Electric Power Systems Research 158 (2018) 105–114

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Bond graph approach for port-controlled Hamiltonian modeling for SST

R.V. Meshram [a,*], S.V. Khade [a], S.R. Wagh [a], N.M. Singh [a], A.M. Stanković [b]

[a] Electrical Engineering Department, VJTI, Mumbai, India
[b] EECS Department, Tufts University, MA, USA

ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form
29 December 2017
Accepted 31 December 2017

Keywords:
Bond graph (BG)
Dirac structure
Energy based modelling
Microgrid
Port controlled Hamiltonian system (PCHS)
Solid state transformer (SST)

ABSTRACT

Energy-based modeling is often very appropriate for physical system modeling for development and analysis of multi domain dynamic system models. One such tool for modelling of system is bond graph (BG), which allows to model complex system, with clear interconnection rules and preserving the physical structure of the system. In various engineering system, operation is carried out on various time scale. One such area of generic system is microgrid, where multidisciplinary microgrid components operating on various time scales. In such hybrid system, flows and efforts comprise a very good choice of variables to link components for system stability and performance analysis. Since components are typically connected through various power electronics devices, mathematical modeling capable of capturing high frequency behavior is of utmost concern in stability analysis. Solid state transformer (SST) is one such device playing a key role in bi-directional power flow between the grid and various renewable sources. This paper proposes the use of the BG approach to recognize the energy representation of the microgrid in port-Hamiltonian form by looking at the energy transformation aspects of microgrid components. The port-controlled Hamiltonian systems (PCHS) are the mathematical description of bond graphs which allows integration of subsystems of hybrid microgrid using energy as the linking concept. To illustrate the utility of BG in hybrid systems, basic PI controller is implemented. The aim of the paper is to show how to model complex systems in bond graph domain.

1. Introduction

Solid state transformer (SST) is one of the new power electronic components that has found its application in renewable energy integration and power quality conditioning. SST converts the voltage from ac to ac for step-up or step-down, paralleling the functionality of a conventional transformer, but with additional benefits.

Solid state transformer was first proposed in FREEDM system [1], which is based on solid state switches with high frequency isolation that behaves like a conventional transformer. The SST replace conventional low frequency transformer, which is connected to medium-voltage (MV) grid to low-voltage (LV) grid and offers the dc connectivity and services to both LV and MV grid [2–4]. The architecture of SST is shown in Fig. 1, where three stage configuration makes dc-link connectivity available. It consist of three stages: an ac/dc rectifier, a dc/dc dual active bridge (DAB), and a dc/ac inverter. The several topologies proposed for SST are based around the idea of bidirectional dc/dc DAB. The bidirectional power flow capability of SST supplies locally generated power back to grid. It is advantageous because of volume and weight reduction (around 20–50%) and efficiency improvement (from 93% to 96%). In electrical distribution system, the SST technology is used for smart grid functionality [5]. According to [6], however, the conventional 60 Hz transformer is replaced by a high frequency transformer to provide isolation and step up/down function with the power electronics converters, which is the key to achieve size reduction, weight reduction and the power quality improvement. The interest in energy-based modeling has been increasing over the years, as it offers a pathway to analysis and controller design techniques for nonlinear, multi-domain systems. Due to an energy-transformation aspect of the SST, it is interesting to investigate the system from an energy-based perspective. According to [5,7], generally, these techniques are based on the network modelling and the port interconnection between several subsystems. As an energy-based modeling tool, BG describes the physical system dynamics which are related to energy exchanges between system components.

A BG is a graphical, network-based description of a physical system, and describes the energy interconnection between its

* Corresponding author.
E-mail address: raginimeshram18@gmail.com (R.V. Meshram).

https://doi.org/10.1016/j.epsr.2017.12.035
0378-7796/

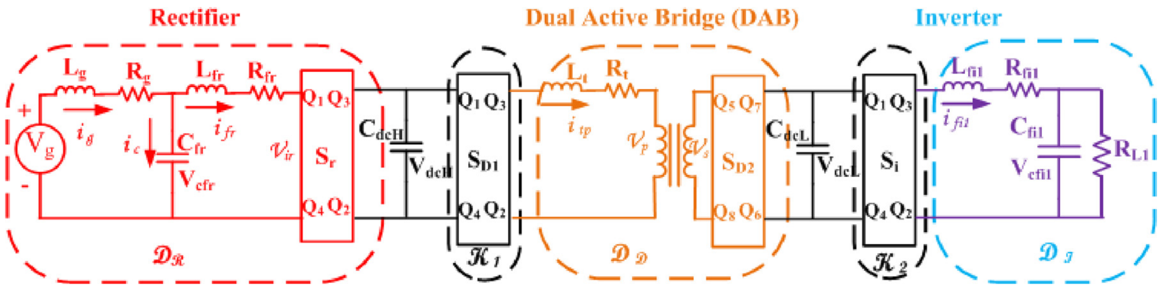

Fig. 1. Solid state transformer schematic.

generating, storing and dissipating elements. In hybrid SST involving power electronics converters, it is straightforward to obtain dynamical model with the help of BG due to its effectiveness in modelling of switches and capability to integrate subsystems and power transfer represented by bonds. This feature of BG is largely unavailable with other modelling techniques.

Our focus is on the mathematical description of BG called port-Hamiltonian systems or port-controlled Hamiltonian systems (PCHS) which allows modeling of interdisciplinary system as explained in [8–11]. Along with specifying systems in a modular, flexible and non-domain-specific way, BG theory allows a natural implementation of PI controller for 3-stage SST in PCHS form. This form is useful in study of nonlinear behavior, stability analysis, and for design PI controller to improve stability and characterize performance of SST when connected in microgrid.

The contributions of the paper are listed as:

1. The first major contribution of the paper lies in validating the strengths of well-established BG theory for complex network such as hybrid microgrid application.
2. Similarly, usefulness of BG is demonstrated in development of well-known port-controlled Hamiltonian system (PCHS) model for microgrid application which is best example of complex network.
3. The problem of interconnecting/coupling variables in development of nonlinear controller is easily resolved by inherent features of BG, which offers a graphical representation minimizing complexity in numerical computations. The effectiveness is exhibited with a main grid integrated with a hybrid microgrid having various renewable sources.
4. The key component of hybrid microgrid is SST, which provides isolation for dc and ac microgrids. In this paper, the systematic procedure is developed for formation of PCHS model using modular SST components including its interconnection links between various modules.
5. Though, the PI controller is well known, the focus of the paper is in development of energy based model of SST and expands it for complex network (hybrid microgrid) which is multi-scale and multidisciplinary. Hence, the PI controller used is just a representative controller and any advance linear or nonlinear controller can be developed for specific desired performance. In short, the paper focuses more on advocating unique features of BG in development of multidisciplinary model rather than particular controller development.

The BG modelling starts from the intuitive and physical approach that a dynamic system is composed of subsystems, components, or basic elements that interact by energy exchange. With reference to [12], an undirected BG displays the components of a system and their energy based interconnection. The transfer of energy between subsystems is enabled by means of engineering links, e.g., mechanical shafts, electrical wires, hydraulic conduits, hoses, or glass fibre optics cables. Since subsystems, components, and elements are represented by BG vertices and their energetic interaction by power bonds, BGs reflect the physical structure of a system, the way real engineering system components are connected. As long as BGs are constructed according to certain rules and are not simplified, they exhibit a strong topological affinity to the initial schematic of a mechanical system, an electrical circuit, or a cross sectional representation of a hydraulic device. Therefore, topological connections in a system schematic can guide the construction of a BG model which could be achieved by drawing a BG directly on top of a schematic.

In addition, BG can contribute and support quantitative model-based fault detection and isolation for systems that are appropriately described by a hybrid model. When system gets affected by more than one fault at the same time, advanced fault diagnostic method based on parameter estimation could be used. Sensitivity BG formulation allows real-time parameter estimation and thus it is possible not only to isolate multiple faults but also to quantify the fault severities [13].

This paper is organized in the following manner. Section 2 gives necessary preliminaries for Hamiltonian formulation. In Section 3 PCHS formulation of SST components using BG is carried out. Section 4 explains interconnection scheme to obtain PCHS model for 3-stage SST system from BG model of integrated SST with associated transformation. Section 5 interprets and demonstrates simulation results obtained for proposed BG models and Section 6 concludes the paper.

2. Necessary preliminaries

2.1. Bond graph model

BG technique is graphically oriented, and represents power flows between different elements of a system [14]. Mathematical equations suitable for simulation can easily deduced from the BG representation, either manually or using specialized software. This is advantageous for complex and large systems made of smaller subsystems. A graphical representation of a multiport system consisting energy flows called Generalized Bond Graph (GBG) is discussed in [15,16] and the topology of the interconnection of the systems components is represented [17,18] that appear in the GBG model as shown in Fig. 2. The part of a GBG that contains the topological information is known as the Generalized Junction Structure (GJS) is discussed in [17,19]. Every multibond can be associated to two power variables: effort e^r and flow f^r, where $r \in \{S_e, S_f, E, R\}$. They belong to dual spaces and their duality product $\langle e^r|f^r\rangle$ represents the power that goes from/to the junction structure, depending on the positive orientation indicated by half-arrow, to the R-type multiport or vice versa.

2.2. PCHS model

The notion of a port-Hamiltonian system is based on a Dirac structure as presented by Karnopp and Duindam in [20,21]. Dirac structure is power conservative, where it links the various port