Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Power Sources 122 (2003) 95–108
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Application of VTB in design and testing of satellite electrical power systems

Zhenhua Jiang*, Roger A. Dougal, Shengyi Liu

Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

Received 3 February 2003; accepted 10 February 2003

Abstract

Satellite electrical power systems (SEPS) are strongly interdisciplinary, exhibit complex nonlinear behavior, and operate over a wide range of power levels. The Virtual Test Bed (VTB) provides a unified computational environment that allows rapid modeling, simulation and virtual-prototyping of such complex systems. VTB handles modeling in a comprehensive and efficient way by using both topological and mathematical descriptions. The VTB is also endowed with mechanisms to import models and to co-simulate with other standard software. This paper presents a study of two representative SEPSs to demonstrate design and testing of such systems in the VTB. The performances of Li-ion and $Ni–H_2$ batteries are compared in a particular system.

Keywords: Battery; Solar array; Satellite electric power system; Shunt regulator; Virtual Test Bed

1. Introduction

A typical satellite electrical power system (SEPS) comprises a primary power source (solar array), an energy storage system (rechargeable batteries such as Ni–Cd, $Ni–H_2$, or Li-ion, or possibly new technologies such as flywheels), a shunt regulator, a power distribution and control unit (PDCU) and loads, as shown in Fig. 1. It contains components from multiple disciplines such as photovoltaics, electrochemistry, electrical system, control system and power electronics, complex nonlinear behaviors, for example, in the solar array and battery, and a wide range of power levels for power handling and signal processing. Due to the high manufacturing cost and complexity, it is necessary and important to perform simulation studies and build virtual-prototypes for satellite electrical power systems prior to construction of real hardware. Such prototypes help the engineers optimize the system architecture, components, and the system performance in terms of efficiency, power density, cost and lifetime. Many simulation tools have been proposed to study SEPS including circuit-oriented packages such as SPICE [1,2], PSpice [3], general-purpose state-flow or signal-flow simulators such as MatLab/Simulink [4], EASY5 [5,6] and application-specific software such as EBLOS [7]. Each of these simulation environments favors only one model formulation method, either structural modeling (circuit schematics), or behavioral modeling (mathematical equations). The circuit-oriented approach is intuitive and easy to understand, but in practice, it is often difficult, or even impossible to model a complex system because some parts of the system do not yield to easy expression of their characteristics in terms of existing circuit components. Therefore, it is advantageous to express some models in a mathematical formulation. The best parts of both modeling approaches can be accomplished by using a more integrative environment—the Virtual Test Bed (VTB) [8,9], the philosophy of which is consistent with IEEE standard [10]. VTB allows handling natural power flow, signal and data coupling between devices from multi-disciplines and offers a combination of both topological and mathematical expressions in model formulation for a comprehensive and efficient modeling process. In addition to the powerful capabilities for modeling, the VTB is endowed with mechanisms for

Abbreviations: ACSL, advanced circuit simulation language; BCDC, battery charge/discharge controller; BJT, bipolar junction transistor; DC, direct current; DET, direct energy transfer; EBLOS, energy budget low orbit satellite; HIL, hardware-in-the-loop; Li-Ion, lithium ion battery; MOSFET, metal-oxide-semiconductor field effect transistor; Ni–Cd, nickel cadmium battery; $Ni–H_2$, nickel hydrogen battery; PDCU, power distribution and control unit; RC, resistive companion; SEPS, satellite electrical power system; SOC, state of charge; SOD, state of discharge; SPICE, simulation program with integrated-circuit emphasis; VTB, Virtual Test Bed

* Corresponding author. Tel.: +1-803-777-9314; fax: +1-803-777-8045.
E-mail address: jiang@engr.sc.edu (Z. Jiang).

0378-7753/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0378-7753(03)00360-4

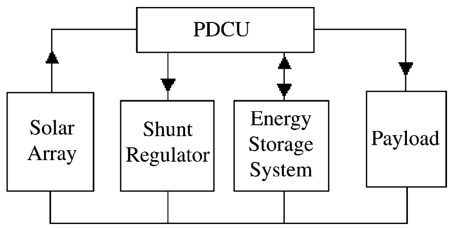

Fig. 1. Block diagram of the satellite electrical power system.

co-simulating with MatLab/Simulink, for importing models from ACSL (including co-simulation), for network-based simulation, and for simulation with hardware-in-the-loop (HIL) [11–13]. Because of these capabilities, VTB can assist in integrating expert knowledge from many disciplines, allowing study of the dynamic behaviors of complex interdisciplinary systems.

Complexity in modeling and simulation arises from satellite electrical power systems for several reasons. (1) The energy conversion and storage devices, such as the solar array and battery, involve multi-physics processes including photoelectric, electro-thermal and electrochemical processes. While conventional simulators are optimized for simulation in specialized disciplines, they are often incapable of dealing with the interdisciplinary modeling in a consistent and convenient manner, and in addition, they have difficulties in tackling strong nonlinearities existing in these devices. (2) The power distribution and control unit, responsible for power distribution and bus voltage regulation, has both devices for power handling and devices for signal processing and control. Using VTB, it is possible to express both the system topology and the component behavior in the most appropriate way (for example, using MatLab/Simulink for signal flow modeling of controllers, ACSL for state-based modeling of dynamic systems, etc.). It is thus easy to build a virtual prototype of the entire system that is suitable for detailed study of the system performance, even when people from different technical areas have contributed to definition of the various components of the system.

The method used in this paper models the interdisciplinary devices in the native VTB format, to designs the control system in Simulink, and then simulates the entire system in the VTB environment by importing the Simulink models. In this paper, interdisciplinary model formulation of various power handling components using native VTB resistive companion (RC) method [14] and model formulation of the regulator and control systems in MatLab/Simulink are presented. A direct energy transfer (DET) system is first studied to investigate the operation and performance of the shunt regulator. An example satellite electrical power system is then assembled using a combination of native and imported models. A simulation study is conducted to investigate the performance of the battery charging/discharging controller. The performances of Li-ion and Ni–H_2 batteries are compared.

2. Native RC modeling of the components

Both natural components and control systems are involved in a SEPS. Natural components, i.e. those to which energy conservation principles apply, are formulated by following the resistive companion approach as described in [14]. The method starts with mathematical expression of the device physics (or process) and yields a discretized set of time-domain linear equations in terms of terminal across and through variables.

The resistive-companion model of a n-terminal device, as illustrated in Fig. 2, described by its across variable vector $V(t)$ and through variable vector $I(t)$, has a standard form as follows:

$$I(t) = G(t-h)V(t) - B(t-h) \quad (1)$$

where $G(t-h)$ is the device conductance matrix, $B(t-h)$ is the through-variable history vector, and

$$G(t-h) = (g_{i,j}(t-h))_{n\times n} \quad (2)$$

$$B(t-h) = -I(t-h) + G(t-2h)V(t-h) \quad (3)$$

where h is the time step size taken by the time-domain solver. The formulation of the equations is not discipline specific, so unlike structural modeling, which tends to be discipline specific, the approach can be applied to physical processes of any discipline.

In the following, solar array, battery system and power converter are modeled here in detail, which are the important energy conversion and conditioning devices in a satellite electrical power system.

2.1. Solar array

The process of converting solar energy into electric energy in a semiconductor solar cell is well known [15–19]. Accompanying the process is heat generation due to direct infrared absorption and ohmic heating. Since the energy conversion process is affected not only by the cell properties and the load condition, but also by the solar irradiance and the temperature, it is necessary to build a multi-physics model [20] involving three energy domains: light, electricity and heat. Fig. 3 shows an equivalent circuit of the solar cell based on consideration of its interactions with its surroundings. The terminals v_0 and v_1, denoted by their across variables (voltages in V), are electrical in nature and deliver electric energy to the load. The terminal v_2 (or P, the solar

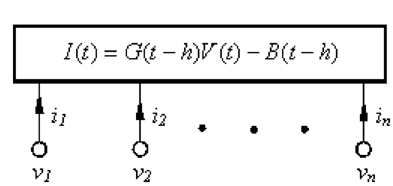

Fig. 2. A device of n terminals described by the resistive companion model.