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PVTOOLBOX SIMULATION OUTPUT COMPARED WITH MONITORED DATA FROM PV HYBRID TEST BENCH

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ABSTRACT

The CETC-Varennes has developed two advanced tools for the investigation of photovoltaic hybrid system behaviour. First, PVToolbox is a library of component models facilitating the simulation of hybrid systems in the Matlab® Simulink® environment. Second, a configurable test bench consisting of engine-driven generator ("genset"), array, battery, and control and monitoring equipment has been built on the CETC-Varennes premises.

Data from the hybrid test bench has been very useful in validating the PVToolbox and identifying those areas where it is accurate and those areas where it is not. Thus far, the accuracy of PVToolbox has been quite good. While the goal during development of PVToolbox was that it predict major energy flows (e.g., photovoltaic array output accepted by the system and electrical energy provided by the genset) with an error of 10% or lower, in some recent tests errors of around 1 to 2% —roughly the accuracy of the measuring devices—has been observed. Not only were average energy flows accurate, but the timing of genset starting and stopping was closely modelled by the simulation.

This study shows that while the simulation tool can be quite accurate, it will not, in general, achieve this 1 to 2% error level. When variable loads are used in place of constant current loads, or when voltage thresholds instead of a time criterion determines the end of genset operation, simulated behaviour does not coincide with reality so well: errors in energy flows of 5 to 8% are more typical.

Two aspects of the simulation tool merit further attention. First, the battery model is less accurate under conditions of changing current. The reasons for this are explored; it is expected that the limitations associated with this battery model also apply to many other published models. It is proposed, as a consequence, that the current accepted by a battery under constant voltage charging be used as a test of any battery model. Second, the algorithm for dividing solar irradiance on the horizontal into beam and diffuse components is somewhat inaccurate. This shortcoming has been explored elsewhere.

INTRODUCTION

Photovoltaic (PV) hybrid systems are used throughout Canada to power small electrical loads in locations where grid electricity is unavailable or very expensive (Martel and Turcotte, 2000). Consisting of a photovoltaic array, fossil-fuel powered genset, battery, controls and power converters as required, the hybrid system combines the advantages of PV and the genset: the PV provides power with no fuel costs, and the genset guarantees power availability even during extended periods with little sunshine.

Proper dimensioning and control of a PV hybrid system is not trivial, despite the apparent simplicity of the system. Complications arise due to the stochastic nature of the solar resource and loads, the complex behaviour of the battery, and the freedom to start and stop (or "dispatch") the genset—a freedom not present in systems powered solely by solar or wind.

Optimization of system design and control is, therefore, a major objective of the CETC-Varennes PV hybrid system program. A wide range of variables related to climate, load, system configuration, component sizing, component characteristics, and control needs to be investigated. Ideally, testing on real systems would be used to do this. Unfortunately, not only would the number of potential system and control configurations be prohibitively large, and the time required to run tests on them prohibitively long, but the results would be difficult to compare unless all systems experienced the same conditions of solar radiation.

Fortunately, simulation can address these difficulties: the influence of the different variables can be investigated under controlled and repeatable conditions of solar radiation and load in a reasonable amount of time. But simulation involves models that only imperfectly reproduce the behaviour of the underlying systems; conclusions drawn on the basis of simulation will be suspect unless the simulation models have been shown to accurately model similar systems under similar situations, or until the conclusion has been tested on a real system. There is a role, therefore, for a real "test bench" system as well as a simulation package.

The PVToolbox simulation tool was developed by CETC-Varennes to provide a flexible, research-oriented library of component models for simulation of energy flows within PV hybrid systems. The design objective was a tool that would be accurate to within 10% in its prediction of the energy provided by the genset, the output of the PV array, and the energy flows into and out of the battery. It was not intended for the modelling of very short term (i.e., seconds or less) transient behaviour.

The CETC-Varennes PV-hybrid test bench comprises a 7.5 kVA diesel genset, a 24 V bank of absorbed glass mat batteries with a capacity of 600 Ah, a photovoltaic array configurable up to 1.5 kW, a 48 Amp pulse-width modulation charge controller, a 3 kW inverter/charger, variable DC and AC resistive loads, and a monitoring and control system. The interior temperature of the building housing the testbench is controlled by an electric heater, a fan, a fresh air damper, an exhaust air damper, and a damper that can route the genset cooling air either inside or outside the test bench.

This article examines some of the comparisons that have been made between PVToolbox and the CETC-Varennes PV-hybrid test bench. It attempts to 1) provide some indication of the accuracy of the tool under different operational conditions, 2) examine the causes of inaccuracies in the tool and suggest possible avenues for improvement, and 3) identify operational conditions that are particularly difficult to simulate accurately.

PVToolbox is implemented in the Matlab® Simulink® environment, which facilitates the interconnection of different component models in response to particular research needs. Simulations run with a variable time step, and weather and load data at any (reasonably fine) time resolution can be used—e.g., data for each hour, two minute, or fifteen-second period. Other than the environment and the variable time step, PVToolbox is not unlike many other PV hybrid simulation tools: its component models are relatively conventional. Thus, the accuracy of the PVToolbox is likely a reasonable indicator of the accuracy of similar PV simulation tools.

COMPARISON OF SIMULATION OUTPUT AND MEASURED DATA

Battery Discharge and Recharge Cycle: The most complex component in the PVToolbox, and the one most likely to be significantly in error, is the battery model. A single cycle of discharge and recharge has been found, in fact, to be a relatively stringent test of a battery model and its associated charge controller model. In particular, a charge composed of a constant current charge up to a certain voltage threshold ("bulk" charge), followed by a constant voltage charge at the threshold ("absorb" charge), and finishing with a constant voltage charge at a reduced voltage threshold ("float" charge), is a good test because the constant voltage portions of the charge make it apparent whether the model is able to handle continuously changing currents (Ross, 2003).

Figure 1 examines the PVToolbox output over such a test. The simulation was run in such a way that the elapsed time of the discharge and the combined bulk and absorb charging matched the elapsed time of discharge and genset charging on the test bench. In general, the correspondence is quite good. Had the simulation been run with the discharge ending at 23.4 V, as in reality, and the absorb charge lasting a specified elapsed time, the correspondence would have been less good.

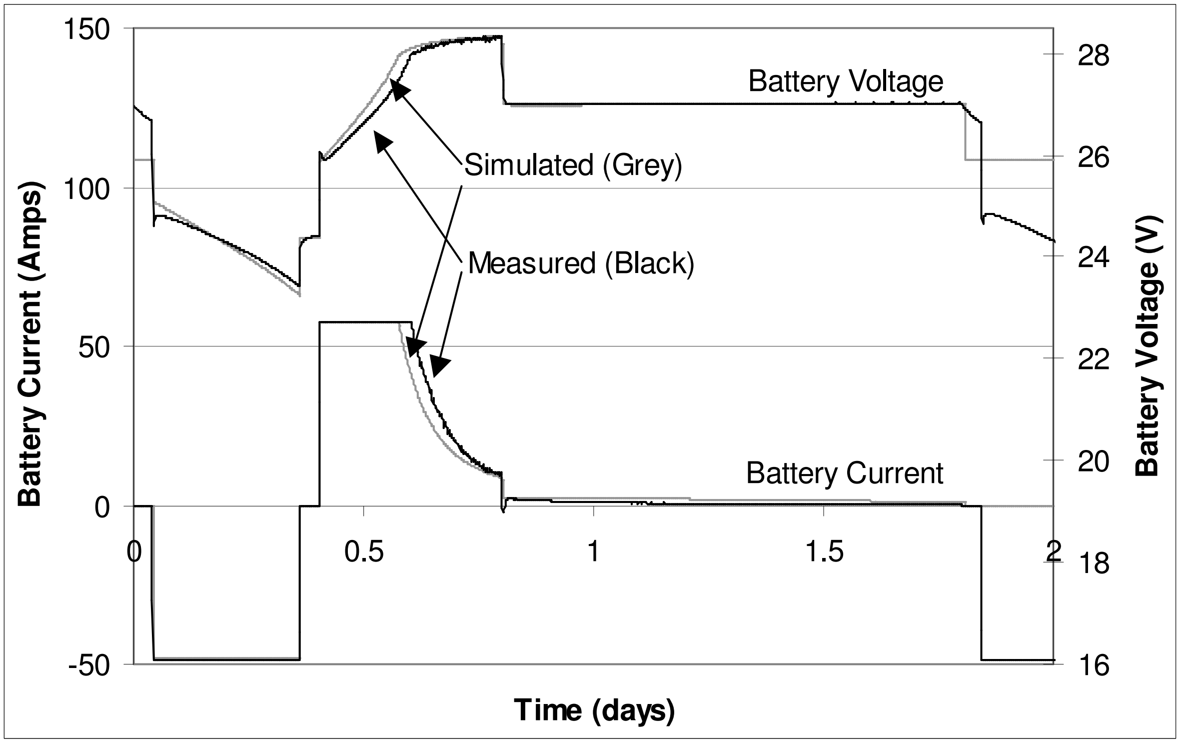

Figure 1: Monitored and Simulated Battery Voltage and Current during Discharge/Charge Test

It is encouraging that during absorb charging, the current falls in roughly the same way for both the simulation and the real battery. In previous tests, using earlier versions of the battery model, the model would be reasonably accurate during constant current charging, but taper the charge current far too quickly during constant voltage charging. On the other hand, since the preceding bulk charge ends prematurely in the simulation, the state-of-charge of the battery should be lower at a given point in the absorb charge, so ideally the simulation would have the current tapering less quickly than it does in reality. During the same elapsed time, bulk and absorb charging supplied 10.55 kWh to the battery in reality but only 9.72 kWh in simulation—a difference of 8%. As a consequence, on the subsequent float charge, 403 Wh is returned to the real battery, but 1108 Wh is returned to the simulated battery.

The rounded shape of the battery voltage during absorb charging is due to the resistance of the wires connecting the charger and the battery; the charger maintains the absorb threshold at its terminals, and the voltage drop in the wires falls as the current tapers.

The battery temperature varied during the test, rising from 21ºC at the beginning of discharge to 24º at the beginning of charge, and then shooting up to 30º at the beginning of constant voltage charging, whence it fell gradually starting with float charging. In contrast, the battery temperature is assumed to be constant at 25ºC throughout the simulation; this may account for some of the discrepancy between simulation and reality.

The coulombic and round-trip (energy) battery efficiency over the course of the discharge and charge is presented in Table 1. The errors in the values calculated for the simulation are minimal.

The simulation can provide information that is either difficult or impossible to measure in testing. Figure 2 provides two examples. The simulated state-of-charge (SOC) and fraction of the battery charge current that is wasted in gassing and other parasitic reactions are shown, along with, for reference purposes, the battery voltage. In reality, the battery state-of-charge at the end of absorb charging is probably higher than the 95% level indicated by the simulation, since the simulation underestimates the charge entering the battery during bulk and absorb charging.

	Test bench	Simulation	Error
Coulombic Efficiency	92.9%	93.7%	0.9%
Round-trip (Energy) Efficiency	83.0%	83.3%	0.4%

Table 1: Battery Efficiency during Discharge/Charge Test

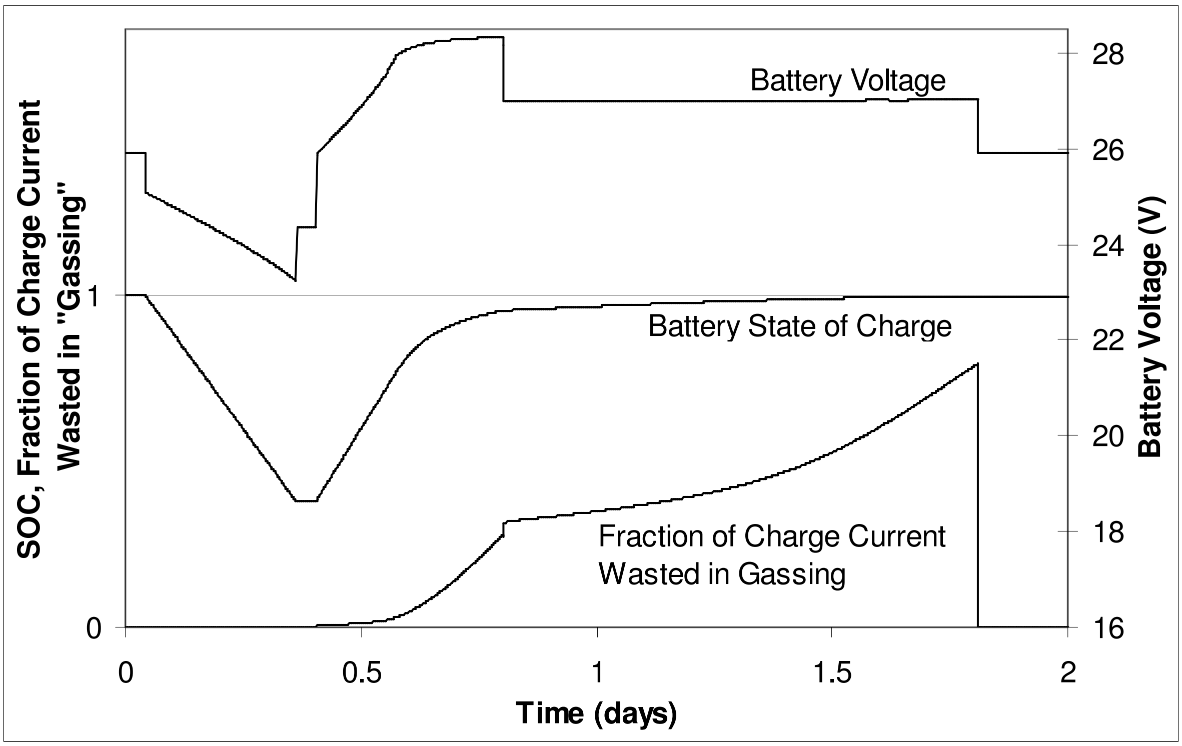

Figure 2: Simulated Battery Voltage, State-of-Charge and Gassing Losses during Discharge/Charge Test

Battery Cycling without Absorb Charging: The above test started with a battery that had been fully charged. This will be an unusual situation in a photovoltaic hybrid system, which will normally cycle between different partial states-of-charge. To examine system operation under such conditions, a test was run in which the battery was discharged to 2.03 Vpc (Volts per cell) at a 12.3 A rate, open circuited for an hour, and then bulk charged with the genset to a voltage of 2.34 Vpc (Ross, 2004). Following an open-circuit rest period, this cycle was repeated four additional times. Note in Figure 2 that, according to simulation, charging the battery to 2.34 Vpc (the onset of absorb charging) raises the SOC to 80%.

During this test, the battery temperature varied quite widely, as seen in Figure 3. Unfortunately, this makes interpretation of the results difficult, since the battery model assumes a 25ºC battery, there being insufficient calibration data for operating the model at other temperatures.

The simulation can be run in two ways: the measured battery current can be used, and the real and simulated battery voltage compared, or the voltage thresholds used to start and stop the genset can be used, and the real and simulated behaviour compared.

Figure 4 shows the battery voltage and current when the simulation uses the measured battery current; for the final recharge the absorb voltage threshold and elapsed time are used instead. In general, the simulated battery voltage is quite accurate on discharge, but on recharge, it is too high at the beginning and too low at the end. One hypothesis could be that the falling battery temperature causes this, but since the discharge voltage is relatively accurate, there may be other factors at play.

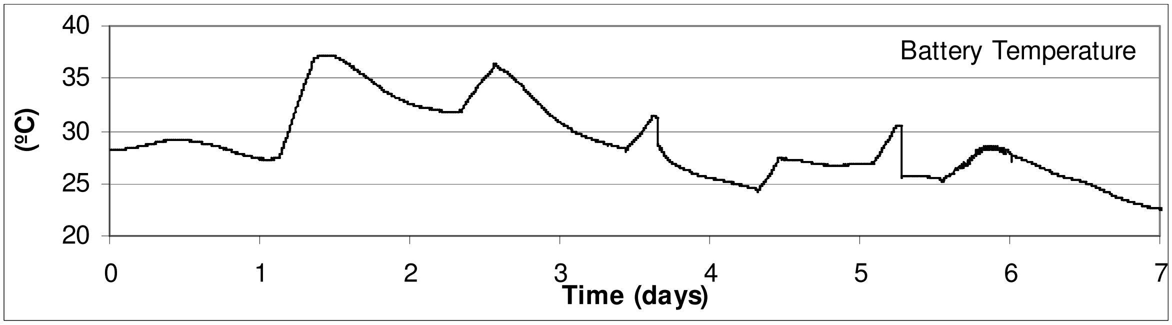

Figure 3: Battery Temperature during "Battery Cycling without Absorb Charging" Test

During the final recharge, the simulated battery voltage fails to capture the sharp upturn in the real battery voltage at the end of bulk charging and the simulated absorb current falls much too quickly; this should be compared with Figure 1, where the simulated voltage rises too quickly during bulk charging and the absorb current's decline is simulated accurately. Since the battery temperature during the final recharge is very similar to the temperature during bulk and absorb charging in Figure 1, the difference in the behaviour of the battery must be attributed to "memory" of the preceding cycles.

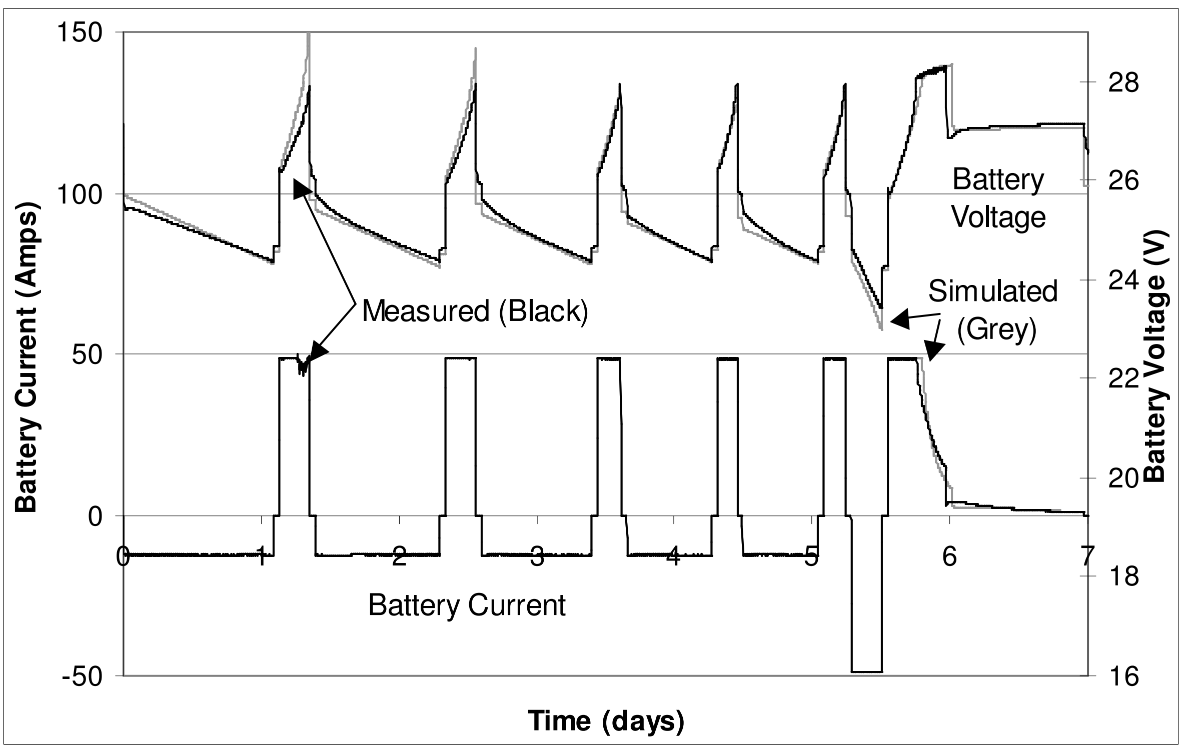

Figure 4: Reality vs. Simulation Using Measured Battery Current

The charge returned to the battery on each cycle falls with every cycle up to the last, and consequently the discharge is also shorter on every cycle. This is reflected in the battery state-of-charge, shown in Figure 5, as estimated by the simulation. This confirms that while the state-of-charge at the end of discharge changes little from cycle to cycle, the SOC at the end of charge declines.

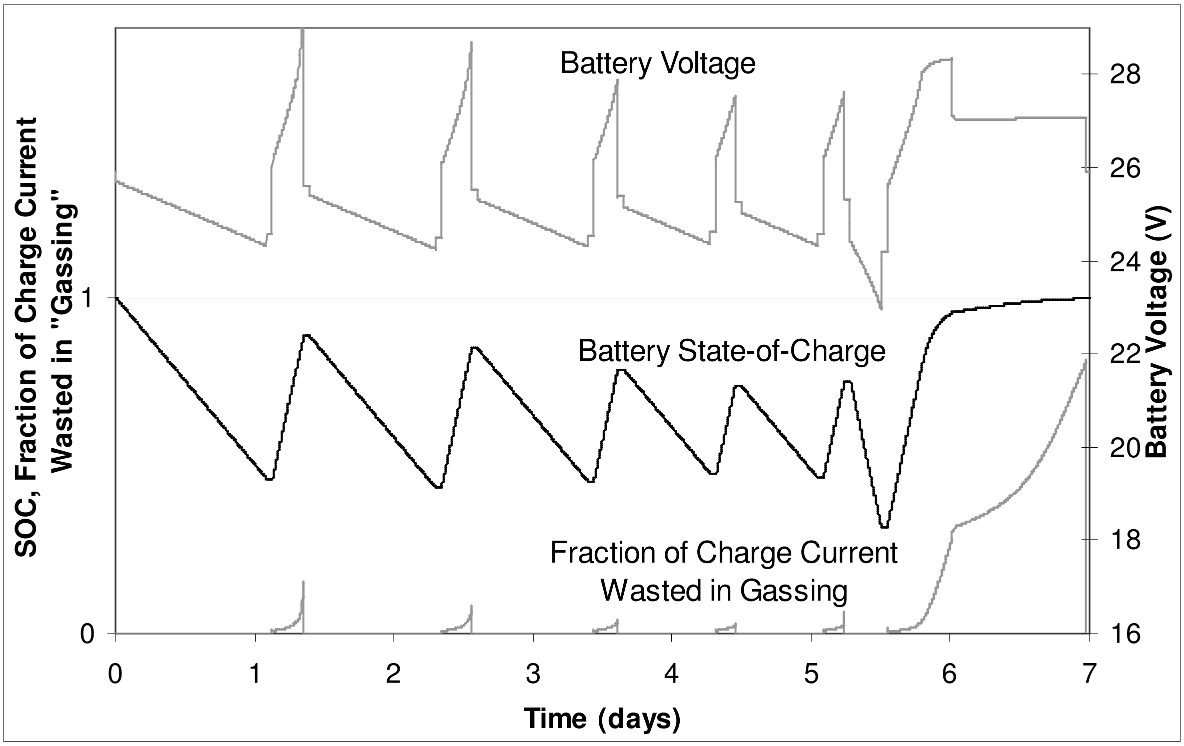

Figure 5: Simulated Results Using Measured Battery Current

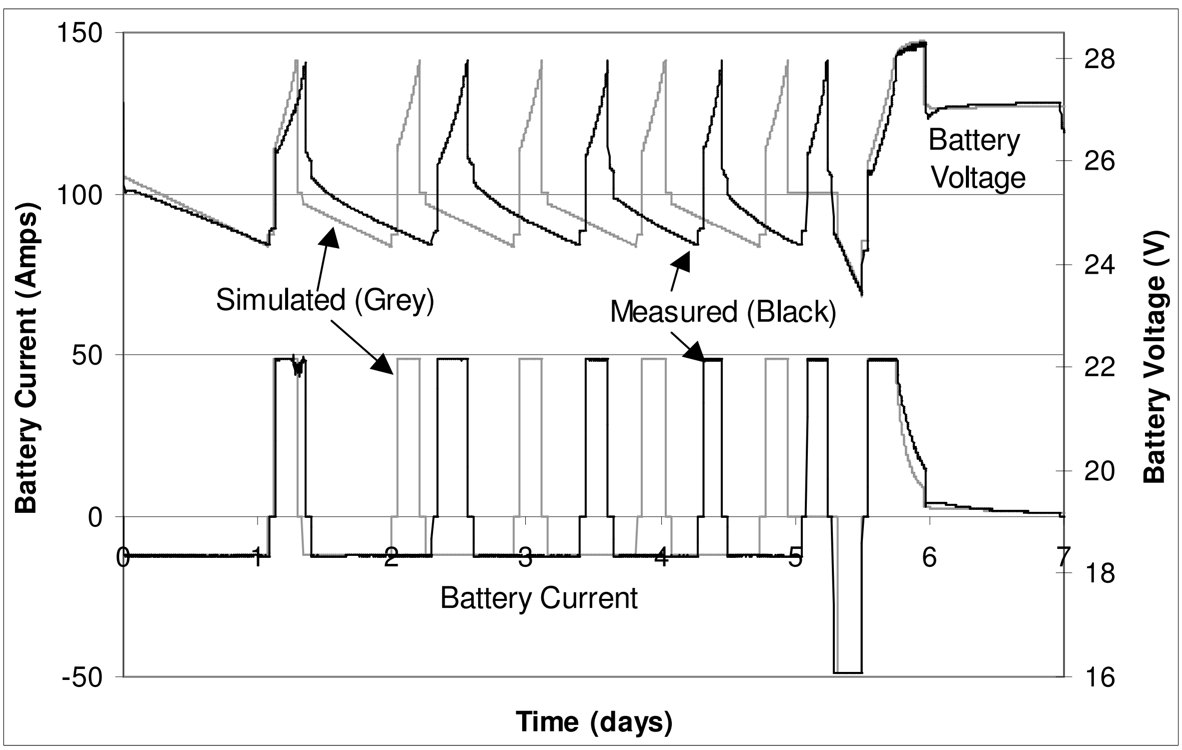

Figure 6: Reality vs. Simulation Using Voltage Setpoints

A very different picture emerges when the same simulation is run not with the measured battery current, but rather with the voltage thresholds used to terminate charging and discharging (Figure 6). Five cycles are shown; since these five cycles are completed before the five cycles of the real test, an open-circuit wait period has been inserted such that the end of the final discharge is coincident in the simulation and in reality. The simulation is relatively accurate up until the start of the first recharge. Then the voltage rises too quickly, and as a consequence charge is terminated prematurely. This causes the simulated charge and discharge cycles to occur at times different from those in reality.

Note that, since the voltage setpoints and battery current are the same in every cycle, the simulation predicts that the voltage and state-of-charge profiles will be the same in every cycle, as seen in Figure 7. This should be compared with Figure 5, which is a more accurate portrayal of the SOC. Some of the difference can be attributed to the changing battery temperature over the course of the test. It is also possible that the characteristics of the battery are changing from cycle to cycle in a way that is not fully captured by the use of a single state variable (the SOC).

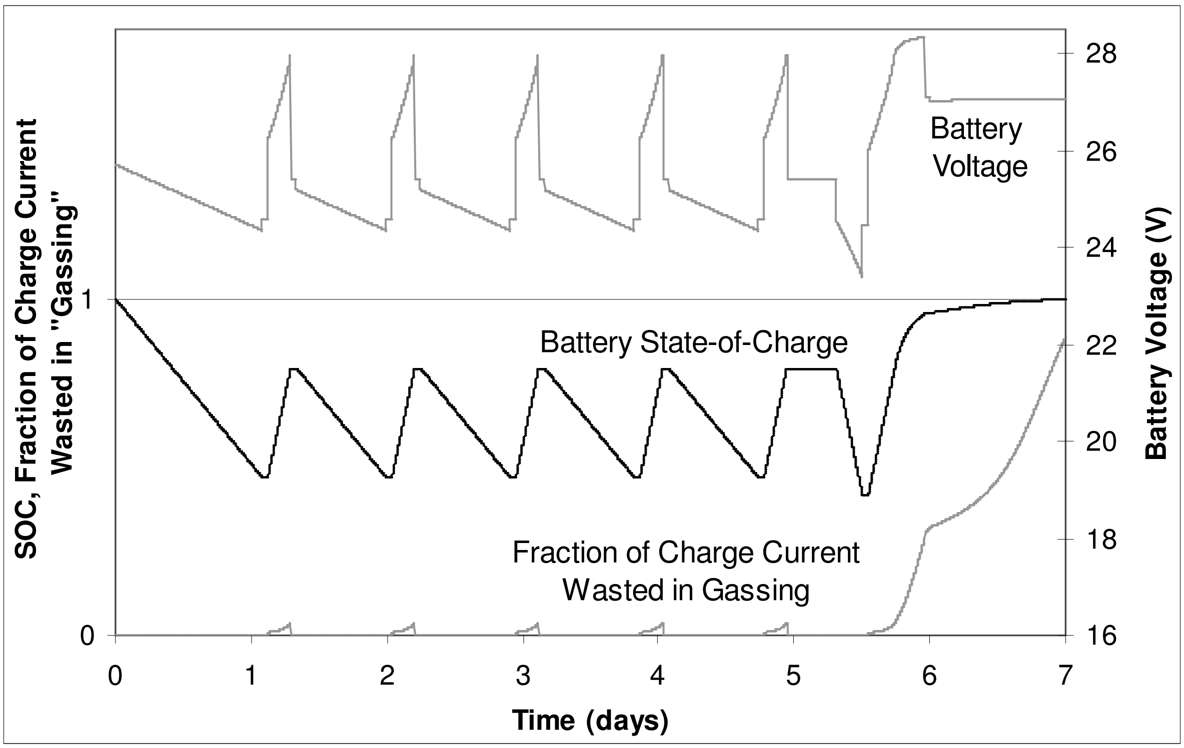

Figure 7: Simulated Results Using Voltage Setpoints

Despite the inaccuracies in the simulation, the energy flows of the test are reproduced with acceptable accuracy, as shown in Table 2. In the test using voltage setpoints, charge into and out of the battery as well as energy into and out of the battery are underestimated by around 8 to 9%—that is, within the desired 10% range. As in the previous test, the coulombic and energy efficiency of the battery is very accurately simulated: the error is -1.1. to -1.2%.

	Monitored	Simulation Error	
		w/ Measured Currents	w/ Voltage Setpoints
Charge in	1483 Ah	na	-8.1%
Charge out	1440 Ah	na	-8.5%
Coulombic Efficiency	97.1%	na	-0.4%
Energy in	39.9 kWh	0.7%	-7.5%
Energy out	35.6 kWh	-0.4%	-8.6%
Energy Efficiency	89.3%	-1.1%	-1.2%

Table 2: Energy Flows and Battery Efficiency During Test of Battery Cycling without Absorb Charging

On the basis of this test, it can be expected that simulations will be less accurate when battery temperature deviates widely from 25ºC and control decisions are based on voltage or current thresholds, rather than elapsed time criteria. The use of voltage or current thresholds to trigger non-linear control decisions such as turning a genset on or off demands a high level of accuracy from the battery model.

PV Hybrid System Test #1: The previous tests did not incorporate the varying and unpredictable current associated with a photovoltaic array. This was first included in a five-week test run during September and October, 2004 (Ross, 2005a). A 1.2 kWp, nominally 24 V, PV array was connected to the battery, without maximum power point tracking, via a bulk/absorb/float charge controller. The genset was started whenever the battery voltage reached 2.03 Vpc (or 24.36 V) except during one period when, due to operator error, it was permitted to discharge to voltages lower than this. With the genset on, the charger supplied 48.5 A. Once started, the genset would run for 3.5 hours, or until a battery voltage of 28.0 V was reached. The test ended with a final discharge to 23.4 V and a bulk/absorb/float charge. The load was 6.5 A for the first 16.5 days of the test, and 8 A following this. The load was entirely DC. Battery temperature remained near 25ºC throughout the test.

Global horizontal, diffuse, direct beam, and total plane-of-array irradiance averages were recorded every two minutes. The PVToolbox was used to predict the insolation in the plane of the array (due south ±5º, tilted at 45º) based on the global horizontal irradiance, as seen in Figure 8 for a five-day period. For all reliable two-minute data from the test, the mean bias error was –5.9% and the root mean squared error was 13.8%. The mean bias error is nearly in the neighbourhood of uncertainty associated with the measured data; the use of two-minute data, rather than data over longer averaging periods, no doubt increases the root mean squared error, due to rapid transitions in the solar irradiance during periods of mixed sun and cloud. Indeed, when hourly data is used, the mean bias error is –7.8% and the root mean squared error falls slightly, to 13.1%.

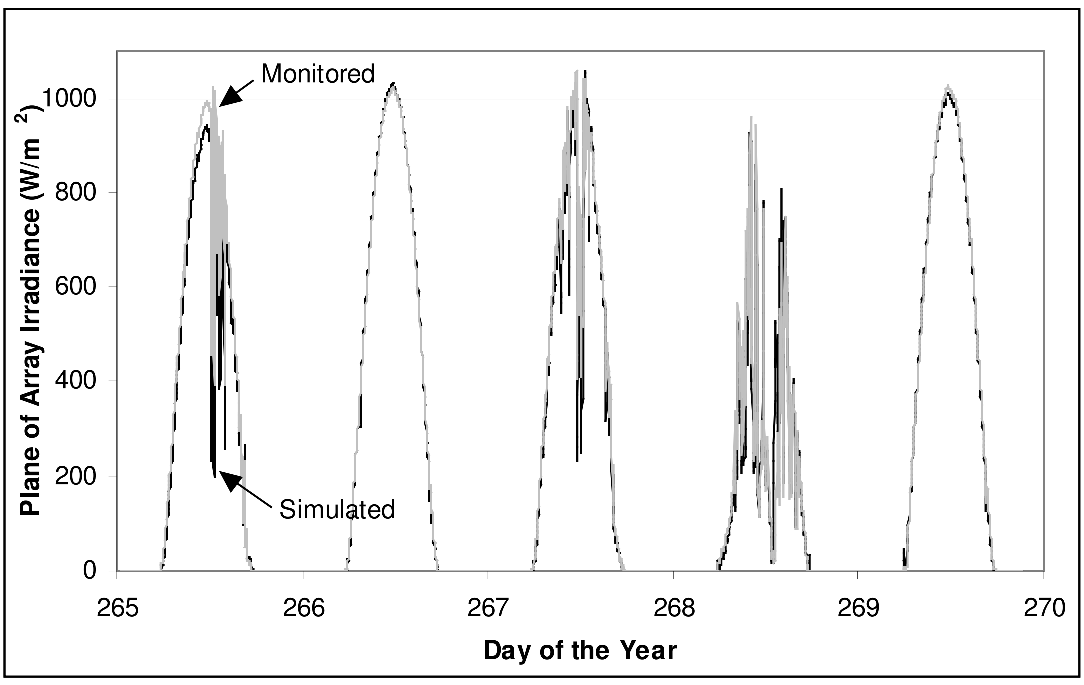

Figure 8 : Plane of Array Irradiance—Measured versus Simulated, 2 Minute Data

To avoid confounding errors in the plane-of-array irradiance calculation with errors rooted in other system components, a simulation of the system was run using plane-of-array irradiance data[1]. The

[1] This is the case for all subsequent system simulations discussed in this article.

simulation used nominal voltage thresholds and elapsed time setpoints to control the starting and stopping of the genset. The accuracy of the simulation was excellent. The test started on September 14th, which is the 257th day of the year. The genset did not run until day 278. Despite the elapsed time of over 20 days, the timing of genset operation in simulation and reality coincided nearly perfectly. This continued up until day 290, when the timing diverged (Figure 9). This level of accuracy is surprising.

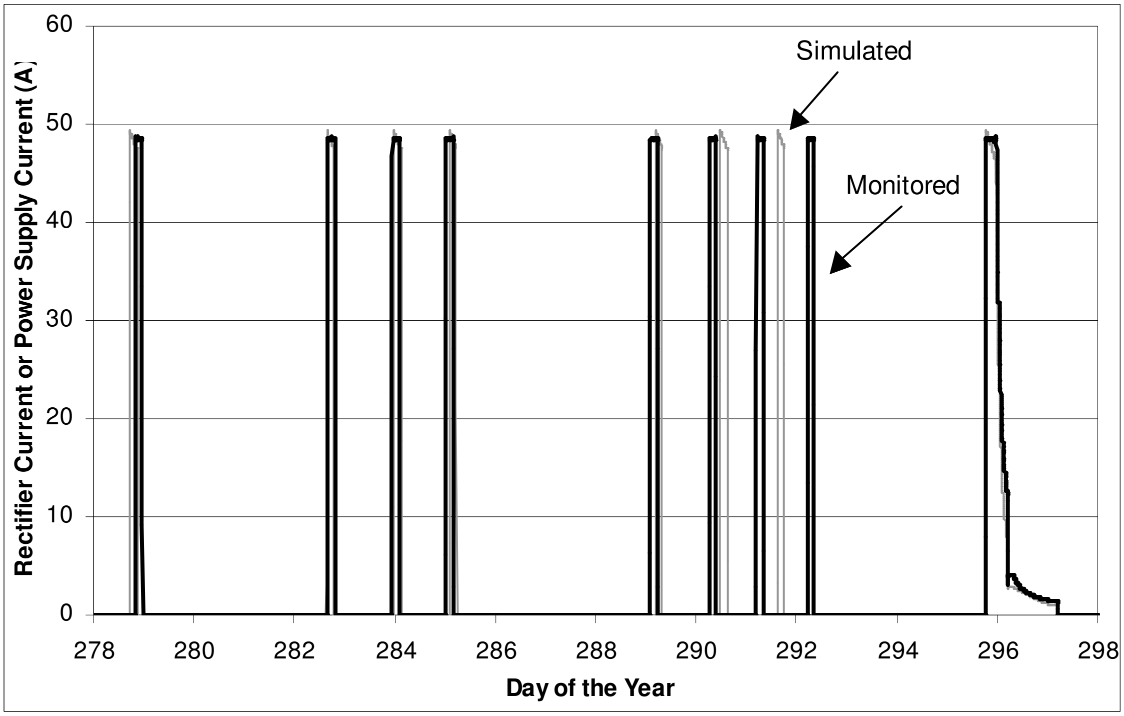

Figure 9: Rectifier Output—Measured versus Simulated, PV Hybrid Test #1

Following day 290, a minor error in the predicted battery voltage caused the simulated genset start to fall behind that of the real system, as seen in Figures 9 and 10. On day 292, when the genset turns on for the final time prior to the final discharge/recharge, the real battery voltage is 24.36 V but the simulated battery voltage is 24.50 V—an error of only 12 mV per cell. Just following the start of the genset, however, dawn arrives, and photovoltaic current raises the battery voltage before the simulated battery voltage reaches the genset start threshold. Had dawn arrived a couple of hours later, the simulated system would have run eight times prior to the final discharge and recharge, just like the real system. As it was, the genset ran only seven times, and after day 292 the voltage of the battery is badly off. That such a small error in the battery voltage can cause such divergence in system operation underlines the astonishing fidelity of the simulation up until day 290.

Over the entire test, the mean bias error in the simulated battery voltage is only 7 mVpc, or 81 mV for the 24 V battery; the root mean squared error is 39 mVpc, largely due to the divergence following day 292. Most of this error is in the simulated voltage during charge. The energy supplied by the photovoltaic array, measured at the output of the charge controller, is accurate to within several percent, and the charge and energy into and out of the battery are in error by only 2.6 to 5.5%. As a result, the measured battery coulombic efficiency of 92.7% and energy efficiency of 86.3% are matched to within 3% by the simulation.

The excellent accuracy of the simulation is less surprising considering that while a voltage threshold was used to determine when the genset should be started, it was turned off on the basis of an elapsed time criterion.

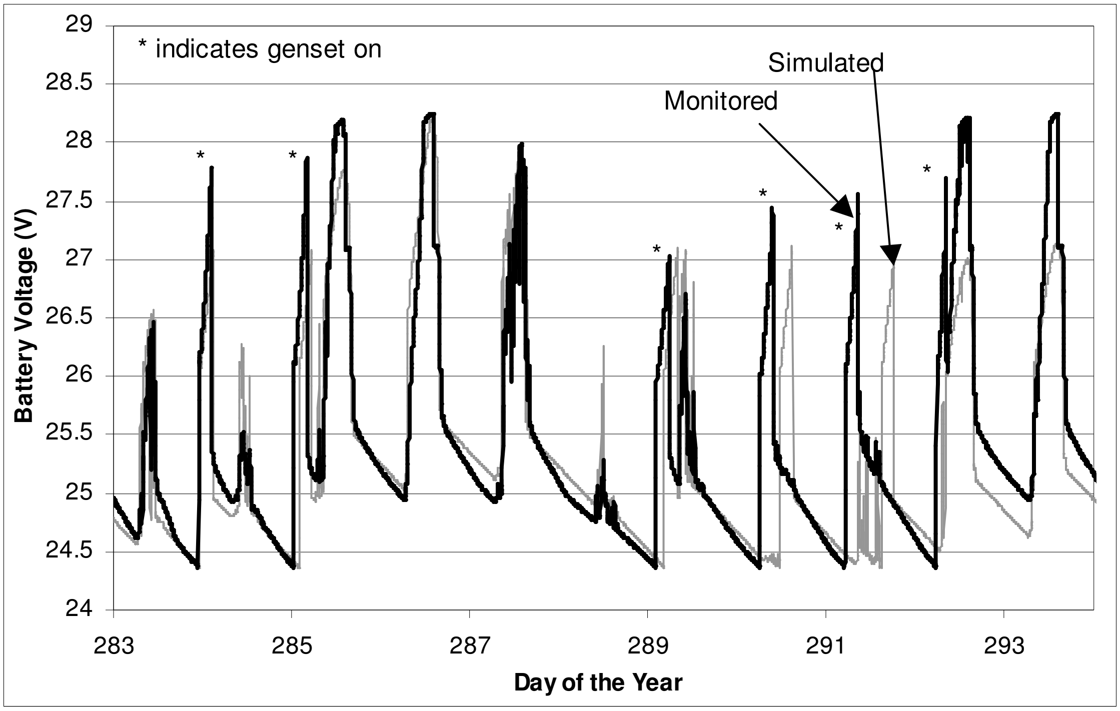

Figure 10: Simulated and Measured Battery Voltage, Days 283 to 294, PV Hybrid Test #1

PV Hybrid System Test #2: The solar fraction for the previous test was around 0.8; a similar test was run with a solar fraction of around 0.5 (Ross, 2005b). This results in cycling of the battery between partial states-of-charge without the battery ever approaching full charge. A 24.0 V threshold was used to determine when the genset should be started; then it was run long enough to supply the system with around 150 Ah of charge above what was consumed by the load during that period. For the first half of the test, the rectifier charge current was around 48.5 A, so with a load of around 13.5 A, the effective charge current was about 35 A, and the genset ran for 4.2 hours. For the second half of the test, the rectifier charge current was about 95 A, so the genset ran for around 1.8 hours. The battery started the test fully charged; the test ended with a final discharge to 23.4 V and bulk/absorb/float recharge.

The correspondence between between simulation and reality is excellent for both battery voltage and the timing of genset operation (Figure 11). (The inverter failed on the sixth day of the test; the simulated genset run is curtailed to account for the failure, and the simulated inverter is not permitted to start again until the inverter had, in reality, been replaced). The photovoltaic array output is also simulated accurately, as suggested by Figure 12. The error on the simulated energy from the PV array is only -1.2%; for energy into the battery it is -1.8%; for energy out of the battery it is -0.8%; and for energy from the genset—perhaps the most critical metric of all—it is -0.6%.

Careful examination of the monitored battery voltage (black trace) at the termination of genset operation reveals that it rose throughout the test (beyond the increase seen on the seventh day of the test, due to the doubling of the charge rate). This echoes the behaviour seen in the cycling test without absorb charging, discussed above. In that test, the culprit could have been varying battery temperature; here the battery is held near 25º C throughout the test. This is more evidence of the battery retaining “memory” of past cycling; note that measurements of cell voltages throughout the test indicated that no “weak” cells were unduly influencing the results. The simulation is unable to capture this memory, but since the termination of genset operation is controlled on the basis of the net charge into the battery, simulation accuracy is little affected.

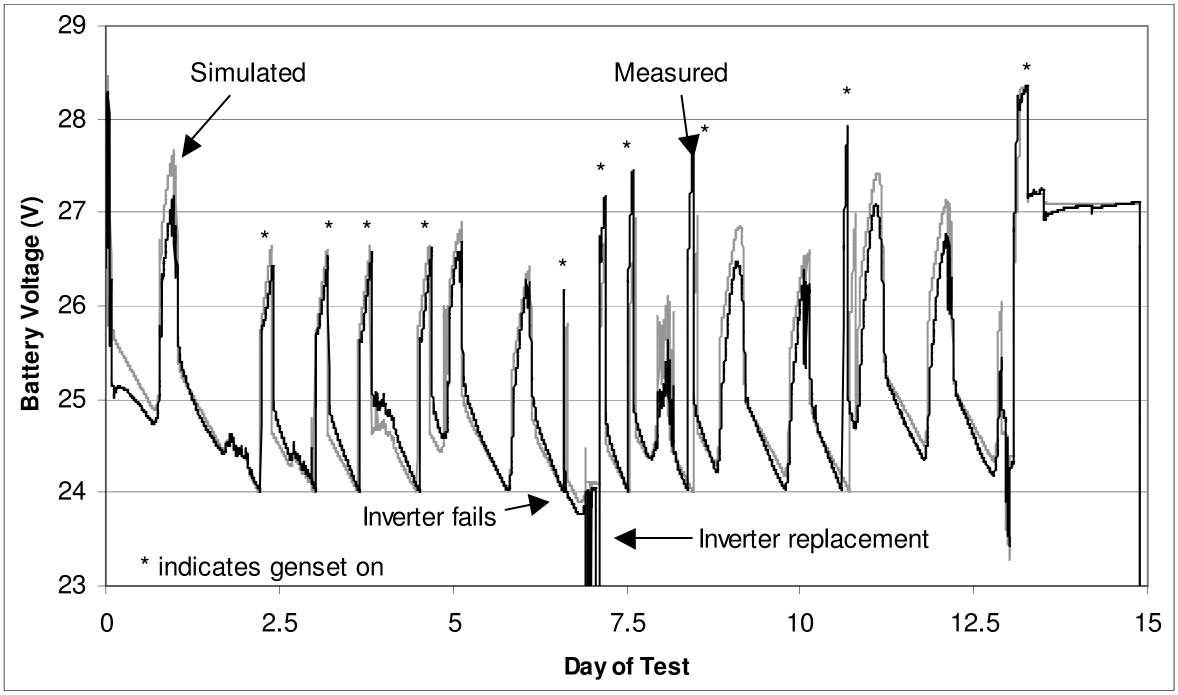

Figure 11: Battery Voltage During the PV Hybrid Test #2

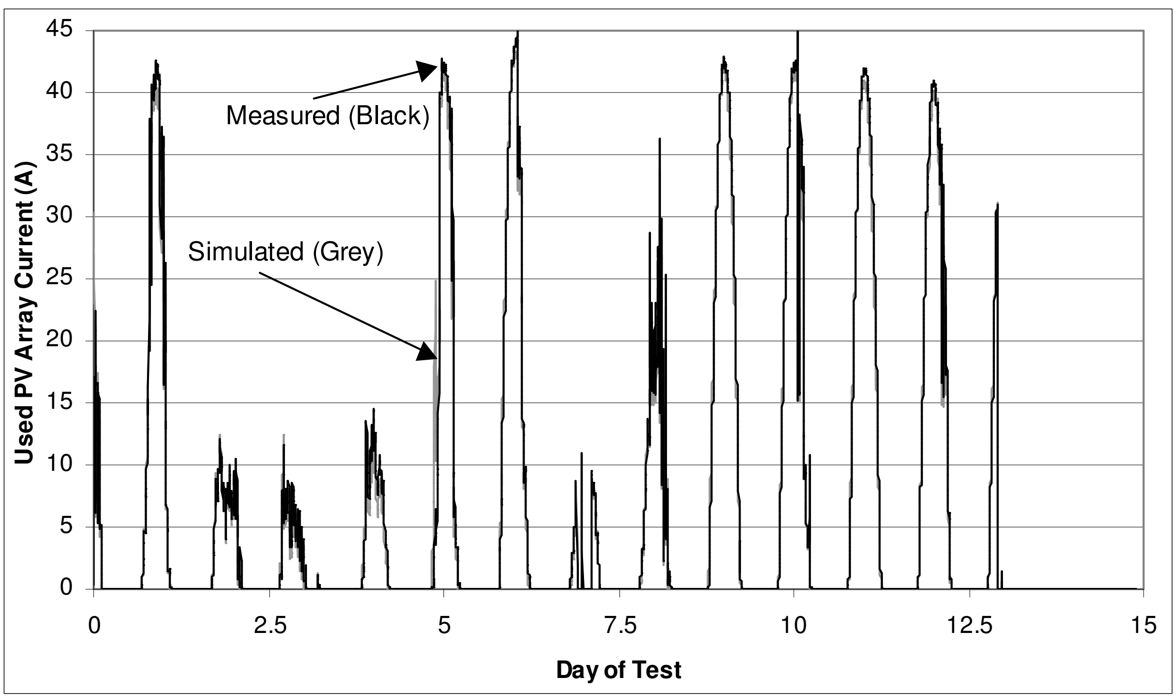

Figure 12: PV Array Output During PV Hybrid Test #2

PV Hybrid System Test #3: To this point, this paper has examined tests with constant DC loads. To investigate how the combination of control by voltage thresholds and rapidly and widely varying loads affects simulation accuracy, a test was run which included, for five days of the test, a DC load that fluctuated between 5 and 50 A. The same daily load profile was repeated for each of the five days; the load was low through the night, but then peaked in the morning, was moderate through the day, and rose again in the evening. The average daily load for this varying load profile was 13 A; prior to the five day period when the loads varied, a constant 13 A load was used.

The test was conducted from March 23rd through April 20th, 2005. The control algorithm started the genset when the battery voltage reached 23.85 V, and ran it until the battery voltage reached around 28.05 V, indicating the start of absorb charging. The rectifier charge current was around 95 A. At the end of the test, the PV array was disconnected and a final discharge, at 48.6 A, was conducted. This ended at a battery voltage of 23.4 V, and was followed by a bulk and absorb charge.

Two complications arose during this test. On the 30th of March (day 90 of the year), maintenance operation of the genset caused some spurious spikes of charging current. Between day 94 and 99, problems related to frozen exhaust condensate prevented genset operation; the load was turned off during much of this period, but a relatively deep battery discharge occurred nevertheless. At the end of the period, the genset was run under manual control for several hours, charging the battery at a current of around 50 A.

The battery voltage is shown in Figures 13 and 14. The influence of load variation over days 103 to 108 is evident. Initially, the simulated and real voltage agree quite well, but by day 93, minor errors in the simulated voltage cause the genset to start at times quite different from those observed at reality; this compounds the voltage error, and the timing of simulated genset starts falls further and further behind. Then, following the start of varying load, the genset is started, both in reality and simulation, by peak currents occurring in the morning. These start the real genset every morning, but the simulated genset is started only every other morning.

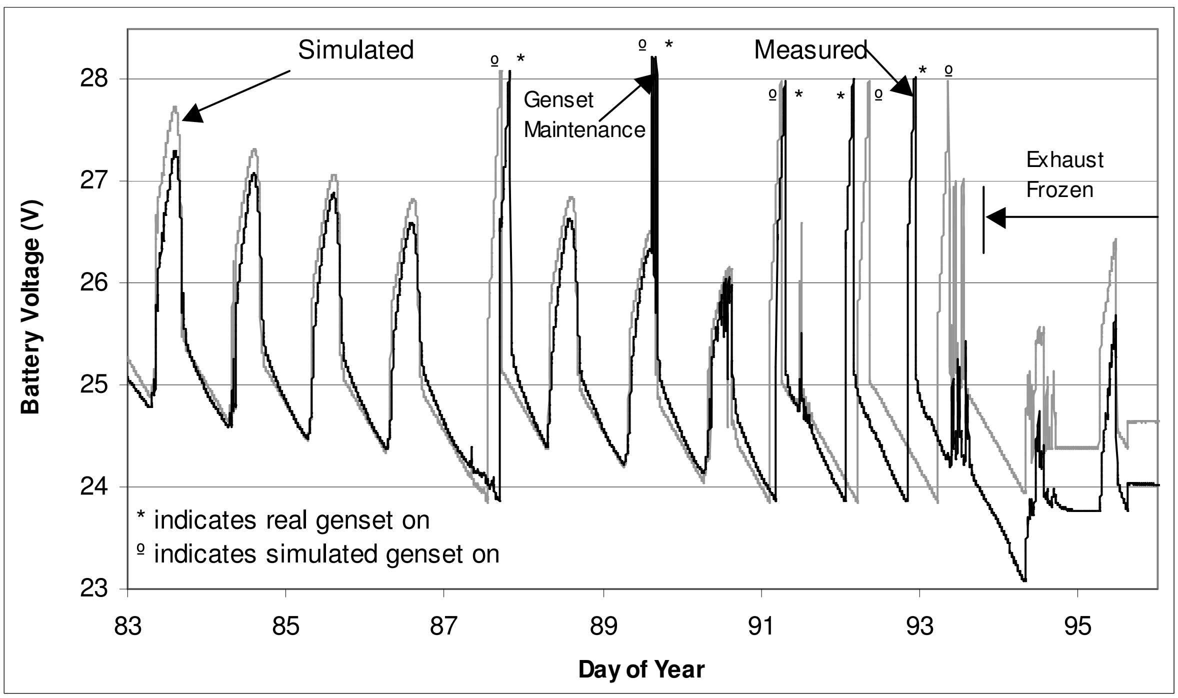

Figure 13: Battery Voltage during First Half of PV Hybrid Test #3

The simulated genset starts only 8 times prior to the final recharge, not counting maintenance runs, whereas the real genset started 13 times. The total run time is less dissimilar, however: 22.3 hours for the test bench versus 24.0 hours for the simulation.

It is worthwhile examining the causes of this divergence. The real genset consistently generated less electrical energy in a run than the simulated genset, and its output per run declined precipitously during the test (Table 3). In the first test bench run, the simulation predicted output of 9.5 kWh, but the real genset put out only 8.6 kWh. This first run included 26 minutes of absorb charging; when this was eliminated in the second and subsequent genset runs, the simulated output fell to around 8.5 kWh per run.

The real genset output per run immediately dropped to 6.5 kWh, however, and then continued to decline: in the last two runs before the load started to vary, it put out only 3.9 to 4.6 kWh. It should be noted that prior to the point at which the load started to vary, test bench genset operation did not coincide with significant solar radiation, and the reduced time required to drive the battery to 28.0 V cannot be attributed to additional PV current. In contrast, this does occur with the simulated genset on days 92 and 98; the resulting 0.6 to 1.0 kWh reduction in the genset output is modest in comparison to the decline seen in the real genset output.

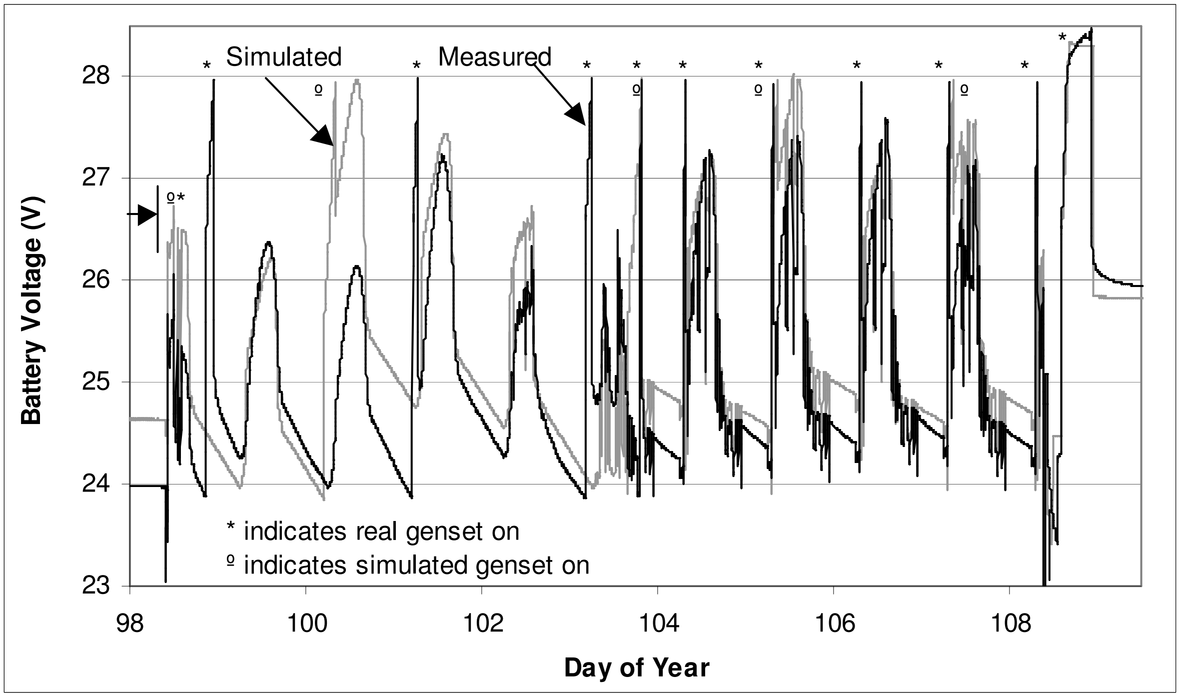

Figure 14: Battery Voltage during Second Half of PV Hybrid Test #3

Test bench			Simulation		
Start Time (day)	Energy (Wh)	Time (mins)	Start Time (day)	Energy (Wh)	Time (mins)
87.68	8593	216	Test bench – 3.1 h	9503	236
91.19	6516	160	Test bench – 2.2 h	8519	210
92.05	6514	158	Test bench + 3.8 h	8497	210
92.83	6193	144	Test bench + 9.4 h	7890*	194
98.86	5843	144	Test bench + 32.4 h	7520*	184
101.21	3914	98			
103.18	4624	114			
Varying load begins					
103.78**	1950	50	103.67**	8897	220
104.29**	1922*	50			
105.29**	1751*	46	Test bench + 4 min**	3816*	94
106.29**	1779*	46			
107.29**	1800*	48	Test bench + 4 min**	3708*	92
108.29**	2141*	56			
* Significant PV current at termination of genset run ** Genset start coincides with high load					

Table 3: Genset Start Times, Energy Output, and Elapsed Runtime, PV Hybrid Test #3

This reduction in the real genset output prior to the onset of varying loads is probably related to the types of memory effects observed in previous tests: battery temperature and diverging weak cells do not appear to be the cause. The voltage-current-SOC characteristics of the battery appear to change quite drastically over time. In Hybrid Test #2, the voltage at the end of genset charging rose throughout the test, but because a time criterion was used to start the genset, this did not affect the amount of charge returned to the battery. In this test, however, the voltage criterion permitted a drastic decline in the charge returned to the battery.

Once the load began to vary, the genset output per run fell even further. Peak loads of around 50 A, although of short duration, momentarily dragged down the battery voltage to the point that the genset was started, even though the state-of-charge was relatively high. With the real genset, this occurred every morning, and the genset put out only 1.75 to 1.95 kWh per run. With the simulated genset, around 3.7 kWh of energy was generated per run, and this was sufficient for the genset to start only every other day. Nevertheless, the effect of the peak loads on system operation was drastic. This illustrates the potential pitfalls of a simple voltage criterion for starting the genset; it should be noted that this is, nevertheless, common practice.

Despite the apparent divergence of simulation and reality, the simulation was within the 10% error range desired of it. Over the whole test, energy from the PV array and genset were each predicted within 5% error, and energy into and out of the battery was in error by less than 3%. Simulation predicted a solar fraction of 62.1% of the energy supplied, close to the real figure of 64.3%. Battery efficiencies were accurate to within around 1%. These averages mask some less favourable results when the test is considered exclusive of the final discharge and recharge. For example, the energy from the genset was overestimated by 8.6% during this period.

WEAKNESSES: BATTERY MODEL AND TILTED INSOLATION PREDICTION

Two aspects of PVToolbox merit further attention, for they appear to give rise to the majority of the error in its predictions. These are the battery model and the model for converting global solar radiation on the horizontal to radiation in the plane-of-array.

Battery Model: One evident shortcoming of the battery model is the assumption that the battery temperature is 25ºC. In large measure, this reflects the paucity of calibration data available for higher and lower temperatures. But there is perhaps a more serious weakness in the battery model, one that it shares with the majority of simple battery models used in photovoltaic system simulation: that is, it uses a single state variable—the state-of-charge—to determine the battery voltage-current characteristics. There is much in the tests examined in this paper to suggest that this is insufficient.

When the battery is cycled between partial states-of-charge, its characteristics appear to change from one cycle to the next. This is observed in the shortening cycles of the battery cycling without absorb charging test and the hybrid system test #3 examined here. It also manifests itself in the rising battery voltage at the end of genset charging seen in the hybrid system tests #1 and #2. When control decisions with non-linear effects (e.g., genset turned on or off) are based on voltage or current thresholds, the changing battery characteristics have a profound effect on system behaviour.

There are a number of possible explanations for the memory seen in the battery. One would be that a single weak cell is diverging from the rest of the battery, but continuous cell voltage monitoring has eliminated this explanation. Another would be that the battery electrolyte is stratifying under the influence of gravity. One paper, citing Japanese work, asserts that absorbed glass mat batteries “can suffer from acid stratification” (Newnham and Baldsing, 1996). Given that in the test bench the major axis of the battery plates is horizontal—a configuration that minimizes stratification—it would be imprudent to blame stratification for everything observed here.

Newnham and Baldsing propose another mechanism in a more recent paper (2004). They indicate that in cycling between partial states-of-charge, the “ToCV”, or voltage at the end of a recharge returning a fixed amount of charge to the battery, rises significantly from cycle to cycle in absorbed glass mat batteries used for hybrid electric vehicle operation. This is attributed to the accumulation of lead sulfate on the surfaces of the negative plates. This lowers the negative plate electrode potential significantly, "reduces the rechargeability of the battery and, if allowed to reach a critical level, curtails battery life". While the hybrid electric vehicle cycling involves much higher currents than used here, Newnham and Baldsing believe that this mechanism is at play in PV hybrid systems.

The effect observed by Newnham and Baldsing simply be a special case of inhomogeneities in the composition of the plate arising from limited diffusion of reactants and varying plate resistivity. Bode (1977) relates the results of x-ray microprobe examinations of the $PbSO_4$ distribution in a cross-section of a plate at various states of discharge and various constant currents. These show that while at low average current densities the plate discharges uniformly across its cross-section, at high current densities the discharge is more complex. Starting with a fully charged plate, discharge is initially concentrated at the center of the plate, nearest the current collecting grid. The reactions at the centre of the plate make use of acid that has diffused into the electrode prior to discharge; at high current densities the diffusion of electrolyte into the plates during discharge cannot keep up with the reaction. When the acid concentration contained in the inner section of the plate falls to sufficiently low levels, the outer sections of the plate begin to react, even though the active material at the center of the plates has not been fully discharged. The outer sections achieve a more-or-less complete discharge, and then the discharge ends. The rate of diffusion of acid does not permit full utilization of the center of the grid.

As mentioned earlier, Bode found that these inhomogeneities in the $PbSO_4$ distribution occurred only with currents on the order of the one hour rate or higher. These currents are much higher than those associated with either the hybrid test bench data or the calibration data. But Bode's tests were conducted on plates 1.5 to 2 mm thick. Batteries intended for deep cycling will have much thicker plates than this. The Absolyte plates used in this test appear to be in the neighborhood of 6 mm. Bode indicates that inhomogeneous $PbSO_4$ distributions will occur at significantly lower current densities with thicker plates.

Bode does not discuss what occurs during charge, but it must be at least as complex as during discharge. $PbSO_4$ is only slightly more than half as dense as the lead of a fully charged negative electrode (anode) and certainly less than two-thirds as dense as the lead dioxide of a fully charged positive electrode (cathode). As a consequence, the discharged sections of the plate are less porous: the pores must give way for the additional volume occupied by the lead sulfate itself. This hinders diffusion. Furthermore, $PbSO_4$ is a semiconductor, and has a resistivity about 12 to 14 orders of magnitude higher than the lead or lead dioxide (Barak, 1980). Together, these suggest that inhomogeneities on charge should be observed at currents lower than that required for discharge.

The PVToolbox battery model is calibrated on the basis of data taken from constant current charge and discharge tests, each preceded by a complete charge. Once the likelihood of limited diffusion and inhomogeneous lead sulfate distribution (and therefore, plate resistivity) is recognized, it is not hard to imagine how a constant current charge could have difficulty predicting battery behaviour with partial state-of-charge cycling or the ever-changing current of absorb charging. In partial state-of-charge cycling, there is no complete charge to wipe clean the inhomogeneities in the lead-sulphate distribution. In absorb charging, falling currents may open up new sites for recharge: the voltage drop across the current path falls and a smaller concentration gradient will sustain the diffusion of necessary reactants. These sites would have already been recharged during a constant current charge at the lower current rate. Thus, the use of absorb charging as well as constant currents to test a battery model may be highly telling.

The above arguments suggest that the battery has memory on several levels, and the state-of-charge may be insufficient to capture all the effects of this memory on the voltage-current characteristics of the battery. The stratification that would occur with a flooded battery would add another layer of complexity and memory. To have accurate prediction of these characteristics, it may be necessary to know the lead-sulfate distribution across the plates as well as the electrolyte concentration across the plates. If this is the case, the state-of-charge used for our model, as well as many other models (despite the "dynamic" appellation in some cases), can give approximate results but will never be able to fully model the effects of varying current and partial state-of-charge cycling.

Tilted Insolation Prediction: In the first hybrid system test discussed in this article, the conversion of global insolation on the horizontal to the insolation in the plane of the array was found to be accurate to within 6 or 7%. But this apparently good result masks underlying inaccuracies. Figure 15 shows the measured and simulated diffuse irradiance on the horizontal for the same period as shown in Figure 8. The accuracy is quite poor, even on those days, such as 266 and 269, when the resulting estimate of the plane-of-array irradiance is very good—overestimating the diffuse fraction necessarily implies a lower estimate of the beam irradiance, and vice-versa, which tends to compensate for the error.

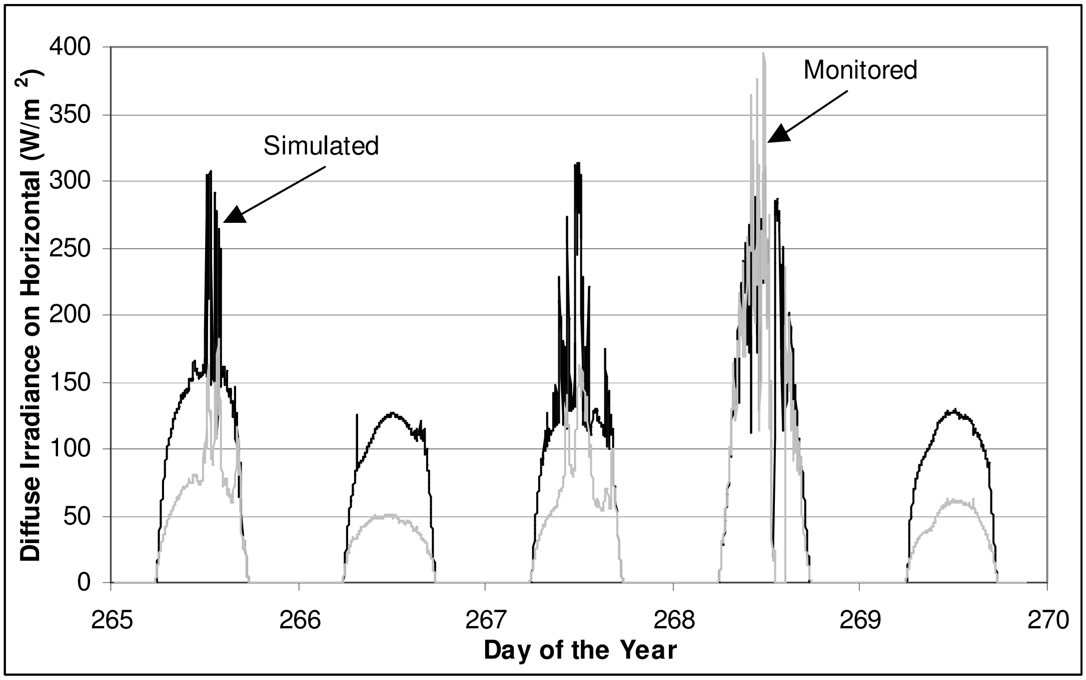

Figure 15: Measured and Simulated Diffuse Irradiance on Horizontal, Five days from PV Hybrid Test #1

The PVToolbox's algorithm for splitting the global radiance into beam and diffuse components is rather crude, but is typical of PV simulation tools. A function is used to estimate the diffuse fraction based solely on the clearness index; this is a common approach (Duffie and Beckman, 1991). In fact, numerous publications, including (Iqbal, 1983), (Garrison, 1985), and (Skartveit and Olseth, 1987), have shown that this is not the case, and explored the variables that affect the diffuse fraction. These indicate that the diffuse fraction is in reality a function of the global solar irradiance, the solar elevation, the surface albedo, and the extent to which the atmosphere blocks or scatters solar radiation.

While it would be difficult to account for the influence of all these variables in PVToolbox, the albedo and solar elevation are of particular interest in the Canadian context. Snow cover during winter ensures that high albedos will be experienced in Canada for much of the year. Furthermore, moderate and high latitude sites will tend to make use of higher tilt angles, and thus arrays will "see" more of the ground. The low solar elevations of Canadian winters tend to be associated with pronounced deviations from the commonly assumed functions relating diffuse fraction to clearness index.

This article has shown that PVToolbox is relatively accurate in its plane-of-array predictions for measurements taken during September and October at a site near Montréal. The fact that PVToolbox does not account for solar elevation, surface albedo, and other variables, means that it may not perform so well during winter, or at more northern sites.

CONCLUSIONS

The developers of the PVToolbox PV hybrid system simulation toolbox anticipated a tool capable of predicting average major energy flows—the energy out of the array, into and out of the battery, and out of the genset—with an error of 10% or less. Comparison of PVToolbox simulations with a number of tests run on the CETC-Varennes hybrid test bench reveal that this level of accuracy has been obtained. In fact, errors of 5% or less are typical. The tool is similarly accurate in predictions of the battery efficiency (both coulombic and round-trip) and solar fraction.

Simulations can be accurate, at least over periods of weeks or months, to within 1 to 2% when control decisions with non-linear effects (e.g., the switching on or off of a genset) are not based on voltage or current thresholds. With such thresholds, minor inaccuracies in the battery model can lead to major discrepancies between simulated and real system behaviour, further compounding model inaccuracies. Nevertheless, major energy flows appear to predicted with acceptable accuracy.

The reliance on a battery model using a single variable, the state-of-charge, to capture the state of the battery inevitably leads to inaccuracies, which are particularly pronounced with partial state-of-charge cycling and varying currents. Improvements would probably require a model accounting for the distribution of lead sulphate and electrolyte concentration gradients within the plate.

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