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Survey paper

A survey on modeling of microgrids—From fundamental physics to phasors and voltage sources[☆]

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ABSTRACT

Microgrids have been identified as key components of modern electrical systems to facilitate the integration of renewable distributed generation units. Their analysis and controller design require the development of advanced (typically model-based) techniques naturally posing an interesting challenge to the control community. Although there are widely accepted reduced order models to describe the dynamic behavior of microgrids, they are typically presented without details about the reduction procedure—hampering the understanding of the physical phenomena behind them. Preceded by an introduction to basic notions and definitions in power systems, the present survey reviews key characteristics and main components of a microgrid. We introduce the reader to the basic functionality of DC/AC inverters, as well as to standard operating modes and control schemes of inverter-interfaced power sources in microgrid applications. Based on this exposition and starting from fundamental physics, we present detailed dynamical models of the main microgrid components. Furthermore, we clearly state the underlying assumptions which lead to the standard reduced model with inverters represented by controllable voltage sources, as well as static network and load representations, hence, providing a complete modular model derivation of a three-phase inverter-based microgrid.

1. Introduction

1.1. Motivation

It is a widely accepted fact that fossil-fueled thermal power generation highly contributes to greenhouse gas emissions (Lund, 2007, 2009; Machowski, Bialek, & Bumby, 2008). In addition, a growing stream of scientific results (Hansen et al., 2005; Houghton, 1996; Solomon, 2007) has substantiated claims that these emissions are a key driver for climate change and global warming. As a consequence, many countries have agreed to reduce their greenhouse gas emissions.

Apart from a reduction of energy consumption, *e.g.*, through an increase in efficiency, one possibility to reduce greenhouse gas emissions is to shift the energy production from fossil-fueled plants towards renewable sources (Chowdhury & Crossley, 2009; Lund, 2007, 2009). Therefore, the worldwide use of renewable energies has increased significantly in recent years (Teodorescu, Liserre, & Rodriguez, 2011).

Unlike fossil-fueled thermal power plants, the majority of renewable power plants are relatively small in terms of their generation power. An important consequence of this smaller size is that most of them are connected to the low voltage (LV) and medium voltage (MV) levels. Such generation units are commonly denoted as distributed generation (DG) units (Ackermann, Andersson, & Söder, 2001). In addition, most renewable DG units are interfaced to the network via DC/AC inverters. The physical characteristics

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of such power electronic devices largely differ from the characteristics of synchronous generators (SGs), which are the standard generating units in existing power systems. Hence, different control and operation strategies are needed in networks with a large amount of renewable DG units (Green & Prodanovic, 2007; Teodorescu et al., 2011; Varaiya, Wu, & Bialek, 2011).

1.2. The microgrid concept

One potential solution to facilitate the integration of large shares of renewable DG units are microgrids (Chowdhury & Crossley, 2009; Green & Prodanovic, 2007; Hatziargyriou, Asano, Iravani, & Marnay, 2007; Katiraei, Iravani, Hatziargyriou, & Dimeas, 2008; Lasseter, 2002; Strbac et al., 2015). A microgrid gathers a combination of generation units, loads and energy storage elements at distribution or sub-transmission level into a locally controllable system, which can be operated either in grid-connected mode or in islanded mode, *i.e.*, in a completely isolated manner from the main transmission system. The microgrid concept has been identified as a key component in future electrical networks (Chowdhury & Crossley, 2009; Farhangi, 2010; Lasseter, 2011; Strbac et al., 2015).

Many new control problems arise for this type of networks. Their satisfactory solution requires the development of advanced model-based controller design techniques that often go beyond the classical linearization-based nested-loop proportional–integral (PI) schemes. This situation has, naturally, attracted the attention of the control community as it is confronted with some new challenging control problems of great practical interest.

It is clear that to carry out this task it is necessary to develop a procedure for assembling mathematical models of a microgrid that reliably capture the fundamental aspects of the problem. Such models have been developed by the power systems and electronics communities and their pertinence has been widely validated in simulations and applications (Coelho, Cortizo, & Garcia, 2002; Katiraei & Iravani, 2006; Mohamed & El-Saadany, 2008; Pogaku, Prodanovic, & Green, 2007). However, these are reduced or simplified, *i.e.*, linearized, models that are typically presented without any reference to the reduction procedure—hampering the understanding of the physical phenomena behind them.

1.3. Existing literature

For the purposes of this survey, previous work on microgrid modeling can be broadly categorized into two classes. The first class focuses on modeling and control of inverter-interfaced DG units in microgrid applications, but the model derivation is restricted to individual DG units and the current and power flows between different units are not considered explicitly (Bidram, Davoudi, Lewis, & Qu, 2013; Bidram, Lewis, & Davoudi, 2014; Green & Prodanovic, 2007; Guerrero, Loh, Chandorkar, & Lee, 2013; Katiraei & Iravani, 2006; Pogaku et al., 2007; Rocabert, Luna, Blaabjerg, & Rodriguez, 2012; Zhong & Hornik, 2012). The second class discusses models of microgrids including electrical network interactions, but the model derivation is based on linearization (*i.e.*, the so-called small-signal model) (Katiraei, Iravani, & Lehn, 2007; Mohamed & El-Saadany, 2008; Pogaku et al., 2007). Furthermore, this class of modeling is often tied to specific network control schemes, such as droop control (Coelho et al., 2002; Pogaku et al., 2007) or to specific test networks (Katiraei & Iravani, 2006; Katiraei et al., 2007; Miao & Domijan, 2011; Mohamed & El-Saadany, 2008). Building on this previous work and in a survey-like manner, the present paper brings both aforementioned classes together to formulate a generic modular model of a microgrid.

Going beyond a mere review of existing microgrid models, we employ model reduction via a time-scale separation together with the subsequent derivation of the well-known power flow equations, which is a standard procedure in SG-based networks (Venkatasubramanian, Schattler, & Zaborszky, 1995). A similar approach has also been employed for microgrids in Luo and Dhople (2014), Mariani, Vasca, and Guerrero (2014a,b) and Riverso, Sarzo, and Ferrari-Trecate (2015). However, neither reference provides a detailed model derivation for inverter-interfaced units. Also, the analysis in Mariani et al. (2014a,b) is restricted to an AC microgrid consisting of two inverters connected via a resistive-inductive line and two local resistive-inductive loads, while the modeling procedure of the present paper applies to networks with generic topology and arbitrary number of units.

1.4. About the survey

The present survey is an attempt to provide a guideline for control engineers attracted by this fundamental application for Smart Grids to assess the importance of the main dynamical components of a three-phase inverter-based microgrid as well as the validity of different models used in the power literature. To this end, we at first review some fundamental concepts and definitions in power systems, including a survey on the notion of instantaneous power. Subsequently, we introduce the reader to the microgrid concept and discuss its main components. We illustrate that inverter-interfaced units are the main new elements in future power networks, detail the basic functionality of inverters and review the most common operation modes of inverter-interfaced units together with their corresponding control schemes. This paves the path for – starting from fundamental physics – presenting detailed dynamical models of the individual microgrid components. Subsequently, we clearly state the underlying assumptions which lead to the standard reduced model with inverters represented by controllable voltage sources, as well as static network and load representations. This reduced model is used in most of the available work on microgrid control design and analysis (Ainsworth & Grijalva, 2013; Dörfler et al., 2015; Münz & Metzger, 2014; Schiffer, Ortega, Astolfi, Raisch, & Sezi, 2014a; Simpson-Porco, Dörfler, & Bullo, 2013b).

We focus on purely inverter-based networks, since inverter-interfaced units are the main new elements in microgrids compared to traditional power systems. However, we remark that the employed modeling and model reduction techniques can equivalently be applied to standard bulk power system models as well as to power systems with mixed generation pool. For modeling of traditional electro-mechanical SG-based units, the reader is referred to standard textbooks on power systems (Anderson & Fouad, 2002; Kundur, 1994; Machowski et al., 2008).

The main contributions of the present survey paper are summarized as follows.

- Provide a detailed comprehensive model derivation of a microgrid based on fundamental physics and combined with detailed reviews of the microgrid concept, its components and their main operation modes.
- Answer the question, when an inverter can be modeled as a controllable AC voltage source and depict the necessary underlying model assumptions.
- Show that the usual power flow equations can be obtained from a network with dynamic line models via a suitable coordinate transformation (called dq-transformation) together with a singular perturbation argument.
- By combining the two latter contributions, recover the reduced-order microgrid model currently widely used in the literature.