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Standalone DC microgrids as complementarity dynamical systems: Modeling and applications

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ABSTRACT

It is well known that, due to bimodal operation as well as existent discontinuous differential states of batteries, standalone microgrids belong to the class of hybrid dynamical systems of non-Filippov type. In this work, however, standalone microgrids are presented as complementarity systems (CSs) of the Filippov type which is then used to develop a multivariable nonlinear model predictive control (NMPC)-based load tracking strategy as well as Modelica models for long-term simulation purposes. The developed load tracker strategy is a multi-source maximum power point tracker (MPPT) that also regulates the DC bus voltage at its nominal value with the maximum of $\pm 2.0\%$ error despite substantial demand and supply variations.

1. Introduction

Microgrids are the building blocks of the modern power grids. In fact, the near future distribution grids can be seen as a network of several interconnected microgrids which locally generate, consume, and even store energy (Guerrero, Chandorkar, Lee, & Loh, 2013). Intermittent solar and wind energies, coupled with battery storages, contribute to the energy resources for supplying variable load demands of the microgrids (Nema, Nema, & Rangnekar, 2009). Due to some challenges that ac microgrids face with hosting several distributed energy systems (Balog, Weaver, & Krein, 2012; Guerrero, Loh, Lee, & Chandorkar, 2013), such as the need for synchronization, dc microgrids have gained more popularity particularly for standalone applications in avionic, automotive, or marine industries as well as the remote rural areas (Guerrero, Chandorkar, et al., 2013; Justo, Mwasilu, Lee, & Jung, 2013). There are various interests in employing nonlinear model predictive control (NMPC) technique (Findeisen & Allgöwer, 2002; Grüne & Pannek, 2011) to develop coordinated multivariable control strategies for the standalone microgrids (e.g. Qi, Liu, & Christofides, 2013; Schuler, Schlipf, Cheng, & Allgöwer, 2013). However, such control strategies require the use of an adequate mathematical model of the microgrids in order to predict their behavior during the prediction horizon. Moreover, in smart grid applications, such a model is needed to simulate the microgrids behavior for at least one day ahead (Gkatzikis, Koutsopoulos, & Salonidis, 2013). There are three major considerations that need to be taken into account when developing a mathematical model for the microgrids: (i) the algebraic constraints presented by the PV module, wind turbine, and battery bank; (ii) the battery bank as a sub-system with two modes of operation, namely charging and discharging; and (iii) the cycle life of the battery bank as a discontinuous differential state.

Algebraic constraints and bimodal operation of battery bank lead to a description of standalone dc microgrids as a set of hybrid differential algebraic equations (hybrid DAEs) (Dizqah, Maheri, Busawon, & Kamjoo, 2014; Fritzson, 2011). Therefore, the standalone dc microgrids can be represented by an acausal model for the control and simulation purposes. Unlike the causal approach, which requires the system being decomposed into a chain of causal interacting blocks consisting of only ordinary differential equations (ODEs), the acausal modeling is a declarative approach in which individual parts of the model are described as hybrid DAEs (Fritzson, 2011). Acausal modeling, as the mathematical representation of the system, is an effective way to model and simulate complex systems and such a model is also applicable to develop NMPC strategies. Modelica (Fritzson, 2004), as an object-oriented and equation-based language to describe complex systems, provides the capability to acausally model the class of hybrid dynamical systems (Fritzson, 2011).

Moreover, the cycle life of the batteries, as discontinuous differential states, causes the system to be of the non-Filippov type (Filippov & Arscott, 1988), which is more challenging to analyze. The cycle life is defined as the total number of complete charging/

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discharging cycles a battery can undergo before its capacity falls down below 80% of its nominal value. Apart from the cycle life, standalone dc microgrids can be modeled as differential inclusions (DIs) (Dizqah, Maheri, Busawon, & Fritzson, 2013) of the Filippov type. Biegler (2010) argued that the NMPC strategies to control the hybrid systems of the Filippov type may be solved by employing a variable element length version of the collocation method. Applying this flexible version of the collocation method transfers such a NMPC problem into a mathematical programming with the complementarity constraints (MPCC). Then, employing the penalization method, the resulting MPCC can be transformed into a nonlinear programming (NLP) problem which can be solved by general purpose NLP solvers. However, in order to transform the NMPC problem to a MPCC, such problem should be of the complementarity class of the hybrid dynamical systems (Heemels & Brogliato, 2003).

The main aim of this paper is to provide a mathematical model of the standalone dc microgrids applicable to NMPC strategies as well as long-term simulation purposes. For this aim the standalone dc microgrids are modeled as complementarity systems (CSs) including differential and algebraic constraints as well as mixed complementarity problems (MCPs). The discontinuous cycle life differential state is reformulated with a continuous approximation. Such a reformulation transforms the proposed dc microgrid model to be of the Filippov type. Moreover, the bimodal operation of the battery bank is also modeled as separate complementarity constraints. The developed model is then used in two different applications: (i) the equivalent model in the form of DIs is employed to simulate the standalone dc microgrids; and (ii) a NMPC strategy based on the presented model is developed to track the load demands and regulate the dc bus voltage despite substantial generation fluctuations. It is shown that the developed model can be solved with DASSL general purpose DAE solver (Petzold, 1983) equipped with the event detector and consistent re-initialization features. The obtained results indicate that the proposed model is accurate for simulating different variables of the dc microgrids using the OpenModelica environment (Fritzson et al., 2005). Moreover, it is shown that the developed model is agile enough to be solved with available NLP solvers in order to be used in NMPC control strategies.

The remainder of this paper is organized as follows. Section 2 briefly describes the standalone dc microgrid studied in this paper. Section 3 provides preliminaries on mathematical concepts mentioned throughout the paper. Section 4 deals with the modeling of a standalone dc microgrid as a CS. Sections 5 and 6 present and discuss the above-mentioned two applications of the developed model of the standalone dc microgrids. Finally, the conclusion of the study is given in Section 7.

2. Standalone dc microgrids

Fig. 1 illustrates a topology of a standalone dc microgrid for the small-scale applications. It consists of wind, solar, and battery branches which are connected to the dc bus through dc-coupled structures, i.e. via dc–dc converters. The microgrid supplies a variable linear dc load which is connected directly to the grid bus.

The wind turbine operates at variable speeds and is connected to a permanent magnet synchronous generator (PMSG) directly, i.e. direct-drive coupling. The direct-drive coupling provides some advantages in terms of high reliability and is more popular for small-scale wind turbines (Li & Chen, 2008). In spite of high cost, the PMSG is the most dominant type of the direct-drive generators in the market (Li & Chen, 2008), chiefly due to higher efficiency. The solar branch, in other hand, consists of a photovoltaic (PV) array that injects harvested energy into the microgrid through a boost-type converter. Fakham, Lu, and Francois (2011) showed that

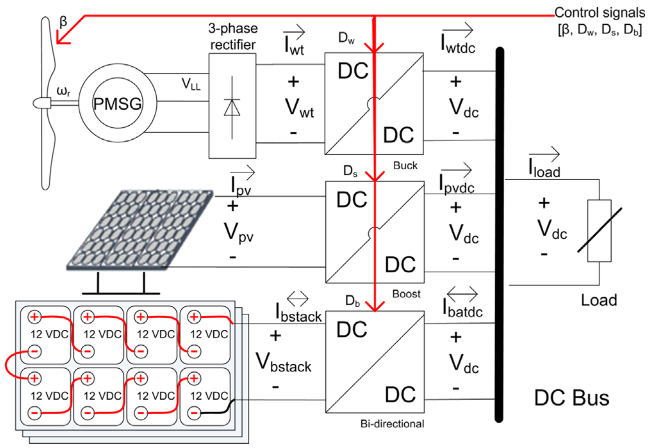

Fig. 1. The topology of a small-scale and standalone dc microgrid.

employing a dc-coupled structure to connect the battery bank to the dc bus is more flexible in terms of implementing different charging and discharging regimes and despite power losses.

From Fig. 1, it can be seen that the presented dc microgrid is controlled by four manipulated variables, i.e. the wind turbine pitch angle and the switching duty cycles of three different dc–dc converters. While increasing the wind turbine pitch angle promotes pitching to feather, the operating points of the PMSG, PV, and battery bank can be changed by varying the dc–dc converters duty cycles.

3. Preliminaries

3.1. Introduction to the differential inclusions (DIs) of the Filippov type

Consider the following system:

$$\dot{\mathbf{x}} \in \mathcal{F}(\mathbf{x}, \mathbf{u}; t). \tag{1}$$

where $\mathcal{F}$ is a non-empty, bounded, and closed set of functions.

This piecewise continuous class of differential equations, which is known as differential inclusions (Filippov & Arscott, 1988), presents discontinuous right-hand sides. A differential inclusion given by Eq. (1) is of the Filippov type on an interval $[a, b]$ if the differential states remain continuous on that interval.

The following Eq. (2) indicates a specific representation of the differential inclusions with two modes of operation (Biegler, 2010):

$$\dot{\mathbf{x}} = \begin{cases} f_-(\mathbf{x}, \mathbf{u}; t) & \text{for } \sigma(\mathbf{x}(t)) < 0, \\ \nu(t) f_-(\mathbf{x}, \mathbf{u}; t) + \\ \quad (1-\nu(t)) f_+(\mathbf{x}, \mathbf{u}; t) & \text{for } \sigma(\mathbf{x}(t)) = 0, \\ f_+(\mathbf{x}, \mathbf{u}; t) & \text{for } \sigma(\mathbf{x}(t)) > 0. \end{cases} \tag{2}$$

where $\mathbf{x}(t)$ and $\mathbf{u}(t)$ are the states and manipulated control signals, respectively. The switching function $\sigma(\mathbf{x}(t))$ determines transitions between two modes of operation while a convex combination of the two models is allowed at the transition point with $\nu(t) \in [0, 1]$.

3.2. Introduction to complementarity systems (CSs)

CSs, as specific types of the class of hybrid dynamical systems, arise in several engineering applications dealing with multi-modal systems. A CS is formulated as the following general form which consists of orthogonal inequality (Eq. (3c)) also known as