Virtual-Prototyping Satellite Electrical Power Systems
Using the Virtual Test Bed

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ABSTRACT

The satellite electrical power subsystems (SEPS) consist of components of a wide range of power levels, complex nonlinear behaviors, and multiple disciplines. High manufacturing cost and complexity of SEPS make it essential to perform simulation studies and build virtual-prototypes prior to construction of real hardware. The Virtual Test Bed (VTB) provides a computational environment that allows rapid modeling, simulation and virtual-prototyping of such complex systems. The VTB is also endowed with mechanisms to import models, and to co-simulate with other standard software packages. In this paper, a representative satellite electrical power system is virtually prototyped in VTB to demonstrate: 1) modeling of interdisciplinary devices such as solar array and battery system, and other power devices such as power converters, 2) co-simulation using MatLab/Simulink models for battery charge/discharge controller, and protection circuits, and 3) virtual-prototyping and simulation of the system to optimize performance. The simulation study focuses on the dynamic behaviors of solar array and battery in orbit cycles, and the system responses under different fault conditions.

I. INTRODUCTION

Due to high manufacturing cost and complexity of satellite electrical power systems (SEPS), it is essential to perform simulation studies and build virtual-prototypes prior to construction of real hardware. Such prototypes help to optimize the system architecture, component choices, and the system performance in terms of efficiency, power density, cost and lifetime. Many simulation tools have been used to study SEPS including circuit-oriented packages such as SPICE [1, 2], and PSpice [3], general-purpose state-flow or signal-flow simulators such as MatLab/Simulink [4], or EASY5 [5, 6] and application-specific softwares 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. In this paper, we describe how the best parts of both modeling approaches can be accomplished by using a more integrative environment - the Virtual Test Bed [8, 9]. The philosophy of the VTB environment is consistent with IEEE standard [10], which allows handling natural power flow, signal and data coupling between devices of multi-disciplines and it 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 importing models from ACSL (including cosimulation), for co-simulating with MatLab/Simulink, for network-based simulation, and for simulation with hardware-in-the-loop (HIL) [11, 12, 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.

A typical SEPS comprises of a primary power source (solar array), an energy storage system (rechargeable batteries such as Ni-Cd, Ni-H2, or Li-Ion, or possibly new technologies such as flywheels), a power distribution and control unit (PDCU), and loads, as shown in Fig. 1. Complexity in modeling and simulation arises for several reasons. 1) The energy conversion and storage devices, such as solar array and battery, involve multiple-physics such as photoelectric, electro-thermal and electrochemical processes. While conventional simulators are optimized for simulation in specialized disciplines, they are often incapable of coping with the interdisciplinary modeling in a consistent and
convenient manner, and in addition to that, they have difficulties to tackle strong nonlinearities existing in these devices. 2) The power distribution and control unit, responsible for power distribution, bus voltage regulation, and battery protection, 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 system performance, even when people from different technical areas have contributed to definition of the various components of the system.

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

In the following, we will first describe interdisciplinary modeling of energy conversion devices and other components using the resistive companion (RC) method [14]. Then we will describe how the control systems were modeled using MatLab/Simulink. An example satellite power system is finally assembled using a combination of native and imported models. A simulation study is conducted and focused on the dynamic behaviors of the solar array and battery, and system response under fault conditions. Conclusions are given in the final section.

II. NATIVE RC MODEL FORMULATION

Natural components, those to which energy conservation principles apply, are formulated by following the resistive companion approach as described in reference [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 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.

A. 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. 2 shows an equivalent circuit of the solar cell based on consideration of its interactions with its surroundings. The terminals \( v_0 \) and \( v_d \), 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 irradiance on the cell surface in W/m\(^2\)) is a light-receiving terminal. And the terminal \( v_3 \) (or \( T \), the temperature of the cell in K) is thermal in nature and it conducts heat power to the ambient.

\[
i(t) = \frac{1}{R} \left[ v(t) - g_x(t) \ln \left( \frac{I_{sat}(t) + i(t) - \frac{v(t)}{R_{sh}} + 1}{I_{sat}(t)} \right) \right] \frac{v(t)}{R_{sh}}
\]

where \( v \) and \( i \) are the voltage (volts) and current (amps) at the solar cell terminals, \( g \) is the cell diode ideality factor, and \( R_c \) and \( R_{sh} \) are the cell body series and shunt resistances (\( \Omega \)). The thermal potential \( v_{th} \), saturation current \( I_{sat} \), and the diode current \( i_d \) can be expressed, respectively, as

\[
v_{th} = \frac{kT}{e} \ln \left( \frac{T}{T_0} \right)
\]

\[
I_{sat} = I_{sat0} \left( \frac{T}{T_0} \right)^3 \exp \left( \frac{e \left( E_g(T_0) - E_g(T(t)) \right)}{kT} \right)
\]

\[
i_d = I_{sat} \left( \exp \left( \frac{v_x(t)}{g_x v_{th}} \right) - 1 \right)
\]

where \( k \) and \( e \) are Boltzmann constant and the electronic charge respectively, \( T_0 \) the reference temperature, \( T \) the cell temperature, \( I_{sat0} \) the saturation current at the reference temperature, \( E_g \) the energy band gap, and \( v_x \) the diode voltage. The light-induced current is directly proportional to the irradiance, which is given by

\[
I_p = gAP(t) + C \left( T(t) - T_0 \right) \frac{P(t)}{P_0}
\]

where \( A \) is the cell active area (m\(^2\)), \( C \) is the temperature coefficient of light-induced current due to temperature change (A/K), \( P \) is the irradiance, \( P_0 \) is the irradiance at the temperature \( T_0 \), and \( g \) is the spectral-averaged responsivity (A/W).
To construct a natural heat power transport terminal, a thermal current \( i_T \) (W/K) is defined such that the product of the temperature and the thermal current equals heat power (W). The heat transported through the thermal terminal is characterized by the energy balance equation, as given by following equation [20].

\[
c_p M \frac{dT(t)}{dt} = \frac{[v(t) - v_d(t)]^2}{R_i} + \frac{[v(t)]^2}{R_{sh}} + i_T v_d(t) + (1 - \rho - \tau - \eta) A P(t) + i_T \cdot T
\]

where \( c_p \) is the averaged specific heat (J/kg/K), \( M \) is the averaged mass (kg), the symbols \( \rho \), \( \tau \), and \( \eta \) denote the reflection coefficient, transmission coefficient and quantum efficiency of the cell. Equation (6) explains that the energy absorbed by the cell (resulting in temperature increase) is due to the heating by electro-thermal processes (the first three terms on the right-hand side), direct absorption (the fourth term) and heat exchange with connected structures (the last term).

The standard RC model equations can then be derived based on Eqs. (1) through (6).

**B. Battery System**

Energies in battery systems are of chemical, electrical and thermal forms. Internally, the battery converts chemical energy into electrical energy during discharge (or the reverse during charge), and it generates heat due to both irreversible processes (e.g., ohmic heating) and reversible processes (entropy change). Externally, the battery interacts with its surroundings both electrically (delivering electric power via the electrical terminals) and thermally (transporting heat through its surface). Here, we use Ni-H2 battery to illustrate modeling of the electrochemical and thermal processes involved in a battery system.

Several detailed Ni-H2 battery models have been published, among that of Wu, White and Weidner et al [21-24], which includes considerable details of the electrochemical kinetics and thermodynamics. VTB allows to capture their expertise in the electrochemical discipline by integrating their battery models in the VTB environment for system studies. The Ni-H2 battery model presented here results from collaboration with these authors. The present model is somewhat simplified, but it still captures the major features of Ni-H2 characteristics. In the model, only two reactions are considered: the nickel reduction/oxidation at the positive electrode, which is a decisive reaction for the battery potentials; and the water oxidation (or oxygen evolution), which dominates the over-charge process. Hydrogen reaction at the platinum electrode, intermediate reactions and side reactions are ignored. In addition, the kinetics of reactions is ignored. The reactions under consideration are listed below.

\[
\text{Ni(OH)}_2 + \text{OH}^- \Leftrightarrow \text{NiOOH} + \text{H}_2\text{O} + e^- \quad (7)
\]

\[
2\text{OH}^- \Leftrightarrow \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \quad (8)
\]

The equilibrium potential, \( E_0(T, x) \), corresponding to the nickel reaction, and the resulting current from the oxygen reaction, \( i_{O_2}(T) \), are determined by Eqs. (9) and (10).

\[
E_0(T, x) = E_0^0(T) + \frac{RT}{F} \ln \left[ \frac{(1 - x)}{x} \right] - \frac{RT}{2F} \left( \frac{E_a(T)(2 - 3.5x) + B_2(T)(2 - 6x + 3x^2)}{1 - \alpha_{O_2}} \right) \quad (9)
\]

\[
i_{O_2}(T) = A_l \cdot \alpha_{O_2}(T) \exp \left[ \frac{RT}{F} \left( v_b - E_{O_2}(T) \right) \right] \quad (10)
\]

where \( R \) is the gas constant (8.314 J/mol/K), \( F \) is the Faraday constant (96,485 coulombs/mol), \( x \) and \( T \) are state of discharge (SOD) and temperature of the battery, both of which are functions of time. \( A \) and \( L \) are the electrode area and thickness respectively, \( \alpha_{O_2} \) is the transfer coefficient for oxygen reaction, \( v_b \) is the battery voltage. \( E_{Ni}^0(T) \), \( E_{O_2}(T) \), and \( \alpha_{O_2}(T) \) are given by

\[
E_{Ni}^0(T) = \begin{cases} 1.569 - 0.00084 \cdot T, & \text{for discharge} \\ 1.629 - 0.00084 \cdot T, & \text{for charge} \end{cases} \quad (11)
\]

\[
E_{O_2}(T) = 1.711 - 0.00168 \cdot T \quad (12)
\]

\[
\alpha_{O_2}(T) = 10^{-5} \exp \left[ -12.025 \left( \frac{1}{T} - \frac{1}{298} \right) \right] \quad (13)
\]

\( A_0 \) and \( B_0 \) are two-parameter activity coefficients [24], and they can be related to the temperature as

\[
A_0(T) = -0.0231 \cdot T + 11.5 \quad (14)
\]

\[
B_0(T) = 0.0492 \cdot T - 19.4 \quad (15)
\]

The state of discharge, at any instant time \( t \), is determined by the available active material in the battery. It can be conveniently related to the nickel reaction current \( i_{Ni} \) as,

\[
\frac{dx}{dt} = - \frac{i_{Ni}}{Q_{max}} \quad (16)
\]

where \( Q_{max} \) is the maximum charge stored in the battery.

The heat energy in the battery is characterized by the energy balance equation given in Eq. (17).

\[
c_p M \frac{dT}{dt} = i_{Ni}(v_b - E_{Ni} - T \frac{dE_{Ni}}{dT} + i_{O_2}(v_b - E_{O_2} - T \frac{dE_{O_2}}{dT}) + i_T \cdot T \quad (17)
\]

where \( m \) is the battery mass (kg), \( c_p \) is the average specific heat (J/kg/K). Notice that heat terms include both resistive and reversible ones. The last term on the right-hand side is the heat transported to the surroundings due to cooling mechanisms. Again, the thermal current \( i_T \), represents heat flow out of the thermal terminal, which can be separately described by any one or more mechanisms such as conduction, convection, or radiation.

The pressure inside of the Ni-H2 battery vessel is an indicator for the state of discharge of the battery and of the battery potential. A sensor is usually built inside the battery to detect the pressure for the purpose of protecting against battery overcharge. According to the ideal gas law, the pressure \( P \), and the nickel and oxygen reaction currents \( i_{Ni}(T) \) and \( i_{O_2}(T) \) can be related by the following equations:

\[
P(t) = \frac{\left[ n_{Ni}(t) + n_{O_2}(t) \right]RT(t)}{V_g} \quad (18)
\]
\[ i_{N_2}(t) = 2F \frac{dn_{H_2}(t)}{dt} \]  \hspace{1cm} (19)  
\[ i_{O_2}(t) = 4F \frac{dn_{O_2}(t)}{dt} \]  \hspace{1cm} (20)

where \( n_{H_2} \) and \( n_{O_2} \) are the mole numbers of hydrogen and oxygen. Notice that in writing equation (19), we assume that the nickel reaction current is equal to the hydrogen reaction current.

Fig. 3 shows the icon for the Ni-H\(_2\) battery in VTB schematic view. Behind the icon is the battery physics described by Eqs. (7) through (20) as reduced to resistive companion form. Notice that the pressure terminal is a signal terminal since there is no mass transport through the battery vessel.

C. Power Converter

In the studied SEPS, the battery is charged by a DC/DC converter controlled by a battery charge/discharge controller (BCDC) by dynamically monitoring the voltage, current and temperature of the battery. Since the goal of the system level simulation is to investigate the energy balance in the electrical power system and to monitor the main parameters of the system, the simulation time step can be long, for example, higher than 1 second. In this case, an average-value model of the converter is used and the switching transients are neglected. The power flow in the converter is controlled by adjusting the average ON/OFF duty cycle of the switching. The average output voltage of the buck converter is determined by the following equation.

\[ \frac{V_o}{V_i} = \frac{t_{on}}{T} = d \]  \hspace{1cm} (21)

where \( V_i \) and \( V_o \) are the average input and output voltages of the converter respectively, \( t_{on} \) is the turn-on time of the switch during a period, \( T \) is the switching period, and \( d \) is duty cycle.

D. Other Components

The irradiance model computes the illumination of the solar array based on the date/time and the orbital parameters of the satellite. The user can select between low earth orbit and geo-synchronous orbit. The model can output Earth position, Earth Rotation, and the position of the satellite for use in the visualization system. Included in the studied system are also native models for conventional components such as radiator, sensor, resistor and capacitor, which are not described in detail here.

III. MODELING OF CONTROL SYSTEM

A. Battery Charge/Discharge Controller

In the studied SEPS, the battery charge controller follows a constant current charging/constant voltage floating regimen, and the reference voltage is temperature compensated. The V/T limit control is active simultaneously with the constant current and constant voltage control. Both current control and voltage control are implemented through proportional and integral control strategies. The control scheme can be formulated as follows.

\[ V_{ref} = V_{ref0} - C_T(T - 293.32) \]  \hspace{1cm} (22)  
\[ d = d_{old} + k_i(I_{ref} - I), \text{ if } V < 0.98 \times V_{ref} \]  \hspace{1cm} (23)  
\[ d = d_{old} + k_v(V_{ref} - V) \text{ if } V \geq 0.98 \times V_{ref} \]  \hspace{1cm} (24)

where \( V \), \( I \), \( T \) are the sampled voltage, current, and temperature of the battery respectively, \( d \) and \( d_{old} \) are the current and previous duty ratios used to control the buck converter, \( V_{ref0} \) and \( I_{ref} \) are the desired voltage and charging current of the battery at 293.32K, \( C_T \) is the temperature coefficient with respect to the voltage, \( k_i \) and \( k_v \) are current gain and voltage gain respectively.

The Simulink model for the BCDC is shown in Fig.4. Three input terminals are for the sampled voltage, current, and temperature of the battery respectively. The output duty ratio is obtained from either the voltage-control loop or the current-control loop, depending on the battery voltage. An output memory mechanism guarantees the smooth change between these two control schemes. The switching signal terminal is used to manage the discharging of the battery. When the monitoring voltage is below a preset value (or low voltage disconnection (LVD) setpoint), the controller can output a signal to disconnect the loads in order to protect the battery from over discharging. A hysteresis allows reconnecting the loads when the battery voltage increases to an acceptable level.

![Simulink diagram of BCDC model](image)
B. Overcurrent Relaying Protection

Typically, the overcurrent protection system, as shown in Fig. 5, consists of a power switch, a current sensor and a controller [25]. The switching operation is determined by the inverse-time-overcurrent characteristic defined for the switch, as shown in Fig. 6. Fig. 7 shows a Simulink implementation for the overcurrent relaying that is derived based on the functionality of various parts of the actual circuit. The measured current $I_{sensor}$ is compared with the current set point $I_{sp}$ (below which, the switching signal is always OFF) to generate an error signal which is fed to a PI controller. If the output from the PI controller exceeds a reference signal determined by the current setpoint, a trip signal will be generated to open the power switch. The gains $K_p$, $K_i$, $K_v$ relate to characteristics of a particular relay, and their values are computed based on the parameters of the actual control circuit. $I_{max}$ corresponds to the maximum current rating of the power switch used inside the relay. If the measured current exceeds this level, a trip signal will be generated instantaneously regardless of the current setpoint.

![Fig. 5. Block diagram of overcurrent protection system.](image)

![Fig. 6. Inverse-time-overcurrent characteristics of functional overcurrent relaying model.](image)

![Fig. 7 Simulink implementation of overcurrent relaying protection system.](image)

IV. SYSTEM SIMULATIONS AND RESULTS

A. One-Orbit Cycle Simulation

Based on the native and imported models available in the VTB, a wide variety of systems can be easily configured and simulated in the VTB. A representative SEPS is described in this section. Different systems can be easily obtained by changing the system topology and the parameters of components. The example system, as shown in Fig. 8, comprises a solar irradiance model to illuminate the solar cell, a solar array to convert the solar illumination into electrical power, a Ni-H2 battery array, and a resistive load. Several auxiliary components in the system are responsible for appropriate and efficient operation of the entire system.

![Fig. 8. Schematic diagram of example satellite electrical power system.](image)

The primary energy conversion device is an 88x19 (series connections by parallel connections) array of single junction silicon cells. Each cell has an active area of $2.4 \times 6.6 \text{ cm}^2$, and a responsivity of 0.35 A/W. The battery is a 30x10 array of Ni-H2 cells, each having a nominal voltage of 1.24 V and a capacity of 1.25 A-h. The initial state of discharge of the battery is 0.5. All the solar array cells and all the battery cells are lumped into a single model for this particular orbital simulation, as shown in Fig. 8. An overcurrent relaying protect system is used to isolate the fault on the load side by sensing the load current when it exceeds the reference current. The starting current of the relay is 14 amperes, and then the corresponding relayi ng time is about 2 seconds according to Fig. 6. The charging current reference and floating voltage reference for the battery charge controller are 5A and 42V respectively. The LVD setpoint is 38.5V. An OR logic gate is responsible for handling the tripping signal to the power switch.

This system is simulated for the first 2 hours of the mission, and the calculated results in this system are shown in Figs. 9 through 15. The time axis in these figures is scaled in seconds and the time step for simulation is 100 milliseconds. Fig.9 shows the power profiles of the solar array, battery and load. It can be seen from Fig.9 that when the solar array is ON, it provides power for the load, charging the battery simultaneously. During eclipse, the battery provides power for the load, and the bus voltage decreases from a value approximately equal to solar array...
voltage to the battery voltage, which is shown in Fig. 12. The power dissipated by the resistive load decreases with the bus voltage since it is proportional to the square of bus voltage. After a cycle, the solar array powers the load and charges the battery again.

Figs. 10 and 11 respectively show the sampled data for the voltage and current of Ni-H2 battery. The battery is initially charged at 5A current, and after about 1700 seconds of constant current charging the battery voltage arrives at the 42V set point and thereafter it floats at that voltage. The charging current tapers immediately. When the solar array is in eclipse, the battery begins to discharge. As a result, the battery current reverses and its voltage decreases. The discharge current is not controlled and depends on the loads. It is seen from Fig. 11 that the discharging current is about 5A. At the end of the discharge cycle, the battery voltage decreases to about 39V. It is clear from these two figures that the charge controller performs the constant current charging/constant voltage floating scheme correctly.

Fig. 13 shows the energy conversion efficiency of the solar array, which is about 15%. The efficiency declines as the output current decreases. Fig. 14 shows the state of discharge (SOD) of the battery, which decreases when it is charged and increases when discharged. Fig. 15 shows the temperature of the solar array, which increases rapidly at the beginning of the cycle and then maintains at a relatively stable level. The temperature of solar array decreases during eclipse.

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**Fig. 9.** Power profiles of solar array (solid line), battery (dash), and load (dash-dot).

**Fig. 10.** The battery voltage increases from 41.5V. After about 1700 seconds of 5A charging it arrives at the 42V set point and thereafter floats at that value.

**Fig. 11.** The battery is initially charged at 5A current. After the battery voltage arrives at 42V, the battery current tapers immediately.

**Fig. 12.** Curve of the bus voltage.

**Fig. 13.** Energy conversion efficiency of solar array.

**Fig. 14.** State of discharge of the battery.
B. Response Under Fault Conditions

The system shown in Fig. 8 is also used to study the system responses under fault conditions. A high impedance fault of 4Ω is arranged to take place on the load side of the main bus at 1000 seconds. Figs. 16 and 17 show the current and voltage responses under this fault condition. From Fig. 16, it is seen that when the fault occurs, the load current and solar array current rapidly increase. After about 2 seconds, the overcurrent protection system sends a signal to disconnect the load from the power source, and as a result, the load current drops to zero. Without the load, the solar array then provides a lower current, just to charge the battery. After undergoing a rapid rise in the current, the battery is charged at a current greater than the solar array current due to the buck converter. It is seen from Fig. 17 that the output voltage of the solar array decreases when the fault occurs and increases a little bit when it is isolated. The battery voltage continues to increase after a short moment of oscillation.

When the solar array is in eclipse, the battery discharges and its voltage decreases. At this time a sudden load increase may lead to over-discharge of the battery. Figs. 18 and 19 show the system response to a step change in the load power at 4000 seconds. From Fig. 18 it is shown that when the load increases at 4000 seconds, the battery voltage rapidly decreases. When it drops below 38.5V, the battery charge/discharge controller gives a command to disconnect the load. The battery voltage then remains at the open circuit level. It is seen from Fig. 19 that the load current is below 14A after the step change in load power. Since it does not exceed the setpoint of the overcurrent relaying protection, the protection system does not activate at this time. These two case studies give a good understanding to the different roles of the battery discharge controller and overcurrent relaying protection system in protecting the power sources.

V. CONCLUSIONS

Interdisciplinary models such as solar array and battery system, models of orbit, power converter, radiator, and some other components are developed natively in VTB. The control systems such as battery charge/discharge controller, and overcurrent protect system are modeled in MatLab/Simulink and then imported into VTB. Based on the native and imported models, three case studies are performed. The developed models are integrated into a representative satellite electrical power system and simulated for a one-orbit cycle. The behaviors of the solar array and battery are studied in details. It can be seen that the battery is charged following a constant current/constant
voltage strategy. The solar array in the example system can produce an energy conversion efficiency of 15%. The system responses under two different fault conditions are also studied. The different roles of overcurrent relaying protection and battery discharge controller are demonstrated. From the studies in this paper, it can be seen that the VTB is an effective computational environment for virtual-prototyping multidisciplinary systems and studying dynamic performance of complex systems.

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