STATIONARY BATTERIES IN CYCLING PHOTOVOLTAIC APPLICATIONS

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INTRODUCTION

Contrary to common belief, the term "Stationary Battery" is not synonymous with Standby or Float applications. The term "Stationary" simply means that the battery is in a permanent location, as opposed to being used in a vehicle for motive power or engine starting. Table 1 provides a brief comparison of standby and cycling applications. Batteries designed for cycling applications will not provide good service in a standby application and vice-versa.

In the past, the predominant application for stationary batteries was for standby power systems. However, the use of stationary cycling batteries in photovoltaic (PV) systems has grown exponentially during the past two decades. The total worldwide installed capacity of batteries in PV applications in year 2002 is estimated to be 8,895 MWh[1] and is valued at 3.3 billion dollars. Stationary cycling batteries in "Distributed Energy Resource" applications are also poised for explosive growth.

TABLE I
TYPICAL BATTERY REQUIREMENTS/CHARACTERISTICS BY APPLICATION

Characteristic	Standby Application Typical	Cycling Application Typical
Power (discharge rate)	100C to C/10	C/8toC/100
Discharge frequency	Once per month	Once per day
Cycle depth	<10%, Monthly	10% to 80%, Daily
Recharge	Immediately	Daily
Recharge period	0.1 to 4 hours	One day to 30 days
Recharge source	Grid; constant	Renewable; variable
Equalization required	No	Yes
Ambient temperature	22 to26C	-20 to +50C
Site	Manned	Unmanned
Battery plates	Thin, many	Thick, few
Battery plate alloy	Calcium	Antimony
Battery internal resistance	Low	High
End of life	80% of Rated C	~40% to 80% of C
Typical failure mechanism	Grid corrosion	Sulfation

Batteries in standby applications are relatively common, straightforward, and well understood. Batteries in PV applications (cycling) operate in hostile environments with a load that varies by the minute, the day and the season. The charging source varies in a similar manner.

A remote home, built and powered exclusively with PV energy for the past 15 years, will be used to demonstrate the cycling and charging characteristics of this cycling application. This 2,600 square foot home is located near Prescott, Arizona, at an elevation of 5,200 feet. It has a full complement of the most efficient appliances available. Many people find it surprising that it is practical to live off grid with all of the comforts they are accustomed to having on grid. The house was designed and built to be energy efficient. Many people express surprise when they learn of the practicality of living off-grid—especially when they also learn that they do not have to reduce their standard of personal comfort. Monitoring was accomplished during the first three years with Ampere-hour recording instruments. The author designed and built this home, and he has lived in it for the past 15 years.

Living in a stand-alone PV home offers a unique opportunity to develop an intimate relationship with the PV system - including the batteries. The PV system and environmental conditions have been documented and monitored with a 26-channel data acquisition system (DAS) for the past 12 years. The DAS facilitated understanding the interaction and performance of all components. If the batteries were to become fully discharged, then essential appliances cease to function (e.g., the water pump stops working). However, when properly designed, installed, and maintained, a PV system is one of the most reliable power sources available. This house experienced only two unscheduled power outages in 15 years of operation. The first outage lasted two hours, and the second outage lasted 10 minutes. Both outages were due to voltage regulator failure. Few, if any, electric utilities in the world can match this record of uninterrupted service.

The battery bank is the only component of a PV system that requires maintenance, and it is the only component that must be replaced periodically. The cost of batteries and replacement has a significant impact on the levelized cost of delivered energy. There is significant incentive to maximize battery life (and minimize cost) through proper system design, battery selection, operation, maintenance, and load management. In this case, the homeowner is the "utility manager."

For the residential systems described herein, batteries and other hardware will be referenced by make and model, since data provided are specific to a given make and model.

THE PHOTOVOLTAIC SYSTEM

PV systems typically evolve from small to large over time. This is especially true of remote-home systems, and the system defined herein was no exception. Initially, a temporary PV system was installed in March 1987 to power an onsite travel trailer and construction tools (e.g., saws, drills) during the first 12 months. The initial system consisted of a 150-watt PV array, a 440 Ah at 12 Vdc deep-cycle battery bank, and a 1,800-Watt inverter. Surprisingly, this system was quite adequate at that time.

PV System Evolution

- March 1987. Initial PV system: 150Watt PV, Battery bank 440Ah at 12 V.
- **April 1988**. The initial PV system was replaced with a robust (i.e., oversized) permanent system that was designed for anticipated load growth. This system consisted of a 1.1 KW array, **1050 Ah at 24 Vdc battery bank (Delco 2000),** and a 2-KW inverter.
- April 1991. The first unscheduled power outage occurred in 1991 due to a failed charge controller (voltage regulator). Both of the Trace 30A "on-off" charge controllers were replaced with a single Heliotrope 60 Amp Pulse Width Modulation (PWM) charge controller.
- September 1991. The inverter was upgraded to 2.5 KW, due to the inability of the 2 KW inverter to reliably start the 10-inch radial-arm saw (which the old 1800-Watt, 12 Vdc inverter started every time).
- **January 1996. After 7.5 years of reliable operation, the Delco 2000 battery bank[2] was replaced with a 630 Ah at 24 Vdc Delco 2010 battery bank**. The reduction in Ah capacity from 1050 Ah to 630 Ah was instituted in order to evaluate a deeper cycle depth with the Delco battery.
- April 1996. The 2.5 KW PWM inverter was upgraded to a 4.0 KW sine-wave inverter.
- July 1996. The second PV array (0.9 KW) was added. A second Heliotrope PWM 60A charge controller was added to support this new array and provide redundancy.
- October 1998. A 6.2 KW Generac manual-start, gasoline-fueled emergency generator was installed.
- **January 2001. After 5.5 years of reliable service, the Delco 2010 battery bank[3] was replaced with 900Ah at 24V of Trojan T-105 deep cycle batteries**.
- August 2001. Third PV array (0.8 KW) installed, and a third charge controller [Fire Wind & Rain, 30Amp, Maximum Power Point Tracking, (MPPT)] was installed to support this array.
- November 2002. A 6.2-KW Kohler auto-start, propane-fueled generator was installed.

After fifteen years of evolution, the present system is defined in Figure 1. This is by no means the end of the evolutionary process. A fourth PV array (1.2KW) will be added in 2003, along with a 30A MPPT charge controller. Unlike the first three arrays that are south facing and tilted 30 degrees from the horizontal, the new array will track the sun from sunrise to sunset. Other changes, undefined at the moment, will occur as the need arises.

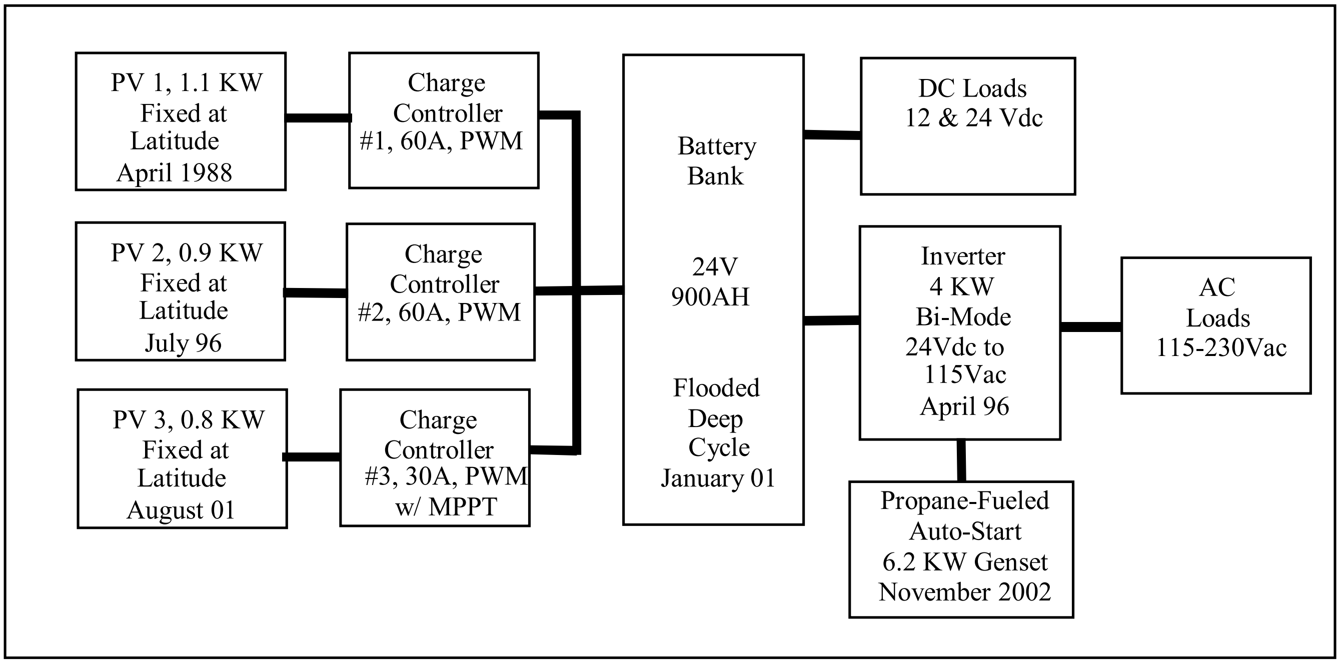

Figure 1. Block Diagram of Residential Stand-alone PV System

THE BATTERY

Cycling Application

Unlike "Stationary Stand-by" battery applications (e.g., Uninterruptible Power Supply, UPS), the batteries in PV applications require that the battery cycle daily. Sometimes the "Daily Depth of Discharge" is as high as 80 percent.

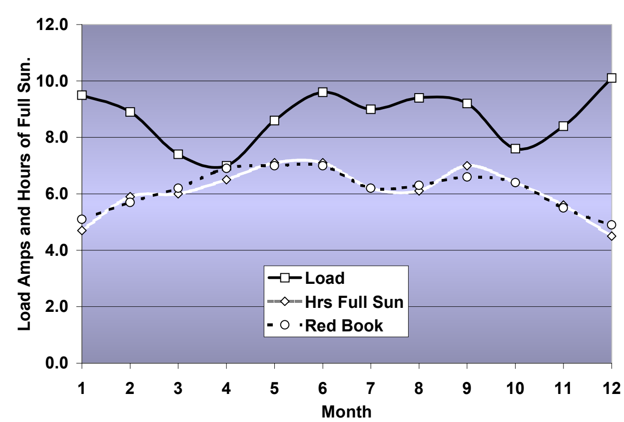

Figure 2. Average Daily Values of Load Amperes and Hours of Full Sun for Each Month in 2001

The daily depth of discharge is a function of a) load and b) available sunlight, both of which vary daily and seasonally. Figure 2 shows the average daily load current for each month in 2001, the average daily hours of full sun (insolation), and the Red Book[4] 22 year average of daily hours of full sun. This chart shows the monthly and seasonal variations in these parameters, but variations from day-to-day can be much greater that the month-to-month variations. For example, it is common to have no sun (i.e., total overcast for four days in a row during December and January. At the end of four days of overcast skies, the battery bank will reach a depth of discharge of 60-80 percent. In December and January, the PV system bears the highest loads, yet it receives the least hours of sunlight. The entire PV system must be designed to handle this worst-case condition.

Figures 3 and 4 show battery performance during December 2001. The battery reached 55% State of Charge (SOC) on December 4th, after four days of reduced sun hours. The generator ran for two hours to prevent the batteries from dropping below 50% SOC. This was followed by four days of clear sky, during which the batteries reached full charge and equalized.

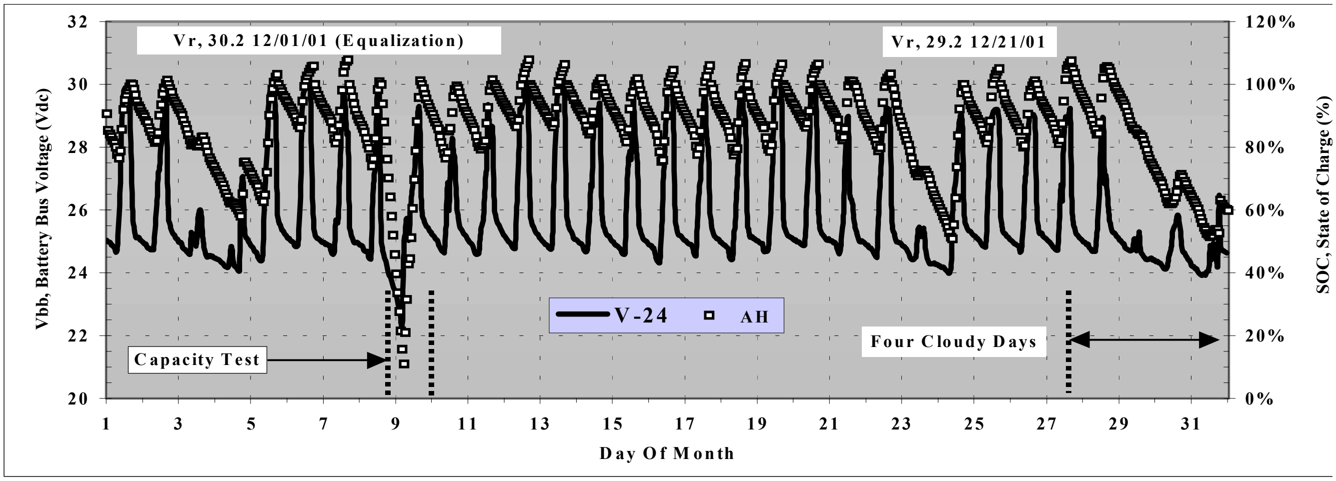

Figure 3. State of Charge (SOC) and Battery Voltage, December 2001

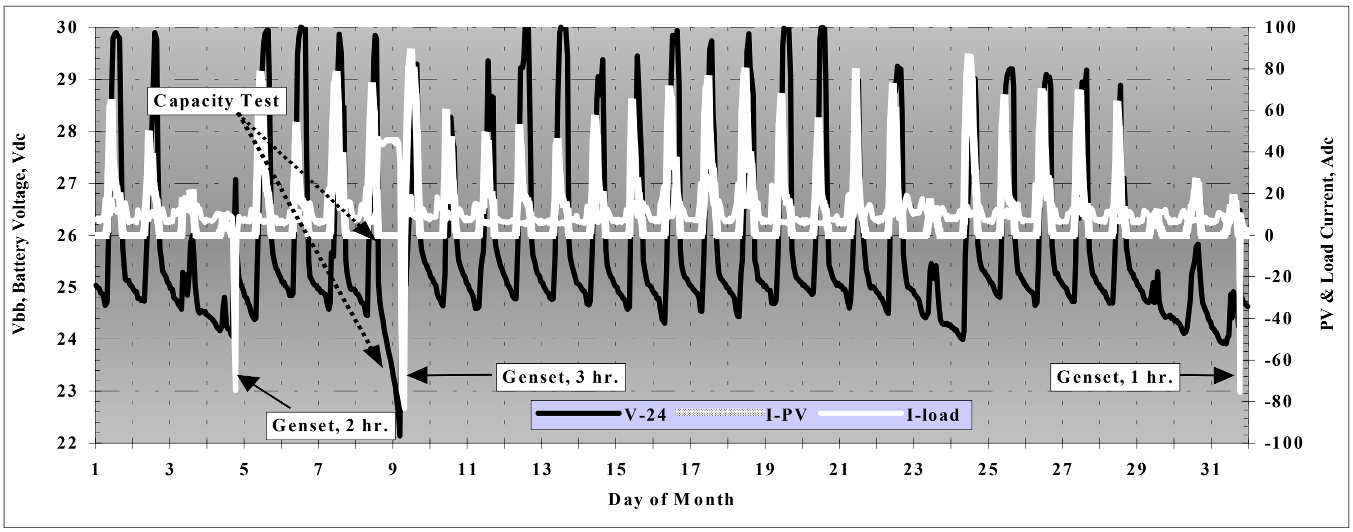

Figure 4. Battery Voltage, PV Current, and Load Current, December 2001

This cycle repeated on December 24th and December 31st with three to four cloudy days and a SOC of 50%. The generator ran one hour on December 31 to prevent the SOC from dropping below 50%. A generator is of great value in managing the battery SOC, and it needs to run for only a few hours in December and January. It also allows for a smaller array size and a smaller battery bank.

Battery Environment

Unlike Standby batteries that are maintained in conditioned space at 77°F, PV batteries are often outside in unheated and non-cooled containers. As such, battery ambient temperatures can span the range of 0°F to 120°F – or beyond. At low temperatures, capacity can be greatly reduced, and at high temperatures, life can be greatly shortened. The relationship between battery temperature and effective capacity is defined in Figure 5 for the Trojan T105. While most battery manufacturers rate their batteries at 77°F, Trojan rates their batteries at 80°F. At 0°F, the effective capacity of this battery is 60% of rated value (225 Ah at the 20-hour rate or 250 Ah at the 100-hour rate). The average load current for December 2001 was 10.1 Amperes, or 2.52 Amperes for each of the four strings, which

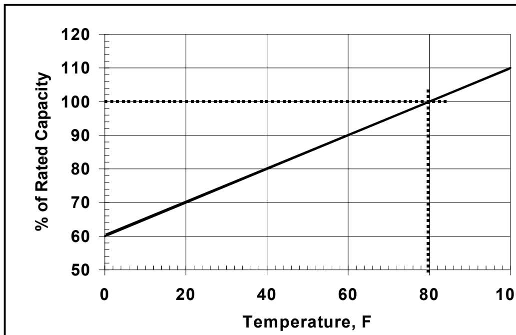

Figure 5. Capacity vs. Temperature

is exactly the 100-hour rate. At 80°F, this battery bank could supply the 10.1-Ampere load for 3.3 days of no sun and be at 20% state of charge.

The batteries for this system are located in the walkout basement (unconditioned space). Figure 6 shows that the average battery temperature in December was 57°F and the average battery capacity was 88.5% of rated value. Thus, in December, the 3.3 no sun days (i.e., 3 days of heavy overcast) are reduced to 2.9 days. To be more realistic, cloudy days usually cause the coldest days of the month and the lowest effective battery capacity. So, rather than use the average monthly temperature, we should use lowest battery temperature (46.2F) and the lowest effective capacity (83% of rated capacity). This results in 2.8 no-sun days during cold, cloudy days.

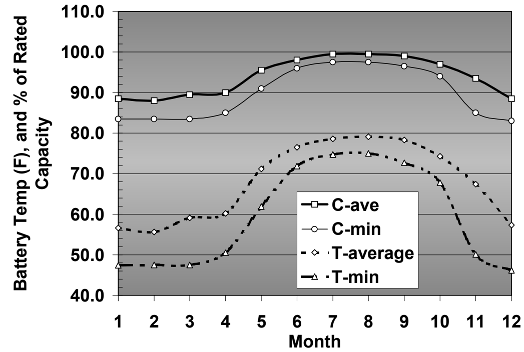

Figure 6. Battery Temperature and Capacity by Month

At temperatures above 80°F, battery capacity increases at a reduced rate, but battery life is reduced by approximately 50% for every 18°F (10°C) above 80°F - due to increased corrosion of the plates. For this system, the average battery temperature never exceeded 80°F during the year (Figure 6).

Imagine what huge fluctuations would occur in battery temperature and effective battery capacity if the batteries were outdoors instead of inside the walkout basement.

Charge Controllers

The charge controller, also known as the voltage regulator, serves the same function as the voltage regulator in your automobile – it can prevent the battery from overcharging or undercharging. The charge controller connects the PV array to the battery through a switch (see Figure 1). The switch is either a mechanical relay or an electronic switch. The characteristics of the charge controller determine how effectively and efficiently the battery charges – or whether the battery charges at all. This component has more influence on life cycle cost than any other system component. It can ruin a bank of batteries within a few months! Undercharging a flooded-vented battery will cause it to sulfate; overcharging a valve-regulated battery will cause it to dry out. Both conditions thereby greatly reducing battery life.

<u>Common Control Methods</u>

ON-OFF. This is the simplest charge controller. When the battery reaches a preset voltage, the PV is disconnected from the battery, and it is reconnected when the battery reaches the reconnect set point. Hysteresis is typically 1.0 Vdc. This control method is inadequate for most PV systems

PWM (Pulse-Width Modulation, also called Pulse Duration Modulation). This is the industry-standard control method. For PV applications, the PV array is electronically connected and disconnected at a frequency of several hundred cycles per second to several thousand cycles per second. Further, the on time (pulse width) and off time can vary from cycle to cycle. This technique allows the current to be effectively “tapered”, and the result is equivalent to “constant voltage” charging. Hysteresis is typically 100 mV. These charge controllers are typically “smart”: fully solid state, microprocessor-driven, and about $200 to $400 in cost. A typical PWM charge controller offers a) three-stage control, b) temperature compensation and c) manual or automatic equalization.

AMPERE-HOUR COUNTING. Amp-hour counting is sometimes used in conjunction with voltage control to precisely measure the amount of discharge and overcharge. For this method to be effective (and precise), the effective capacity of the battery must be known. Since the effective capacity of the battery changes over time and with battery temperature, this is a difficult control method to implement. The only way to know the effective capacity of a battery is to measure it with a load test.

Charging Algorithms.

The charging methodology is often called the charging algorithm. The word algorithm means a "set of well defined rules for the solution of a problem in an infinite number of steps"[5] or "(software) Any sequence of operations for performing a specific task"[6]. A common PWM control algorithm[7] is shown in Figure 7.

Charge controllers #1 and #2, shown in Figure 1, predate the Three-Stage process shown in Figure 7. They provide Bulk and Absorption stage control. Charge controller #3 in Figure 1 does include the three-stage concept, plus it provides Maximum Power Point Tracking (MPPT), which will be discussed later.

Three-Stage Battery Charging

Battery voltage and current vary during the three-stage charging process as follows.

BULK

During this stage, the batteries are charged at the bulk voltage setting and maximum current output of the DC source. When the battery voltage reaches the BULK voltage setting, the controller activates the next stage (absorption). During the bulk charging process, the status LED (green) may blink from one to five times before pausing. The more times it blinks consecutively, the closer the battery voltage is to the BULK voltage setting.

ABSORPTION

During this stage, the voltage of the battery is held at the BULK voltage setting until an internal timer has accumulated one hour. Current gradually declines as the battery capacity is reached. During the ABSORPTION stage, the status LED (green) blinks five times, then pauses and repeats.

FLOAT

During this stage, the voltage of the battery is held at the FLOAT voltage setting. Full current can be provided to the loads connected to the battery during the float stage from the PV array. When the controller has reached the FLOAT stage, the status LED (green) will be solid green.

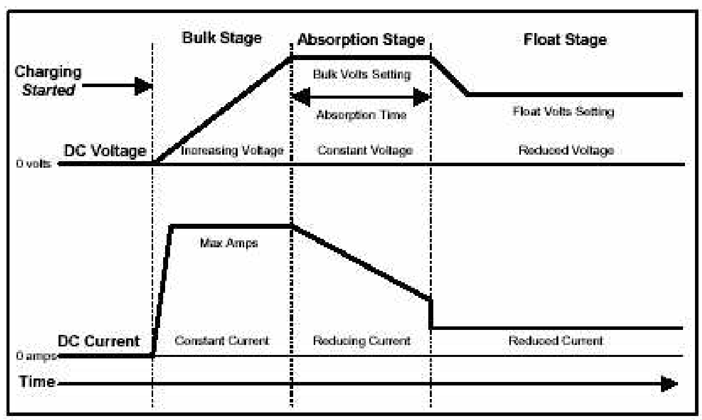

Figure 7. Three-Stage Battery Charging Algorithm

Equalization

Equalization is necessary for all lead-acid battery technologies, but most charge controllers do not provide adequate voltage set-point resolution for VRLA batteries. Batteries with liquid electrolyte that are cycled generally experience stratification. Stratification concentrates the sulfuric acid in the bottom portion of the cell while the solution in the upper part of the cell becomes more dilute. The result is increased corrosion of the lower part of the plates and sulfation of the upper part of the plates, both of which reduce battery life. During equalization, gas bubbles form and cause a mixing of the electrolyte, thereby preventing stratification. Sulfation is reduced or eliminated during equalization.

The equalization voltage is typically 2.5 to 2.6 volts per cell (vpc) and can be initiated either manually or automatically (e.g., every 30 days). For the controller shown in Figure 7, once the equalization process is enabled, the process continues for two hours after the batteries have reached the "Bulk Volts setting."

The effects of equalization can be seen in Figures 3 and 4 for the stand-alone system defined herein.

Temperature Compensation

If the battery temperature exceeds 77°F ±7°F (25°C ± 4°C), then temperature compensation of the charge controller set points is recommended. Most commercial charge controllers will provide this feature.

Max Power Point Tracking

A few charge controllers[8] include a feature called Maximum Power Point Tracking (MPPT). This feature is independent of the charge controller algorithm. The MPPT acts like a dc-to-dc converter that selects the optimum operating point of the PV array (i.e., the maximum power point) and tracks the maximum power point throughout the day. This maximum power is a function of PV module temperature and sunlight intensity. Without the MPPT, the PV array operating point is equal to the battery voltage, which also varies through the day. During the cold winter months, the MPPT can increase the power and energy delivered from the PV array to the battery by 25%. During the hot summer months in desert regions, the MPPT ensures adequate voltage for equalization of the batteries – which could be impossible otherwise.

ELECTRICAL LOADS

Electrical loads for this application fall into one of two major categories: Base Load and Intermittent Load. Base load consists of loads that are ON 24 hours per day (clocks, appliances with a "wall cube" like answering machines, security systems, items that have a remote control, etc.). Intermittent loads are ON as needed (lights, computers, washer, dryer, shop tools, water pumps, etc.). In order to manage loads, it is essential to perform an energy audit. During the energy audit every electrical load that consumes energy from the battery must be measured.

Base loads.

Base loads for this application are defined in Table 2, and they are seen as the low value of load in Figure 4. Data in this table are listed in descending order of Watt-hours per day. Both 115Vac and 12-24Vdc loads are included. The largest single load is the inverter tare loss (line 1) at 20%. While an average continuous load of 81.4-Watts (line 23) may seem small, this constitutes 28% of the total load. See Table 3, lines 28 and 35. One must be very careful of "phantom" loads or hidden loads, as they can quickly become a significant percentage of the total base load. Any appliance (e.g., TV, stereo, VCR) that has a remote control typically consumes about six watts per appliance, even though the appliance is turned off. These remotely controlled appliances can be managed with a master switch and turned off when not in use. Another hidden, but necessary, phantom load is Ground Fault Circuit Interrupters (line 5), which are six percent of the base load.

Table 2. Base Loads: January 2003

	Item	Make/Model/Type	Type	Rated	Measured Watts	Use, Hours per Day	Use, Wh per Day	% of Total
1	Inverter tare losses	Trace 4024, dc-ac	dc		16	24	384	20%
2	AH meters (4)	Bobier AHM10, dc	dc	10	9.2	24	221	11%
3	Timers (3) [Total]	Intermatic TN111(2.5W)	ac		7.6	24	182	9%
4	Internet RF link	Commspeed	dc	Est	5	24	120	6%
5	GFCI (7)[Total]	Levitron 20A, Class A	ac		4.9	24	118	6%
6	Telephone, cordless	Uniden cordless	ac	10	4.2	24	101	5%
7	Telephone, cordless (2)[Total]	Toshiba FT-6604	ac	4.4	4	24	96	5%
8	Microwave, clock/controller	Sharp	ac		3.6	24	86	4%
9	Gas range, clock/controller	Magic Chef, ac	ac		3.1	24	74	4%
10	Tooth brush	Sonicare	ac	Est	3	24	72	4%
11	Voltage regulator	Heliotrope CC-60 #1	dc	Est	3	24	72	4%
12	Voltage regulator	Heliotrope CC-60 #2	dc	Est	3	24	72	4%
13	Voltage regulator	FWR	dc	3	3	24	72	4%
14	Laptop computer #1	Winbook N3, trickle charge	ac	Est	2.5	24	60	3%
15	Laptop computer #2	Winbook Si2, trickle charge	ac	Est	2.5	24	60	3%
16	Laptop computer #3	Winbook Xli, trickle charge	ac	Mea	2.5	24	60	3%
17	Clock, alarm	Cosmo E-803, ac	ac		2.4	24	58	3%
18	Security systems	Radio Shack 49-470, dc	dc		0.8	24	19	1%
19	Lights, stair	LED 26 super bright LEDs	dc		0.4	24	10	0.5%
20	Lights, night (constant on)	Ausitn 11100 (6) Total	ac		0.3	24	7	0.4%
21	Battery equalizer	Vanner 60-10	dc	0.3	0.02	24	0	0.02%
22	Data Acquisition System	CR-10 w/ AM416 Mux, dc	dc		0.02	24	0	0.02%
23	**TOTAL OF INDIVIDUAL LOADS**	**Watts**			**81.0**	**24**	**1,945**	100%

Intermittent Load

Intermittent loads are generally of a much higher wattage than base loads, but it is the product of Wattage and ON time per day that determines the "size" of the load (i.e., energy load). Many of the loads will be seasonal, so the load profile will change each month.

The power (Watts) required by each of these appliances is defined as the battery load current (i.e., the dc current into the inverter) multiplied by the battery bus voltage. This dc-power approach is used instead of ac- power because it takes into account the inverter losses and measures what the battery "sees" as real power; not reactive power.

Table 3. Selected Intermittent Loads: January 2003

	Item	Make/Model/Type	Type	Rated, Watts	Measured, Watts	Use, Hours per Day	Use, Wh per Day	% of Total
1	Bird bath de-Icer - **Night**	Farm Innovators C-150 115Vac	ac	150	150	5.3	795.0	11%
2	Rock polisher	A.O. Smith JB1P107N	ac	80	104	6.0	624.0	9%
3	Entertainment center	27" TV, Satellite dish, stereo	ac		127	4.1	520.7	7%
4	Pump, pressure	AY McDonald 1/2 hp	ac		1280	0.4	512.0	7%
5	Pump, well	1/2 hp	ac		1208	0.4	483.2	7%
6	Refrigerator-freezer section	SunFrost RF16 Freezer (24Vdc)	dc	64	66	6.6	435.6	6%
7	Laptop computer #1, inc. Printer & Fax	Winbook N3, w/ac adapter	ac		25.8	14.0	361.2	5%
8	Microwave oven	Sharp R-220AW	ac	1080	1146	0.3	286.5	4%
9	Refrigerator-refer section	SunFrost Refer (68W, 2.8 h/d) (24 Vdc)	**dc**	64	68	3.0	204.0	3%
10	Hair dryer	Vidal Sasson VS737	ac	1600	1508	0.1	150.8	2%
11	Clothes dryer	Fisher-Paykel	ac		334	0.3	100.1	1%
12	Clothes washer	Fisher-Paykel	ac		225	0.4	90.3	1%
13	Laptop computer #2, inc. printer	Winbook Si2, w/ac adapter	ac		21.1	4.0	84.4	1%
14	Light	18 Watt Flourescent	ac	20	20	4.0	80.0	1%
15	Toaster	Proctor Silex	ac	1050	1110	0.1	77.7	1%
16	Miscellaneous	Other loads	ac		15	3.0	45.0	1%
17	Gas range	Magic Chef, glow plug	ac	400	398	0.1	39.8	1%
18	Coffee pot	BDCM18&D	ac	800	909	0.04	36.4	1%
19	Light	13 Watt flourescent (3)	ac	15	11	3.0	33.0	0.5%
20	Laptop computer #3	Winbook Xli, w/ac adapter	ac		18	1.0	18.0	0.3%
21	Light	7 Watt flourescent (3)	ac	7	5	2.0	10.0	0.1%
22	Saw, circular	Craftsman, 7"	ac	1200	841	0.0	8.4	0.1%
23	Saw, radial arm	Craftsman, 10"	ac	1200	583	0.0	5.8	0.1%
24	Battery charger	Makita Nicad	ac	35	29	0.2	5.8	0.1%
25	Battery charger	Power Sonic PCS 12800A	ac		23.1	0.2	4.6	0.1%
26	Pump, cistern	1/3 hp	ac		393	0.0	3.9	0.1%
27	Gas range	Magic Chef, ignitor (0.6W)	ac		0.6	0.1	0.1	0.0%
28	Evaporative cooler	Champion WC 42, low cool	ac		323	0.0	0.0	0.0%
29	Evaporative cooler	Solar Chill 2024 (at 13.5 Vdc)	ac		61	0.0	0.0	0.0%
30	**Total Daily Intermediate Loads, Wh**						**5,016**	**72%**
31	**Total Daily Base Loads, Wh**						**1,945**	**28%**
32	**TOTAL,Intermediate plus Base, Wh**						**6,961**	**100.0%**
33								
34	**Average Daily Intermittent Load**					**Watts**	**209**	**72%**
35	**Base load**					**Watts**	**81**	**28%**
36	**TOTAL, Ingtremittent plus base loads**					**Watts**	**290**	**100%**

The dc power procedure is to measure battery dc load during normal house loads and the appliance of interest turned off, and to then measure the change in battery load current with the appliance turned on. This change in load current multiplied by the battery bus voltage is the power requirement of that appliance. For inductive loads, such as 115 Vac motors, real power and reactive power are very different. For example, the rock polisher (Table 3, line 2) measured 104 Watts-dc. This same appliance measured 241 Watts-ac (2.1 A-ac*120 V-ac). [Although the battery does not "see" this 137 W-ac of reactive power, the inverter does, and inverter I^2R losses increase substantially.]

Beware of "hidden" loads. For example, who would guess that a gas range would consume 400 Watt of electrical power the entire time that the flame is on (line 17)? As the "glow plug" (the 400 W element) heats up its resistance drops, which allows the gas valve to open and the glow plug is hot enough to ignite the gas.

The general strategy for battery and load management is to operate intermittent loads only during sunlight hours and clear days. Doing so allows these loads to be powered from the array instead of the battery, which results in much longer battery life. All loads in Table 3 are routinely operated during clear days, except the bird bath de-icer (line 1), which necessarily operates from about 8:00 PM through 8:00 AM when the ambient temperature is generally between 20 and 30 degrees Fahrenheit during January. The de-icer is thermostatically controlled - on at 36°F and off at 40°F. This residence is located in an area with much wildlife (deer, javelina, bobcat, raccoon, skunk, and mountain lion) that needs water at night.

Some of the "Use, Hours per Day" numbers in Table 3 would change dramatically from January to July, with the de-icer hours dropping to zero and the Evaporative Coolers changing from zero to about 10 hours per day.

High Starting Current Loads

Although the battery has to deal with the spikes created by motor starting currents, it is the inverter[9] that is often the weak link. Starting currents are generally 3 to 10 times the running current, and these starting currents must be part of the energy, although one could call this a "power audit" rather than an "energy audit". The high starting current loads are listed in Table 4. A power audit that would define the inverter requirements would measure Amps-ac at the appliance. For this paper we are interested primarily in the battery requirements so the data in Table 4 were taken at the dc bus. Only real power was measured. Power measurements (real plus reactive) on the 120 Vac side of the inverter could be twice the values listed in Table 4.

Table 4. High Starting Current Loads

	Item	Make/Model	Measured Power, Watts, Steady-state	Measured Power Watts, Start-Surge	Ratio
1	Saw, radial arm	Craftsman, 10"	583	5,830	10.0
2	Clothes washer	Fisher-Paykel	225	5,042	22.4
3	Clothes dryer	Fisher-Paykel	334	4,208	12.6
4	Pump, pressure	AY McDonald 1/2 hp	1280	3,071	2.4
5	Saw, circular	Craftsman, 7"	841	2,452	2.9
6	Saw, miter	Makita LS 1020	751	2,220	3.0
7	Vacuum cleaner	Eureka 3125, canister	818	2,012	2.5
8	Pump, cistern	1/3 hp	393	1,832	4.7
9	Pump, well	1/2 hp	1208	1,763	1.5
10	Vacuum, shop	Craftsman	586	1,632	2.8
11	Evaporative cooler	Champion WC 42, Low	323	1,250	3.9
12	Vacuum cleaner	Hoover U400, upright	297	422	1.4
13	**TOTAL**			**31,734**	

The battery actually experiences a 5,830 Watt load for the radial-arm saw shown in line 1, Table 4. The clothes washer (line 2) is a combination of washer load and water pressure pump load. The strategy of measuring the combined load was to capture the total energy required to wash a load of clothes, plus measure the peak power during one load of wash. The surge current for the clothes dryer (line 3) is due to the motor starting current plus the solenoid current to turn the gas valve on.

If all loads defined in Table 4 were to start at the same instant (nearly impossible), they would represent a 31.7 KW load. However, it is prudent to manage the loads such that no more than two large loads start at the same time. Further, large KW appliances such as the toaster, hair dryer, microwave oven, and water pump should be limited to 4K at steady-state conditions.

GENERATOR BACKUP

There are a few times per year when cloudy weather occurs for more days than normal (see Figure 4, December 28-31), or guests visit for several days to several weeks. And sometimes both events will occur at the same time. Such events often place severe demands on the battery, and can consume all available battery energy - even when good load management is practiced. A backup generator (genset), used just a few hours per year[10], can avoid the deep discharge (or complete discharge) of the battery during these unusual events - greatly increasing system reliability and providing peace of mind. A backup generator also allows the batteries to be equalized prior to a capacity test and recharged immediately after a capacity test (see Figure 4, December 4, 8, and 9), which is healthier for the battery, and the genset provides additional capacity to operate house loads. It also allows a battery bank to degrade well below 80% of rated capacity.

Emergency generators, such as the Generac PP5000T portable generator, are low cost ($503) and well suited for the unusual events. However, they are manual start, gasoline fueled, and noisy. They are good for about 1000 hours and they can only be overhauled once.

Prime power generators, such as the Kohler 6.5RMY62 (6.2 KW) a) offer automatic start when the battery voltage reaches a preset level, b) can be propane fueled, and c) are quiet. They can be overhauled every 5,000 hours of runtime.

Unlike inverters that can supply surge currents at more than twice the continuous rated value, gensets cannot provide more than the rated current. In fact, they must be derated at 3%/1000' above sea level, 2%/10F above 60F, and 11.1% for LP. Unless one is willing to carefully manage loads, the genset should be rated at twice the rating of the inverter.

BATTERY AND LOAD MANAGEMENT

The homeowners of a remote residential PV system are the managers of their “electric utility”. The following are general guidelines that such managers follow to optimize battery life and minimize life cycle costs:

- Whenever possible, use propane to produce heat (e.g., DHW, space heating, and cooking).
- Buy the most efficient electrical appliances available.
- Use high power/energy loads during daylight hours and clear days whenever practical.
- Turn loads off when not in use.
- Minimize phantom/parasitic loads (e.g. appliances with remote control, 120 Vac clocks and displays, GFCI).
- Minimize “base loads” (i.e., loads that are on 24 hours per day).
- Equalize the batteries every 60 days if the daily depth of discharge is less than 25%, or every 30 days if the daily depth of discharge is greater than 25%.
- When practical, install a backup generator. Run the generator a minimum of 15 minutes every month.

CONCLUSIONS

Photovoltaic systems require cycling-stationary batteries with a daily depth of discharge from 10 percent to 80 percent. Battery load currents vary from minute-to-minute, as well as seasonally. Charging current is proportional to sunlight intensity, and thus it also varies from minute-to-minute and seasonally during daylight hours. Battery ambient temperature can vary from 0°F to 120°F. These operating conditions are similar to motive power applications, and such batteries generally are very appropriate for PV applications. Batteries designed for standby-stationary batteries (e.g., UPS) are not well suited for most PV applications. Both vented and valve regulated battery technologies are used in PV applications.

PV batteries require a “smart” charge controller (often called a voltage regulator) that can bring the batteries to a full state of charge for a preset number of hours and then shift to a float charge for the remainder of the day. It should also be capable of providing an equalization charge at programmed intervals (typically every 30 to 60 days). The most common control method is “pulse width modulation”. Temperature compensation of the charging voltage set points is essential if the batteries are not in a temperature-controlled environment of 77°F. Maximum power point tracking is a desirable feature that is included in some charge controllers.

Developing a detailed “energy audit” and “load profile” is essential for system design and load management.

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[2] The Delco 2000 battery bank had degraded to 60% of rated capacity at the time of replacement.
[3] The Delco 2010 battery bank had degraded to 40% of rated capacity at the time of replacement.
[4] *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, National Renewable Energy Laboratory, NREL/TP-463-5067, April 1994.
[5] McGraw-Hill Dictionary of Scientific and Technical Terms, Fifth Edition, pg. 62
[6] IEEE 100 The Authoritative Dictionary of IEEE Standard Terms, Seventh Edition, pg. 25
[7] Reproduced from the Trace Engineering (Xantrex) C-40 Charge/Load Controllers Owner's Manual
[8] Outback Power Systems and RV Power Products currently market charge controllers with MPPT. Charge controller #3 show in Figure 1 is a prototype, and it is not currently being marketed
[9] A Trace 4024 (4KW at 24 Vdc) inverter is used in this system. It will supply 33 A-ac at 120 Vac continuously, and surge currents up to 78 A-ac (9360 Watts).
[10] The Generac generator ran a total of eight hours during from 1998 through 2000, primarily to recharge the batteries after load tests. It ran 20 hours in 2001 to supplement the battery bank, which had degraded to 40% of rated capacity by December 2000. Batteries were replaced in January 2001

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