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IMPROVING ESP-R'S BATTERY MODEL WITH ACTIVE BATTERY LIFE CONTROL AND COVERAGE OF VANADIUM REDOX FLOW BATTERIES

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ABSTRACT

The ESP-r battery model has been improved by including battery lifetime estimation based upon the actual load pattern of the battery during the simulation, and with a battery life controller that will prevent excessive aging of the battery. The lifetime estimation method and life preserving controller are described and example simulations are presented that clearly illustrates the necessity of a life preserving operating mode.

The ESP-r battery model has a generic structure that allows the model to be used for different battery types. The model was successfully expanded to also represent a Vanadium Redox flow Battery.

INTRODUCTION

Electricity production has been brought within the boundaries of building simulation by a focus shift from large-scale power production to more distributed power generation, an increasing interest in renewable electricity production, and efforts to more efficiently heat buildings by concurrent production of heat and power (cogeneration). Detailed models have been developed in ESP-r for building-integrated photo-voltaics (Kelly, 1998) and residential cogeneration systems based upon internal combustion engines, Stirling engines, and fuel cells (Kelly and Beausoleil-Morrison, 2007). These electricity production systems often include batteries for temporary storage of excess electricity. The batteries are generally charged and discharged on a daily basis, creating a highly-cyclic mode of operation.

Many different types of batteries exist, defined by the specific electro-chemistry that produces the electricity based upon active components. When batteries are used as auxiliary equipment of larger energy conversion systems, most often the lead- acid battery type is chosen due to its low costs.

In practice, lead-acid batteries are well suited for use under highly-cyclic operating conditions when they are treated with care. In order to reach their expected lifetime, often expressed in a number of cycles at a certain depth of discharge (DOD), the batteries need to be fully charged regularly (e.g. once every two weeks) to reverse certain electrochemical degradation processes (Nickoletatos and Tselepis, 2003). Failing to do so will reduce their lifetime drastically. Batteries failing within 6 months are not uncommon.

The existing battery model in ESP-r did not take the influence of the (cycling) mode of operation on the lifetime of the battery into account. Nor did it have the option to control the battery in a life preserving mode by having it perform a mandatory full charge cycle regularly. Both aspects can have a significant influence on the design and operation of the battery assisted power production system. Battery life use information related to the specific load pattern of the battery can be used to optimize battery size versus replacement interval, while the mandatory charge cycle may have substantial influence on the operation of the system. Depending on the chosen charge strategy, fully charging a battery will take a couple of hours and could last up to 40 hours. During this period the system must depend upon its power generation system or grid connection, or the battery pack must be divided into separate sections that will be charged and operated in an alternating way (e.g. see Atcitty et al. 2001).

The first part of this paper describes the battery lifetime estimation module that has been implemented into the ESP-r battery model. An example is given of the influence of mandatory full charge cycles on the expected lifetime and operation of the batteries of a simulated PV-battery system.

Although lead-acid batteries are the preferred type for most applications of building-connected power genera-tion systems, a number of other battery technologies are under development that may replace lead-acid batteries in the near future. One of those technologies, the

Vanadium Redox flow Battery (VRB) has been investigated in detail. A VRB model, based upon the generic ESP-r battery model, has been implemented in ESP-r and is presented in the second part of this paper.

ESP-R'S GENERIC BATTERY MODEL

The ESP-r battery model was originally developed in 2005 to represent lead-acid batteries. However, the model was structured to be generic so that other battery technologies could be incorporated using a different set of input parameter values.

The generic battery model uses an internal resistance to represent the various losses in the battery. The internal resistance can be a function of the battery temperature, current, and state of charge (SOC). However, due to a lack of detailed data, a constant internal resistance is often used in simulations.

The current battery model works as Figure 1 shows. For a given load at a time step, the model needs to calculate the maximum current $|I_{max}|$ first. The absolute value is used here because the current is assigned a positive value for discharging and a negative value for charging. The value of $|I_{max}|$ is found by making sure that the SOC at the end of this time step does not go beyond the predefined limits. In addition, for discharging, the current cannot be greater than the theoretical maximum equal to $E/(2R_i)$, where E is the open-circuit voltage in volts and R_i is the internal resistance in ohms.

Based on I_{max} in amperes, the corresponding power P in watts can be calculated as:

$$P = (E - I \cdot R_i)I \qquad (1)$$

In the current model, the open-circuit voltage is given as a polynomial function of *SOC* while the coefficients are user inputs.

Considering that a too low a temperature can have great impact on the lifetime of lead-acid batteries, a thermal management system is included in this model in order to keep the battery temperature within a reasonable range. The thermal management system operates based on two user inputs: the operating temperature and the emergency temperature. The former indicates the recommended operating condition by the manufacturer while the latter indicates a threshold value below which the heater has higher priority than the external load.

The power used by the heater is determined differently according to the following strategies:

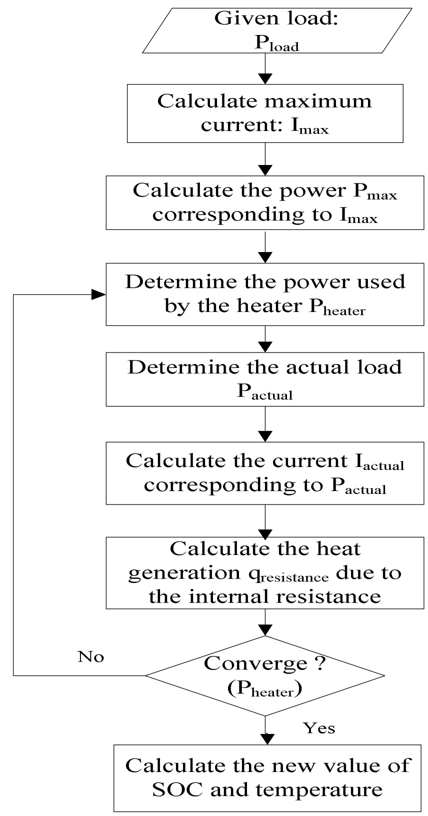

Figure 1 Flowchart for the current battery model

- In charging mode, the load (available power) is first used to bring the battery temperature back to the operating temperature using the electric heater. The battery will only be charged when 1) the battery temperature is at or above the operating temperature and there is excess power available; or 2) the battery temperature is below the operating temperature, but the heater cannot use up the available power due to its capacity limitation. In this case, the remaining power is used for charging.
- In discharging mode, the battery first serves the load as long as the battery temperature is above the emergency temperature. If excess power is still available after satisfying the load, the excess power is used to heat the battery to the operating temperature. At temperatures below the emergency temperature, heating the battery has priority over the load.

After the heater power P_{heater} is known, the actual load applied on the battery can be calculated depending on the power flow paths. Then, the current corresponding to P_{actual} (>0 for discharging; <0 for charging) can be solved from equation 1, that is:

$$I = \frac{E - \sqrt{E^2 - 4R_i P}}{2R_i} \qquad (2)$$

The calculation of P_{heater} considers heat gains due to the internal resistance, which varies with the current. Therefore, iteration is needed to find the final current.

With the current known, the *SOC* and battery temperature at the end of the time step can be determined. For lead-acid batteries, the *SOC* is defined as a ratio of the charge currently stored in the battery to the maximum storage capacity. The *SOC* at the end of the time step is then:

$$SOC_{t+\Delta t} = \frac{Q_t - I \cdot \Delta t}{Q_{t,\max}} \qquad (3)$$

where Q_t is the amount of charge stored at time t (Ah), I is the current (A), which has a positive value for discharging and a negative value for charging, and Δt is the time step in hours. The battery's storage capacity $Q_{t,max}$ in Ah is determined as a function of temperature:

$$Q_{t,\max} = a + bT + cT^2 \qquad (4)$$

where *a*, *b*, and *c* are empirical constants to be inputted by the user.

ESP-r's generic battery model does not consider self-discharge or aging effects. The user of the battery model has the option to active or deactivate the above described thermal management system.

IMPLEMENATION OF A BATTERY LIFE-TIME MODEL AND CONTROLLER

Batteries are chemically active components. Their performance deteriorates over time and the degradation itself depends on the load pattern. During over 100 years of battery technology, a large number of damage mechanisms have been identified. Kaiser et al. (2003) present a detailed overview of battery damage mechanisms and the stress factors that contribute to these damage mechanisms. The most important damage mechanisms are corrosion and sulphatation followed by shedding and active mass degradation. Important stress factors are discharge rates, time at low state of charge, Ah throughput, charge factor, time between full charge, partial cycling, and temperature.

Forecasting the lifetime of a battery is not an easy task due to the large number of damage mechanisms and stress factors. Numerous models exist that try to estimate the battery life based upon a wide variety of mathematical calculations and assumptions (Bindner et al, 2005).

For the ESP-r battery model, a simple though robust lifetime model was made similar to Spiers and Rasinkoski (1995). For each time step the dominant effect on battery life is determined, being either cycle life or corrosion resistance. Corrosion resistance is generally expressed in float-charge time, which is the lifetime of the battery when it is always kept at full load by applying a float charge to it that compensates self-discharge. This lifetime is also called 'float life'. When batteries are not fully recharged regularly, their performance and life expectancy will be drastically reduced. This 'abuse' of the battery is included in the model as a third battery aging mechanism. Each time step the battery life use due to each of the three aging mechanisms is calculated. The greatest of the three will set the resulting battery life use parameter value for that time step.

The battery float life, cycle life, and abuse life are user inputs to the model. The first two parameters are usually available from battery manufacturer specifications; the latter is more often an empirically derived value or based upon expert estimates.

In the ESP-r battery model, the battery life usage due to each of the above described aging mechanisms is calculated per time step Δt:

$$Float\_life\_used = \frac{\Delta t}{Float\_life} \qquad (5)$$

$$Cycle\_life\_used = \frac{|I|\Delta t}{2 \cdot Cycle\_life} \qquad (6)$$

where $|I|\Delta t$ is the number of Ampere-hours charged to or discharged from the battery during the time step. This parameter is calculated for both charging and discharging, therefore requiring the '2' in the denominator. The cycle life itself is defined as

$$Cycle\_life = N_{cycle} \cdot DOD_{cycle} \cdot Cap \qquad (7)$$

where N_{cycle} is the number of cycles, DOD_{cycle} the Depth of Discharge (DOD) of the cycle, and *Cap* the battery capacity (Ah).

The battery life used due to abuse of the battery is calculated similarly to the float life used.

$$Abuse\_life\_used = \frac{\Delta t}{Abuse\_life} \qquad (8)$$

The model assumes the battery to be ‘abused’ when the time elapsed since the last time the battery was at 100% SOC has exceeded a certain user-specified limit.

The ESP-r battery lifetime model only informs the user of the estimated number of battery lives that would be used up when the batteries would be submitted to the specific load pattern used in the simulation. No provision has been made to adjust the battery performance from time step to time step based upon the fraction of battery life used due to the complexity of the matter. Temperature effects are also not considered.

Optionally the user of the battery model can choose to actively control the battery life during a simulation. A dedicated controller has been implemented that will have the battery perform mandatory charge cycles to prevent ‘abuse’ due to a too long an interval between full charges. The current version of the active battery life control system can not be combined with the active thermal management system.

EXAMPLE OF BATTERY LIFETIME ESTIMATION AND CONTROL

Active battery life control can have a major influence on the life expectancy of a battery, as is illustrated by the example given below.

The operation of a grid-connected PV-battery system was investigated through annual simulations using ESP-r. A system model was built consisting of a grid-connected house with PV panels, batteries, and power conditioners (see Figure 2).

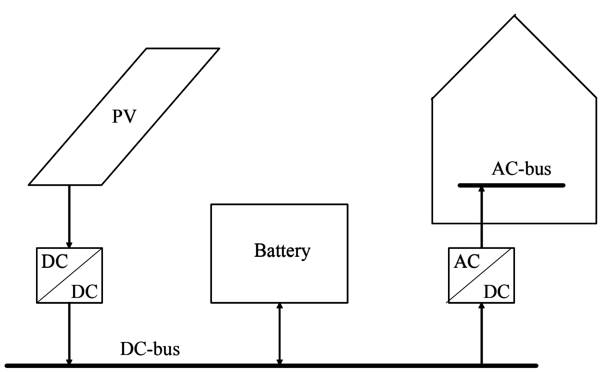

Figure 2 Grid-connected PV-battery system used in the ESP-r simulations

The operation of the system is as follows: Throughout the day the PV panels generate electricity to first meet the load of the house and then to charge the batteries. Any excess energy that can not be absorbed by the batteries is exported to the grid. In case the electric load is greater than the maximum power the PV and the batteries can supply, the remainder is imported from the grid. At night, the batteries, and if necessary the grid, supply the required power to the house. The batteries are not allowed to be depleted totally, as this would have a major impact on their life expectancy. When the batteries have been discharged to their minimum SOC level, the load will be fully met by the grid.

The characteristics of the PV-battery systems and the input parameters for the simulation are given in Table 1. At the start of the simulation, the battery was assumed to have been recently fully charged.

Table 1 Characteristics and simulation inputs of the grid-connected PV-battery system.

Parameter	Unit	Value
PV		
size	m^2	50
tilt angle	degree	30
annual power production	kWh	6101
Battery pack		
capacity	Ah	420
voltage	V	120
energy storage capacity	kWh	50
minimum SOC	%	20
max. SOC (normal operation)	%	100
max. SOC (mandatory charging)	%	105
mandatory charge interval	day	14
float life	year	5
cycle life: number of cycles	-	500
cycle life: DOD of cycle	-	0.8
abuse life	year	0.5
Electrical demand house	kWh	7362
Location	-	Ottawa
Climate data	-	2004

First the PV-battery system was simulated without active battery life control. This means that the battery SOC is determined only by the balance between battery charging due to excess PV power production and battery discharging because of meeting the load. Figure 3 shows the annual evolution of the battery SOC for this case. It is clear that only during the summer period from May-August there is sufficient PV power production to fully charge the battery on a regular basis. For this period, the battery life is determined by a mix of float life use and cycle life use, the latter adding almost 50% to the overall battery life use in comparison to a scenario in which float life use would be the only battery aging mechanism. For the remainder of the year, the battery SOC does not reach the 100% regularly and 'abuse' of the battery has the biggest impact on the battery life usage. At the end of the 1 year simulation period around 1.25 battery lives were used, indicating that under these operating conditions the battery would have to be replaced well before the end of the first year of operation of the PV-battery system.

Figure 4 displays the results of the second simulation case, in which the same PV-battery system was simulated but now with active battery life control. The overall shape of the annual battery SOC curve is quite similar to the one in Figure 3. The main difference is in the mandatory charge cycles that bring the battery up to 100% SOC every 14 days. For the whole year, the battery life use is determined by a mix of float life use

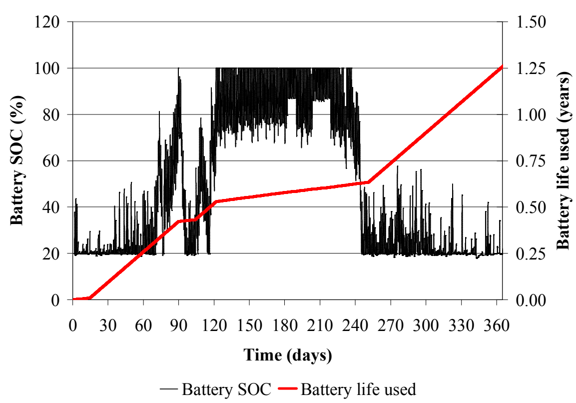

Figure 3 Battery SOC and battery life used for a PV-battery system without active battery life control.

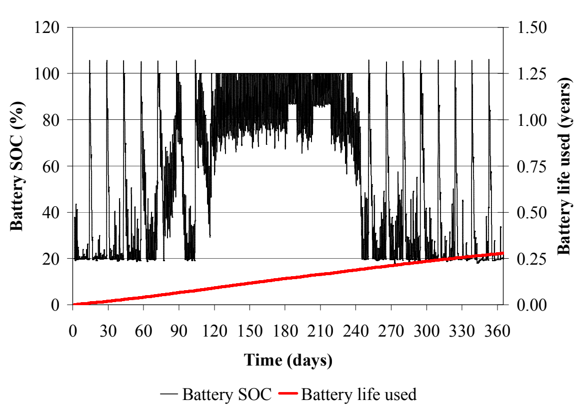

Figure 4 Battery SOC and battery life used for a PV-battery system with active battery life control.

and cycle life use. Now cycle life use has increased the overall battery life use with almost 40% compared to a scenario in which the battery would only age due to float life. The batteries in this simulation are expected to last for 3.6 years, which is 4.5 times the estimated life time of the uncontrolled batteries!

The mandatory charging of the batteries only had a relatively small influence on the operation of the grid-connected PV-battery system. Both annual total grid import and export increased by around 7% compared to the scenario without battery life control. However, the simulated PV-battery system without battery life control already had a substantial grid import and export, equal to approximately 50% and 25% of the total PV power production, respectively. The influence of the mandatory charge cycles could be more pronounced for systems with smaller grid interactions or stand-alone systems.

In the battery life preservation simulation a relatively fast charge cycle was used with a total duration of around 6 hours. The fast cycle was associated with large charge currents and a battery life usage due to cycle life use of up to 10 times the float life use. If charging at lower currents would be desired, this would results in longer charge cycles and increasing periods of unavailability of the battery to supply power to the house.

The battery lifetime model has been implemented in ESP-r and is fully functional. Validation of the battery lifetime model against experimental data could not be conducted by the authors, but would be welcomed by them.

VANADIUM REDOX FLOW BATTERY MODEL

Redox flow batteries have gained acceptance over the last decades as a promising candidate for electrical storage (Skyllas-Kazacos, 2000). In comparison with the conventional lead-acid batteries, redox flow batteries store their energy in the electrolyte rather than on the electrodes. They offer several major advantages including moderate cost, modularity, transportability, and flexible operation (Leon et al. 2006).

As a flow battery, the vanadium redox battery (VRB) works by circulating the electrolyte in two separate loops throughout the cells (Figure 5). The electrolyte is a solution of sulphuric acid containing the V^{2+}/V^{3+}

redox couples in one loop and VO^{2+}/VO_2^+ (V^{4+}/V^{5+}) couples in the other loop. During charging and discharging, the vanadium ions at different valence states are oxidized and reduced at the electrodes. At the same time, hydrogen ions in the electrolyte move across the membrane that divides the two half cells in order to achieve the electrical balance. The chemical reactions involved in the vanadium redox cell can be expressed as:

$$V^{2+} \leftrightarrow V^{3+} + e \tag{9}$$

$$VO_2^{\ +} + 2H^+ + e \leftrightarrow VO^{2+} + H_2O \tag{10}$$

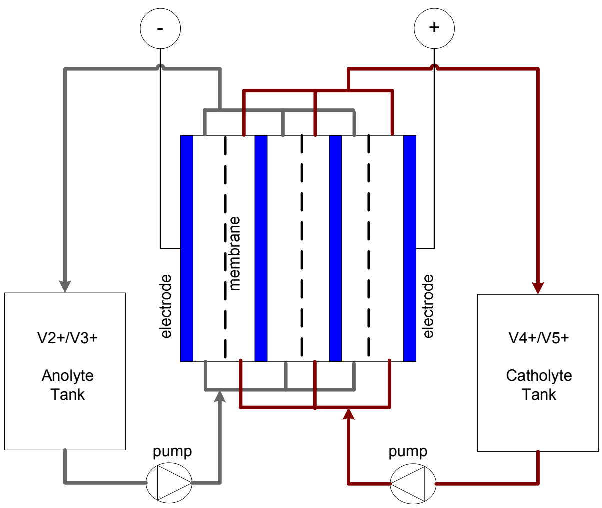

Figure 5 Schematic representation of a VRB system

A simple model was developed in ESP-r to simulate the behaviour of a VRB at a given power demand. This model is based on the general structure for the lead-acid battery as presented in section 2. The major differences in modelling VRB and lead-acid batteries concentrate on the following aspects:

Calculation of open-circuit voltage

For the lead-acid battery, E is calculated from a correlated equation. However, for the VRB it is derived directly from the Nernst equation (Berndt, 2003) as:

$$E = E_T + \frac{RT}{nF}\ln\left(\frac{c_{VO_2^+} \cdot c_{H^+}}{c_{VO^{2+}}} \cdot \frac{c_{V^{2+}}}{c_{V^{3+}}}\right) \tag{11}$$

where E_T is the standard potential (V) at a given temperature T (K), R is the gas constant, n is the number of electrons (=1) participating in the chemical reaction, F is the Faraday constant, and c represents the ion concentration (mol/L).

In equation 11, the standard potential at temperature T can be calculated as:

$$E_T = E_0 + \frac{dE}{dT}(T - T_0) \tag{12}$$

where E_0 is the standard potential at temperature T_0 = 298.15 K, and dE/dT is the temperature coefficient of the potential (V/K).

To determine the electrolyte temperature, the thermal aspect of the VRB system has to be considered in terms of the heat gains due to the internal resistance and the pumps, the reversible heat change due to the chemical reactions, and the heat loss to the surroundings. This is not an easy task. Thus, the calculation of open-circuit voltage is simplified in the current stage by assuming the electrolyte temperature as a constant (25 ^{o}C).

Because of the static feature of this VRB model, the concentration for each ion is regarded as a constant at a given time step. In actual case, however, due to the chemical reactions, the ion concentration varies as the electrolyte flows through the cell. In order to reduce the impact of using constant ion concentrations on the simulation results, the mean concentrations at the cell inlet and outlet are used. Therefore, the ion concentration can be expressed as:

$$c_i = \frac{c_{i,inlet} + c_{i,outlet}}{2} \tag{13}$$

where the subscript i represents the ions involved in VRB reactions.

At each time step, the ion concentrations at the cell inlet are known and equal to those in the tanks. The outlet ion concentrations can be calculated as (Blanc and Rufer 2007):

$$c_{i,outlet} = c_{i,inlet} + b\frac{nSeries \cdot I}{F \cdot q} \tag{14}$$

where *nSeries* is the number of serially connected cells, q is the electrolyte flow rate in L/s, and b is the coefficient equal to 1 or -1 depending on the ion and the battery status. The value of 1 is used for V^{3+} and VO^{2+} while the value of -1 is used for $V^{2+}, VO_2^{\ +}$ and H^+. Again, the current takes a positive value for discharging and a negative value for charging.

Ideally, there should have been some control on the electrolyte flow rate according to the current. However, this has not been implemented yet and the flow rate is treated as a constant parameter provided by the user.

Calculation of SOC

In the lead-acid battery model, the SOC at the end of a time step is calculated via the change of charge storage (see equation 3). For the VRB, since the energy is stored in the electrolyte tanks, SOC is usually defined as the ratio of ion concentrations:

$$SOC = \frac{c_{VO_2^+}}{c_{VO^{2+}} + c_{VO_2^+}} = \frac{c_{V^{2+}}}{c_{V^{3+}} + c_{V^{2+}}} \qquad (15)$$

With the above definition, the *SOC* at the end of a time step can be calculated according to the electrical balance:

$$SOC_{t+\Delta t} = SOC_t - \frac{nSeries \cdot I \cdot \Delta t}{V \cdot c_0} \qquad (16)$$

where Δt is the time step (h), V is the tank volume (L), c_0 is the initial vanadium ion concentration in either anolyte or catholyte.

Consideration of parasitic power

The parasitic power consumed by a VRB comes from the circulation pumps and the electronics for the control system. Since variable flow rate is not considered in the current stage, the parasitic power takes a predefined value when the VRB is load connected. It is also assumed that no parasitic power is needed when the VRB is not load connected.

The parasitic power is treated in the same manner as the heater power used to maintain a thermal control on the lead-acid battery. This means that the parasitic power is added to the load for discharging and it is deducted from the supplied power for charging. In case that the supplied power is less than the parasitic power, the VRB is deactivated.

Considering that different user inputs are required for the VRB model and the lead-acid battery model, the VRB model was implemented in ESP-r as a new electrical component. However, the model uses the same structure as presented in section 2.

CONCLUSIONS

The existing ESP-r battery model has been improved by including battery lifetime estimation based upon the actual load pattern of a battery during a simulation, and with a battery life controller that, if necessary, will fully charge batteries on a regular basis to prevent excessive battery aging. Simulations of a grid-connected PV-battery system indicate that without a life preserving control strategy, the batteries would die prematurely after an estimated battery life of only 0.8 years. The life expectancy of the batteries would increase to 3.6 years with an active battery life control system. The mandatory charging of the batteries has only a limited impact on the operation of this grid-connected PV-battery system. However, for stand-alone systems the influence could be more pronounced.

A Vanadium Redox flow Battery (VRB) model was added to ESP-r based upon the same generic structure as the lead-acid battery model. This demonstrates that the current lead-acid battery model provides a useful skeleton to incorporate other battery types.

RECOMMENDATION

The example presented in this paper clearly illustrates that building-connected power generation systems (e.g. PV-battery systems, residential cogeneration systems) may require active battery life control to ensure acceptable battery lifetimes. The use of the optional battery life controller in simulating these systems is strongly recommended.

The current battery life controller can only be used for grid-connected systems or systems that have another type of back-up power source. It is recommended to further develop the battery life controller to also cover stand-alone systems.

The VRB model is a relatively simple representation of the technology. It could be improved in many ways. In particular, the thermal aspect of the VRB model could be considered to track the electrolyte temperature. A controller may be added to vary the electrolyte flow rate with the battery current. Aging and self-discharge could be also considered.

The successful implementation of the VRB using the generic structure of the lead-acid battery opens a window for other battery types. The implementation of especially Nickel-Metal Hydride and Lithium-ion batteries would be welcomed.

Validation of the lead-acid battery lifetime model and the VRB model against experimental data is recommen-ded.

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