achieve higher voltage and reduce the number of cells[1] (Mohamed, 2016; O'Keeffe, Riverso, Albiol-Tendillo, & Lightbodyt, 2017; Yadav, Ray, & Lokhande, 2017). Since the dynamics of the boost converter are nonlinear, regulating the output voltage in presence of unknown load demand and uncertain network parameters is not an easy task. For all these reasons, the solution in this paper relies on the Sliding Mode (SM) control methodology to solve the voltage control problem in boost-based DC microgrids affected by nonlinearities and uncertainties (Edwards & Spurgen, 1998; Utkin, 1992; Utkin, Guldner, & Shi, 2009). Indeed, sliding modes are well known for their robustness properties and, belonging to the class of Variable Structure Control Systems, have been extensively applied in power electronics, since they are perfectly adequate to control the inherently variable structure nature of DC–DC converters (Cavallo & Guida, 2012; Shtessel, Zinober, & Shkolnikov, 2002a, b; Sira-Ramirez & Rios-Bolivar, 1994; Sira-Ramírez & Silva-Ortigoza, 2006; Tan, Lai, & Tse, 2006). SM controllers require to operate at very high (ideally infinite) and variable switching frequency. This condition increases the power losses and the issues related to the electromagnetic interference noise, making the design of the input and output filters more complicated (Tan, Lai, & Tse, 2008). SM controllers based on the hysteresis-modulation (also known as delta-modulation) have been proposed in order to restrict the switching frequency (see for instance Cardoso, Moreira, Menezes, & Cortizo, 1992). To do this, additional tools such as constant timer circuits or adaptive hysteresis band are required, making the solution more elaborated and then unattractive. Moreover, this approach (called quasi-SM) reduces the robustness of the control system (Bartoszewicz, 1998). Alternatively, the so-called equivalent control approach and the application of state space averaging method to SM control have been proposed together with the Pulse Width Modulation (PWM) technique (otherwise known as duty cycle control) to achieve constant switching frequency (Mahdavi, Emadi, & Toliyat, 1997). However, computing the equivalent control often requires the perfect knowledge of the model parameters as well as the load and the input voltage (Fadil, Giri, & Ouadi, 2006), or the implementation of observers to estimate them (Oucheriah & Guo, 2013). Alternatively, in Wai and Shih (2011) a total SM controller has been proposed relying on the nominal model of a single boost converter and exploiting a discontinuous control law to reject the model uncertainties.

In this paper, in order to control the output voltage of boost converters in DC microgrids, a fully decentralized Second Order SM (SOSM) control solution is proposed, capable of dealing with unknown load and input voltage dynamics, as well as uncertain model parameters, without requiring the use of observers. Due to its decentralized and robust nature, the design of each low-level local controller does not depend on the knowledge of the whole microgrid, making the control synthesis simple, the control scheme scalable and suitable for be coupled with higher-level control schemes aimed at generating voltage references that guarantee load sharing. Since a higher order sliding modes methodology is used, the proposed controllers generate continuous inputs that can be used as duty cycles, in order to achieve constant switching frequency. Besides, being of higher order, a distinguishing feature of the proposed control scheme is that an additional auxiliary integral controller is coupled to the controlled converter, via suitable designed sliding function. Moreover, with respect to the existing literature (to the best of our knowledge) in this paper the local stability of a boost-based microgrid is analyzed, instead of the single boost converter, theoretically proving that on the obtained sliding manifold, the desired operating point is robustly locally exponentially stable. Additionally, the analysis is useful to choose suitable controller parameters ensuring the stability, and facilitates the tuning of the controllers. The proposed control scheme has been validated through experimental tests on a real DC microgrid test facility at Ricerca sul Sistema Energetico (RSE), in Milan, Italy (Ronchegalli & Lazzari, 2016), showing satisfactory closed-loop performances.

The present paper is organized as follows: Section 2 introduces the main concepts and the description of the considered system. In Section 3 the microgrid model is presented and the control problem is formulated, while in Section 4 the proposed SOSM is designed. In Section 5 the stability properties of the controlled system are theoretically analyzed, while in Section 6 the experimental results on a real DC microgrid are illustrated and discussed. Some conclusions are finally gathered in Section 7.

2. DC microgrid model

Before introducing the model of the considered boost-based DC microgrid, for the readers' convenience, some basic notions on DC microgrids are presented.

Fig. 1 shows the electrical scheme of a typical boost-based DC microgrid, where two DGus, with local loads, exchange power through the distribution line represented by the resistance R_{ij}. The energy source of a DGu, which can be of renewable type, is represented, for simplicity, by a DC voltage source V_{DC}. The boost converter feeds a local DC load with a voltage level V higher than V_{DC}. Note that, the boost converter allows to obtain an output voltage level higher than or equal to the voltage input. This is done due to the quick succession of two different operation stages during which the inductance L_t accumulates or supplies energy. The resistance R_t, instead, represents all the unavoidable energy losses. Finally the capacitor C_t is used in order to maintain a constant voltage at the output of the power converter. The local DC load is connected to the so-called Point of Common Coupling (PCC) and it can be treated as a current disturbance I_L.

[1] Battery-powered applications often stack cells in series to increase the voltage level.