Using the Virtual Test Bed for Virtual Prototyping of Advanced Power Systems

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ABSTRACT

Solar power system designs are studies using the Virtual Test Bed (VTB) software environment for virtual prototyping of dynamic systems. We describe here how an electro-thermal model of a solar array was defined, how it was tested in the system context, and summarize the results arising from that testing.

INTRODUCTION

Energy conversion, particularly in hybrid systems, involves physical processes in many disciplines. Each discipline is characterized by its unique physical quantities and a set of computational tools optimized for that discipline. The Virtual Test Bed (VTB) [1] is a computational environment that aims to dismantle the traditional barriers between disciplines, thereby allowing simulation and virtual prototyping of systems of complex systems. The software provides methods for importing models from other simulation or modeling environments, for co-simulation, and for straightforward, object-oriented declaration of the system topology. Natural processes (in which some quantity is conserved) are modeled in terms of quantities appearing at points of connection using across and through variables which translate among disciplines as voltage and current, speed and torque, pressure and flow, etc. Signal and data processes are handled also. The environment also provides high-quality graphic animations of the dynamic system behavior to help instill in the user an intuitive understanding of the system performance.

The Virtual Test Bed provides a schematic editor to define the system topology, a network solver to find the time-domain system response, and a visualization engine to view the system behavior during run-time. Native models of natural components (those obeying natural conservation laws) are built based on the resistive companion modeling method [2]. The ubiquity of across and through variables across disciplinary lines allows the VTB to be used for simulation of multidisciplinary systems. This provides the basis for an environment that allows virtual prototyping of dynamic systems, and thorough study of the interrelations of the discipline specific physical processes. To enhance interdisciplinary uses, the VTB integrates simulation models defined in other environments such as Spice, MatLab, ACSL, via translation and/or co-simulation. This makes the VTB a versatile environment for virtual prototyping.

Though many types of simulation models can be used, we describe here the specific case of construction of a native model that interacts with other system components via natural coupling. Such objects are formulated using the resistive companion method.

![Diagram of a device of k terminals described by the resistive companion model equation (1) to (3).](image)

The resistive-companion model of a k-terminal device, as illustrated in Fig. 1, described by its across variable vector $V(t)$ and through variable vector $I(t)$, has a standard form as follows,

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

where $G$ and $B(t-h)$ are the device conductance matrix and the through-variable (current in this case) history vector, and

$$G = \begin{pmatrix} g_{i,j} \end{pmatrix}_{k \times k}$$

$$B(t-h) = -I(t-h) + G \cdot V(t-h)$$

where $h$ is the time step size taken by the time-domain solver.

In the following sections, we will demonstrate the creation of a model of a photovoltaic energy converter and show simulation results of the advanced power system that incorporates photoelectric, thermal, and electro-chemical system components.
Photovoltaic Energy Conversion Modeling

1. Physical Descriptions of Solar Cells

The process of converting sunlight to electricity in a semiconductor solar cell is well known. The current $i(t)$ (A) drawn by an external circuit can be mathematically related to the cell terminal voltage $v(t)$ (V) as

$$i(t) = \frac{1}{R_s} \left[ v(t) - \gamma \frac{v(t)}{I_{sat}(t)} \ln \left( \frac{I_{ph}(t) + i(t)}{I_{sat}(t)} \right) + 1 \right] + \frac{v(t)}{R_{sh}}$$

where $\gamma$ is the cell diode ideality factor, $R_s$ and $R_{sh}$ are the cell body series and shunt resistances ($Q$). The thermal potential ($V$), the saturation current ($A$) and the photon-generated current [3] ($A$) can be expressed, respectively, as

$$v_{sh}(t) = \frac{kT(t)}{q}$$

$$I_{sat}(t) = I_{sat0} \left( \frac{T(t)}{T_0} \right)^{3/2} \exp \left( \frac{qE_g}{\gamma k} \left( \frac{1}{T_0} - \frac{1}{T(t)} \right) \right)$$

$$I_{ph}(t) = (I_{sc0} + C(T(t) - 298.0)) \frac{P(t)}{1000}$$

In above equations, $k$ and $q$ are Boltzmann constant and the electronic charge. $I_{sat0}$ is the photodiode saturation current at the reference temperature $T_0$ (K). $E_g$ is the energy band gap (eV). $I_{sc0}$ is the cell short-circuit current at a cell temperature of 298 K for the insolation level of 1000 W/m². $C$ is the temperature coefficient of photocurrent (A/K). $P(t)$ is the irradiance of the sunlight in W/m², and $T(t)$ is the cell temperature in K, both are functions of the time. The short-circuit current at $T=298.0$ K is calculated according to

$$I_{sc0} = \Re A_a P(t)$$

where $A_a$ is the cell active area in $m^2$, and $\Re$ is the responsivity in $A/W$. The responsivity is an integrated parameter for the spectral region that evokes the photoelectric effect. Numerically, it gives the amount of the short-circuit photocurrent generated per unit of photon flux. The power conversion efficiency of the solar cell is calculated according to

$$\eta(t) = \frac{v(t)i(t)}{P(t)A_a}$$

Notice that equation (7) is an empirical (behavioral) representation of the photoelectric process; it does not represent the detailed physics. Nonetheless it accurately relates the current to the irradiance and the temperature. In addition to the interrelations with the external circuit (given by equation 4) and with the sunlight (given by equation 7), the solar cell has another important interaction with the environment -- heat exchange via convection and radiation. The thermal energy of the cell is balanced by the internal heating and external cooling, which can be described by

$$c_p M \frac{dT(t)}{dt} = R_s \left( i(t) - \frac{v(t)}{R_{sh}} \right) + \frac{1}{R_{sh}} v(t)^2$$

$$- h A \left( T(t) - T_a \right) - \sigma \varepsilon \left( T(t)^4 - T_a^4 \right)$$

Here, the material parameters are the averaged weight average values of the cell material and the supporting materials. Therefore $c_p$ is the averaged specific heat, $M$ is the averaged mass, $A_a$ is the surface area, $h$ is the convection-cooling coefficient, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon$ is the emissivity, and $T_a$ is the ambient temperature. The term on the left-hand-side is the rate of change of the thermal energy of the material. The first two terms on the right-hand side represent the power dissipated by ohmic heating and the last two terms represent the cooling mechanisms. Notice that the solar cell only radiates the photons that are beyond the energy spectrum of photoelectric effect. This fact can be taken care of by choosing an appropriate value for emissivity.

Equations (4) through (10) form a complete set that describes the photoelectric and thermal characteristics of the photovoltaic cell energy conversion process.

2. Equivalent Circuit for Companion Model

![Fig. 2. The equivalent circuit of a resistive companion model for photovoltaic energy conversion by a semiconductor cell.](image)
The circuit portion between node 0 and 1 is a conventional model that represents the cell electrical characteristics. Node 4 is an internal node of the cell. The circuit branch connected to node 2 represents the photoelectric process. Because of the absence of the detailed physics in (7), terminal 2 is treated as a signal terminal, in which case the branch can be modeled with an arbitrary large resistor and the voltage signal across that resistor is the solar irradiance $P(t)$. The circuit branch with the node 3 represents the thermal process. The detailed physical process is included in (10) for the thermal modeling. Because of the energy balance required by (10), a natural coupling of the node 3 to the external system should be applied so that the power conservation law can be observed. This means that the heat power brought out of the cell by the cooling mechanisms through the terminal should be exactly equal to the product of the across and the through variables of that terminal. To do that, we use a block in that branch to represent the thermal model. Its terminal variables $v_3$ (the temperature) and $i_3$ (the thermal current) simply follow the physical constraint given by (10). The thermal current can be derived by using following equation:

$$i_3 \cdot v_3 = -h_{a} A_{t} (T(t) - T_a) - \sigma_e (T(t) - T_a)^3$$

Notice that the thermal current has units W/K.

The resistive companion model for VTB simulation can then be developed based on the equations and circuit above and the method described in the previous section.

The descriptions for companion modeling process given above are also typical to many other device models. We will therefore in the following discussion omit the descriptions of the modeling of other devices such as battery, irradiance, converter and so on. But we will give a brief explanation of the functions of the devices where necessary. The details of the devices models in the system discussed in the following sections can be found, and the VTB software can be downloaded freely at the website [http://vtb.engr.sc.edu/](http://vtb.engr.sc.edu/).

**System Simulation**

*Fig. 3. The photovoltaic power system with advanced battery for energy storage, and a pulsed power load.*

The advanced power system shown in Fig. 3 comprises a solar array SA_X1 to convert the sunlight into electrical energy, a NiCd battery array NiCd0 to store the energy during the day and to provide the power to the load at night, and a pulsed mode transmitter Transmitter0 as the load. Several auxiliary components in the system are responsible for appropriate and efficient operation of the system. The primary energy conversion device SA-X1 is a 80x10 (series connections by parallel connections) array of single junction silicon cells. Each cell has an active area of 0.01 m², and a responsivity of 0.35 A/W. Including supporting materials, the mass per cell is assumed to be 0.12 kg and the specific heat is 712 J/(kgK). The battery is a 20x15 array (series connections by parallel connections) of NiCd cells, each having a nominal voltage 1.2 V and a capacity of 24 A-h. The transmitter cycles on and off, being on for 200 of every 250 s. When on, it operates with a pulse duty ratio of 0.5, demanding 1 kW in the high power phase, and 250 W during the low power phase. The high/low power phases repeat with a cycle time of 20 seconds. The resulting pulsed power profile is shown in Fig. 4. Note that a constant power converter is incorporated into the transmitter model so that any change of the source voltage does not affect the load power profile (the transmitter simply draws more current).

*Fig. 4. Transmitter power profile (W) as a function of time (s).*

*Fig. 5. Solar irradiance (W/m²) received at the longitude 80 W and the latitude 34 N on the day of July 21 from 4:30 am till the next day 8:30 am. The time scale is in seconds.*
The parameters of the solar irradiance model, Sol0, are set to a location at 80° W longitude and the 34° N latitude. The light-receiving surface (the solar array) is south facing and fixed at 34° all year around for semi-optimum collection of the sun energy without maneuvering of the solar array orientation. The day for the power system operation is set to July 21. Fig. 5 shows the solar irradiance generated for the specified location for the time from 4:30 am of July 21 to 8:30 am of July 22 assuming a clear sky. The figure shows that the sun rises at about 4:45 am, and the sunset time is at about 7:45 pm. The irradiance increases in the morning and reaches its maximum (930 W/m²) at the local noon time. The irradiance on the next day will be slightly different due to the sun’s location change in the sky.

The solar array output power is delivered to the battery and the load through a buck converter (Conv0) that is controlled by a maximum power point tracker, Ctrl_MPPT0. We use an average model of the converter since the switching frequency of the converter is much higher (>1 kHz) than the load operating frequency (0.05 Hz). The maximum power point tracker uses the incremental conductance algorithm [4] to seek the maximum power point for every time step during the daytime, and to shut down the array operation at night. In Fig. 6a to 6d, the array output voltage, current, the power conversion efficiency and the cell temperature are shown for the conditions of the maximum power output under the irradiance shown by Fig. 5. Notice that although the irradiance varies, the output voltage is almost constant (35 V) from 6 o’clock am to 6 o’clock pm. The output current looks similar to the irradiance profile due to the fact that the maximum power point of the solar array is near the open-circuit voltage. The power conversion efficiency shown in Fig. 6c has a nearly constant value of 14% for the daytime from 6:00 am to 6:00 pm, indicating that the tracker is effectively tracking and delivering the maximum power to the load. The temperature of the solar cell shown in Fig. 6d increases as the irradiance goes up, and decreases as the irradiance goes down. But the temperature change lags the irradiance due to the heat capacity of the cell and supporting material. When the sun is behind the earth, both the voltage and the current produced by the solar array are zero. But the temperature of the cells does not immediately become zero (relative to ambient). It takes about 30 minutes or so to cool down to the ambient temperature.

Fig. 6a. The output voltage (V) of the solar array from time 4:30 am of July 21 to 8:30 am of July 22. The time scale is in seconds.

Fig. 6b. The output current (A) of the solar array from the time 4:30 am of July 21 to 8:30 am of July 22. The time scale is in seconds.

Fig. 6c. The power conversion efficiency of the solar array for the voltage and current output shown in Fig. 6a and 6b.
Fig. 6d. The solar cell temperature change (K) for the irradiance and the output conditions shown in Fig. 6a, b and c.

The thermal network connected to the solar array transports heat power to the environment. The ambient temperature (300 K) is modeled by constant temperature source T0. Convection and radiation cooling mechanisms are represented by Convection0 and Radiation0 models, which have the following parameters: convection cooling coefficient 2 W/(m²K), the averaged emissivity of the array is 0.65, and the cooling surface area is 10 m².

The battery in the system is a 20x15 array (series connections by parallel connections) of NiCd cells. The output voltage, the current and the state of charge of the battery array for the same operating conditions are shown in Fig. 7a, b, and c. Notice that the battery experiences a charging process during the day (the state of charge increases while the current is positive), and it undergoes a discharge process during the night (the state of charge decreases while the current is negative). At 4:30 am while it is still nighttime, the battery provides the power to the load, and the state of charge decreases from 50% to 45% till the sun rises, at which time the solar array begins to convert the sun power and energy is restored to the battery. The state of charge continues to increase until sunset at which the state of charge is 87%. The discharging process begins again once the sun sets. The ripples shown in the voltage and the current waveform are due to the pulsed power load. In fact, the ripples have been considerably reduced by the parallel-connected 1-kF ultracapacitor bank (C_DL0). In addition, the battery-ultracapacitor hybrid effectively increases the discharge life of the battery and reduces the power loss, therefore increasing system efficiency and power density [5] [6].

Fig. 7a. The battery voltage (V) for the operating conditions described in Fig. 6. The time is in seconds.

Fig. 7b. The battery current (A) as a function of time (s).

Fig. 7c. The battery state of charge as a function of time (s).
Conclusions

The VTB is an effective computational environment for modeling and simulate multidisciplinary systems. We have demonstrated the modeling procedures for the photovoltaic energy conversion process including its thermal behavior. The model is then used in the advanced solar power system where a battery is used for energy storage and a pulsed transmitter is the load. The behaviors of the solar array and the battery array are simulated and predicted for the irradiance in the period of 4:30 am of July 21 to 8:30 am of July 22. Under the maximum power point tracking condition, the solar array has a nearly constant power conversion efficiency of 14% during the daytime. The battery experiences charge-discharge with a maximum state of charge nearly 90% and a minimum state of charge 20%. Because of the assistance of the ultracapacitor bank, the ripple of the battery voltage is considerably reduced.

References


