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A Battery Life Prediction Method for Hybrid Power Applications

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A Battery Life Prediction Method for Hybrid Power Applications

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Abstract

Batteries in hybrid power applications that include intermittent generators, such as wind turbines, experience a very irregular pattern of charge and discharge cycles. Because battery life is dependent on both depth and rate of discharge (and other factors such as temperature, charging strategy, etc.), estimating battery life and optimally sizing batteries for hybrid systems is difficult. Typically, manufacturers give battery life data, if at all, as cycles to failure versus depth of discharge, where all discharge cycles are assumed to be under conditions of constant temperature, current, and depth of discharge. Use of such information directly can lead to gross errors in battery lifetime estimation under actual operating conditions, which may result in either a higher system cost than necessary or an undersized battery bank prone to early failure. Even so, most current battery life estimation algorithms consider only the effect of depth of discharge on cycle life.

This paper will discuss a new battery life prediction method, developed to investigate the effects of two primary determinants of battery life in hybrid power applications, varying depths of discharge and varying rates of discharge. A significant feature of the model is that it bases its analysis on battery performance and cycle life data provided by the manufacturer, supplemented by a limited amount of empirical test data, eliminating the need for an electrochemical model of the battery. It performs the analysis for a user-prescribed discharge profile consisting of a series of discharge events of specified average current and duration. Sample analyses are presented to show how the method can be used to select the most economical battery type and size for a given hybrid power system application.

1. Introduction

Renewable energy-based hybrid power systems typically combine one or more forms of renewable energy generation (e.g. wind and photovoltaic) with a conventional power source (e.g. diesel generator) to provide continuous reliable power. Applications for such isolated power systems include, remote telecommunication sites, village power in rural areas without grid access, remote military and other government facilities. To maximize utilization of the available renewable resource and/or to minimize use of the backup generator, hybrid power systems usually incorporate some amount of energy storage, and given the experimental status of most other energy storage technologies, batteries are almost always used.

The available power from renewable energy components, particularly wind turbines, is highly variable and somewhat random. Consequently, batteries in hybrid power systems experience a very irregular pattern of charge and discharge cycles. Because battery life is dependent on both depth and rate of discharge (and other factors such as temperature, charging strategy, etc.), estimating battery life and optimally sizing batteries for hybrid systems is difficult. Typically, manufacturers give battery life data, if at all, in terms of cycles to failure versus depth of discharge, where all discharge cycles are assumed to be under conditions of constant temperature, current, and depth of discharge. Use of such information directly in estimating in battery under actual operating conditions can lead to gross errors, which may result in either a higher system cost than necessary or an undersized battery bank prone to early failure. Even so, most current battery life estimation algorithms consider only the effect of depth of discharge on cycle life.

This paper discusses a new battery life prediction method, developed to help quantify the effects of two primary determinants of battery life in hybrid power applications, varying depths of discharge and varying rates of discharge. A significant feature of the method is that it bases its analysis on battery capacity and cycle life data provided by battery manufacturers (perhaps supplemented by a limited amount of additional test data), eliminating the need for an electrochemical model of the battery. It performs the analysis for a user-prescribed discharge profile consisting of a series of discharge events of specified average current and duration. An example analysis is presented to show how the method can be used to help select the most economical battery type and size for a given hybrid power system application.

2. Factors Affecting Battery Life

When considering battery life, one can distinguish between battery aging and battery wear. Battery aging refers to those factors or processes that tend to limit the duration of the battery's physical integrity and its ability to perform its intended function. Battery wear refers to those factors or processes that tend to limit the amount of electric energy that can be stored or delivered. Corrosion is a major component of battery aging, particularly in lead-acid batteries, which are the most common. All batteries, however, are subject to processes that tend to deteriorate and contaminate the plates and/or electrolyte, so that even in continuous float service battery life time is limited. Ageing, of course can be greatly accelerated by adverse environmental conditions or improper maintenance, but these things can presumably be controlled. Battery wear, on the other hand, is much more a function of the particular charge/discharge history the battery is subjected to. An abusive use pattern can cause a battery to fail long before it would cease to be viable merely through aging processes. The life prediction method described here does not address battery aging; it only attempts to predict battery life based on accumulated wear.

A further distinction to be made is between the life of an individual cell and the useful life of a collection of cells in a large battery bank. Small differences between cells in plate availability, state of charge, and temperature can become quite pronounced with repeated cycling of the battery. If these differences are not corrected, the weak cells will drag down the whole battery string, resulting in premature failure. The present analysis is concerned with individual cell life under prescribed discharge pattern. We assume that the battery receives proper periodic equalization charges and

relatively uniform battery temperature control.

Many factors contribute to the useful life of a battery cell in a given application. These include depth of discharge, discharge rate, cell temperature, charging regime, dwell time at low and high states of charge, battery maintenance procedures, current ripple, and amount and frequency of overcharge. The system designer and/or operator has some degree of control over all of these factors except depth of discharge and discharge rate. Once a battery is selected to meet a given load, the power demanded by the load will determine the depth and rate of discharge, which is why these two factors are the focus of this life prediction method. Strictly speaking, in some hybrid power applications, particularly where battery recharging is done primarily with renewable energy, there is very little control over charge rate either. However, there is some evidence that high charge rates at low and intermediate states of charge are not harmful to battery life (and in fact may increase it)[1], and until more research is done in this area, we will not consider the effect of charge rate in our model.

3. Battery Life Prediction Method

The battery life prediction method presented in this paper is based on three premises put forth by Symons[2], which are paraphrased here:

> Premise 1: Each cell has a finite life as measured by the sum of the effective ampere-hours throughput during its useful life. The effective ampere-hours are defined here as the actual ampere-hours as modified by the other two premises cited below. When the cumulative effective ampere-hours (the total of the individual effective amp-hours corresponding to a series of discharge "events") equals the rated charge life of the cell, the cell is will have reached its useful life. The rated charge life Γ_R of the cell is defined as

$$\Gamma_R = L_R \, D_R \, C_R \qquad \textbf{(1)}$$

where C_R = rated amp-hour capacity at rated discharge current I_R

D_R = depth of discharge for which rated cycle life was determined

L_R = cycle life at rated depth of discharge D_R and discharge current I_R

> This premise assumes that the operating conditions of the cell other than depth of discharge and discharge rate are similar to the reference conditions (temperature, periodic boost charge, float voltage, etc.) under which the rated cycle life was determined.

It is well known that cell cycle life decreases with increasing depth of discharge. It is frequently assumed however, that the charge life (total amp-hours throughput) of the battery is constant, i.e. independent of depth of discharge. Premise 2 contradicts this assumption.

> Premise 2: The actual charge life (total ampere-hours throughput) of the cell, not just its

cycle life, is a function of the depth of discharge at which it is cycled.[a] Alternatively stated, the effective ampere-hour discharge in a given discharge event may be more or less than the actual discharge, depending on the actual depth of discharge[b] relative to the rated depth of discharge. We assume here that, providing the cell is fully charged on a reasonably frequent basis, there will be no reduction in life if it is not fully recharged every cycle.

Premise 3: The charge life of the cell, Γ, will be decreased whenever the cell is discharged at a rate faster (higher discharge current) than the rated rate. Furthermore, the reduction in life will have a close functional relationship to the observed reduction in ampere-hour capacity with increasing discharge rate.[c] Alternatively stated, the ratio of the effective ampere-hour discharge to the actual discharge at a certain discharge rate and duration will be functionally related to the ratio of the rated cell capacity to its actual capacity at the actual discharge rate.

3.1 Influence of Depth of Discharge

Premise 2 deals with the effect of depth of discharge on cell charge life. To determine this functional relationship, we propose performing a best fit of the following expression to the cell cycle life data typically provided by the battery manufacturer.

$$L = u_2 \left(\frac{D_R}{D} \right)^{u_0} e^{u_1 \left(1 - \frac{D}{D_R} \right)} \qquad \textbf{(2)}$$

This three parameter function provides considerable flexibility in fitting to manufacturers' data, yet which yields a plausible life cycle versus DOD relationship even with very few data points. For example, Figure 1 shows a best fit curve to four cycle life versus depth of discharge data points provided by a manufacturer of NiCd batteries. Having found the equation parameters u_0, u_2, and u_3, the effective discharge (ampere-hours) for a particular discharge event can be expressed by making the substitutions $L_R = u_2$ and $d_{eff} / d_{actual} = L_R / L$ and rearranging Equation 2.

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[a]Actually, this is a generalization of Symons's Premise 2, which stated that the charge life of the cell, Γ, will always be less than Γ_R when the battery is cycled more deeply than the reference DOD and will be greater than Γ_R when the battery is cycled less deeply. If one is to accept manufacturers' published data as credible, this is not always the case.

[b]Note that in this paper, depth of discharge refers to an absolute discharge relative to the rated cell capacity, not to the state of charge of the cell relative to 100% charge (1 - SOC).

[c]Again, this is a generalization of Premise 3 as stated by Symons, which was that the ratio of actual charge life to rated life will be exactly equal to the ratio of the cell capacity at the actual discharge rate to the rated cell capacity, i.e. $\Gamma_A/\Gamma_R = C_A/C_R$.

$$d_{eff} = \left(\frac{D_A}{D_R}\right)^{u_0} e^{u_1\left(\frac{D_A}{D_R}-1\right)} d_{actual} \tag{3}$$

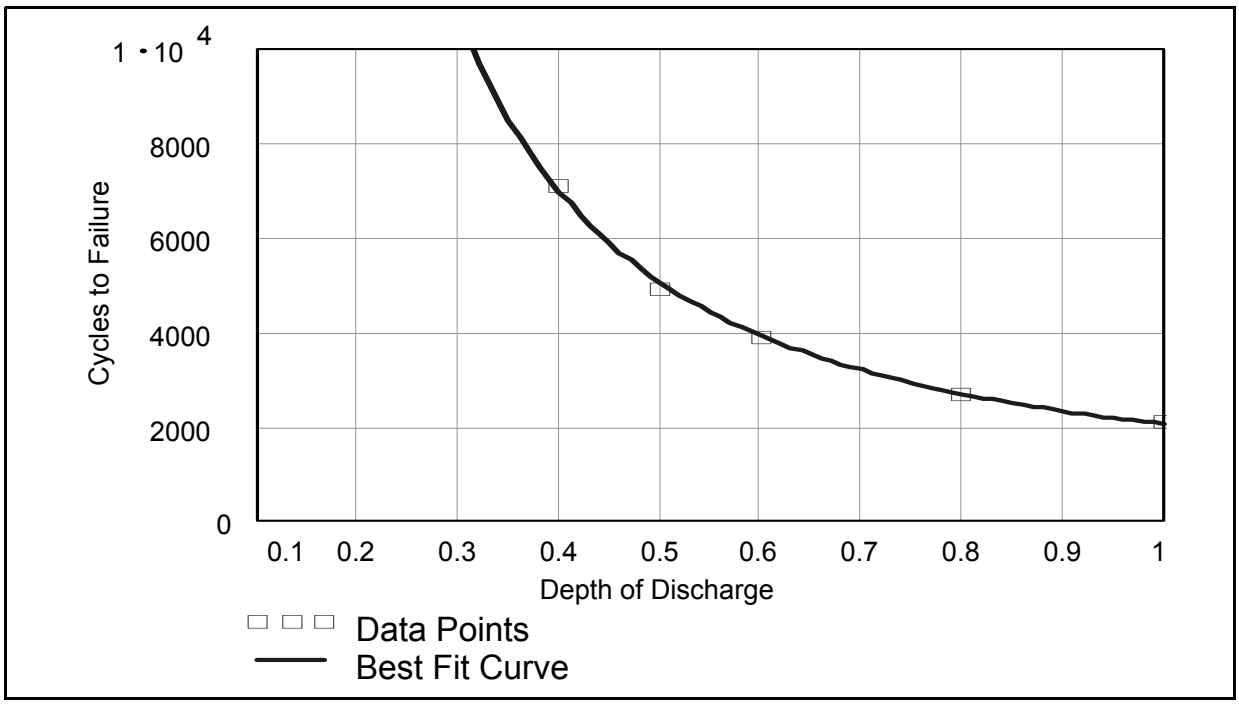

Figure 1 Best fit curve to manufacturer's cycle life data for pocket plate NiCd cells. Equation 3 parameters are $u_0 = 1.67$, $u_1 = -0.52$, and $u_2 = 2055$.

3.2 Influence of Discharge Rate

Premise 3 deals with the effect of discharge rate on the effective discharge for a given discharge event. Although we currently lack data to establish this connection, let alone determine the exact functional relation between, it is plausible in light of the physical processes occurring during battery discharge. Briefly, the higher the discharge rate, the greater the loss in conductivity between adjacent particles in the active material matrix[3 4]. Drawing the same amount of charge through a plate structure that is generally less conductive will lead to uneven current distributions and higher stress on the cell. This increased stress will likely lead to shorter life, in a manner analogous to mechanical fatigue.

Here we postulate that for a given actual discharge, the effective discharge will increase with discharge rate, and that it can be expressed fairly accurately by the following two parameter function:

$$d_{eff} = \left(\frac{C_R}{C_A} \right)^{v_0} e^{v_1 \left(\frac{C_R}{C_A} - 1 \right)} d_{actual} \qquad \textbf{(4)}$$

The capacity C_A at the actual discharge current of interest is determined using the "Amperes on Discharge" tables commonly included in battery specification sheets. Table 1 shows manufacturers data for the amperes on discharge to 1.00 volt for a range of NiCd cell sizes. Each column represents a different discharge duration. Each row represents a different cell size, as indicated by its nominal capacity. The actual charge capacity of a given cell at a given discharge rate is the product of the current and the corresponding discharge duration. From such tables, one can obtain capacity versus current curves as shown in Figure 2, one curve for each cell size. To determine C_A for a given cell size, one simply interpolates along the appropriate curve using the actual discharge current I_A.

Nominal Ah Capacity (5 Hour Rate)	DISCHARGE DURATION (seconds)										
	5	30	60	300	600	900	1800	3600	5400	10800	18000
58	399	326	298	219	171	140	88.7	49.9	34.8	18.6	11.6
67	453	370	338	249	194	160	102	57.6	40.2	21.4	13.4
85	564	462	422	314	248	203	129	73.1	51	27.2	17
93	615	504	460	343	272	223	142	80	55.8	29.8	18.6
102	665	546	498	372	295	243	154	87.7	61.2	32.6	20.4
111	714	587	535	401	318	263	167	95.5	66.6	35.5	22.2
128	814	671	612	460	366	306	194	110	76.8	41	25.6
137	860	710	647	487	389	326	207	118	82.2	43.8	27.4

Table 1 Manufacturer's Amperes-on-Discharge data for a Range of NiCd Cells

Unfortunately, battery manufacturers typically do battery life testing at a single discharge rate, usually the rate for which the cell's rated capacity is given. Consequently, we generally have no data from which to determine the parameters v_0 and v_1. We suspect that one set of values of these parameters will fairly accurately represent the effect of discharge rate for all size cells of a given manufacturer and type. Moreover, it may well be that the best-fit values of these parameters fall within a narrow range for each general type of battery (flooded lead-acid, VRLA, pocket plate NiCd, etc.) To determine values for v_0 and v_1, cell cycle life testing of various cell types at various discharge rates is required. Until such test data is available, we will still be able to crudely estimate the effect of discharge rate using a simplified form of Equation 4, where v_0 is set equal to 1 and v_1 is set to 0:

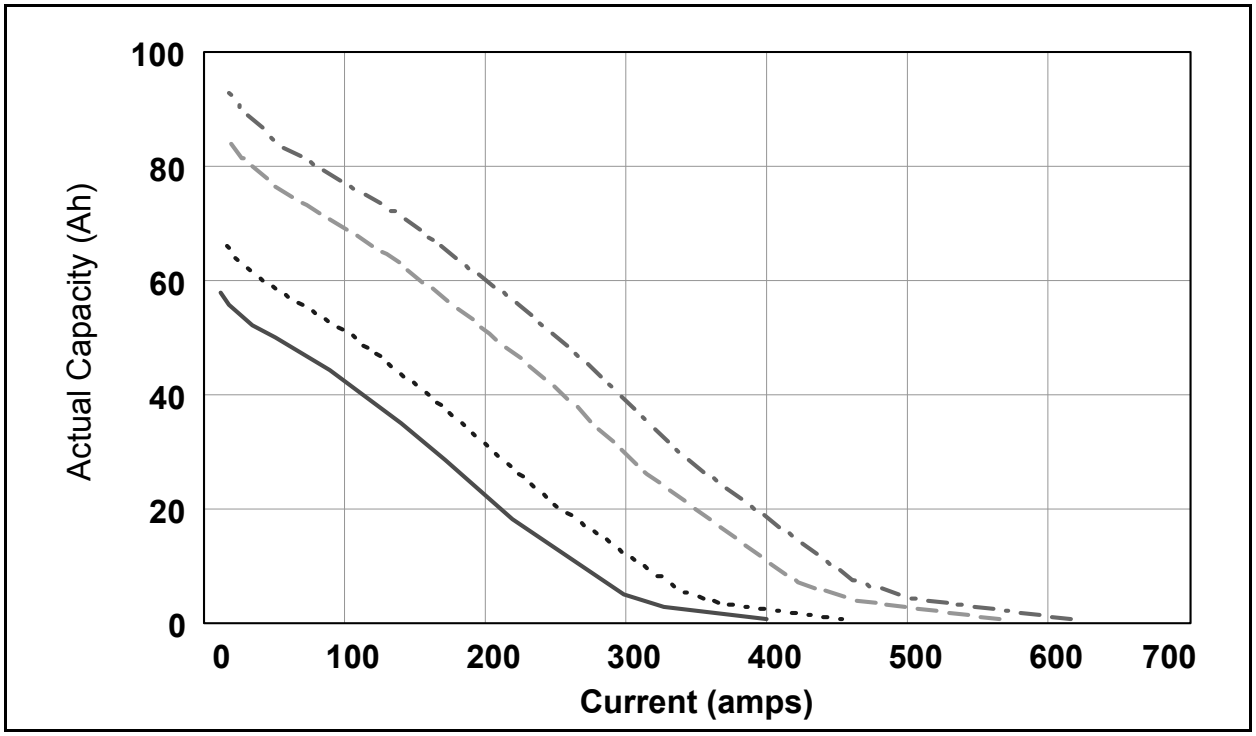

Figure 2 Actual Capacity versus Discharge Current for Four Different NiCd Cell Sizes. (Nominal capacities of cell shown are 58, 67, 85, and 93 amp-hours.)

$$d_{eff} = \frac{C_R}{C_A} d_{actual} \tag{5}$$

Equation 5 simply says that the effective ampere-hour discharge increases in direct proportion to the reduction in useable capacity as the discharge current increases.

3.3 Computing the Effective Discharge

The effects of DOD and discharge rate are combined simply by multiplying the factors expressed in Equations 3 and 4:

$$d_{eff} = \left(\frac{D_A}{D_R}\right)^{u_0} e^{u_1\left(\frac{D_A}{D_R}-1\right)} \left(\frac{C_R}{C_A}\right)^{v_0} e^{v_1\left(\frac{C_R}{C_A}-1\right)} d_{actual} \tag{6}$$

Or, in the simplified form:

$$d_{eff} = \left(\frac{D_A}{D_R}\right)^{u_0} e^{u_1\left(\frac{D_A}{D_R}-1\right)} \frac{C_R}{C_A} d_{actual} \tag{7}$$

Equations 6 and 7 express the effective discharge for a single discharge of specified magnitude and rate. A life prediction for a cell subjected to an irregular pattern of charge/discharge cycles requires that we sum the effective discharges from a series of discharge events. The discharge profile might be obtained by actual monitoring of battery current on an operating system, or it might be obtained by modeling the battery usage on a proposed system. In either case, the prescribed series of *n* discharge events will correspond to a certain period of time of system operation, *T*. The life time L_{time} of the cell under the specified usage pattern is then given by

$$L_{time} = \frac{\Gamma_R}{\left(\Gamma_{eff}/T\right)} = \frac{L_R D_R C_R}{\sum_{i=1}^{n} d_{eff}} T \tag{8}$$

4. Example Analysis

Using the method described above, we estimated the life time of several sizes each of flooded NiCd and glass-mat VRLA cells in a wind-diesel hybrid power system application. (Certainly other battery types might satisfy the requirements of the application. We have arbitrarily chosen these two for the example analysis.) In the modeled case, the battery energy storage is used for short term peak shaving. The battery is therefore exposed to many cycles of high current short duration charging and discharging.

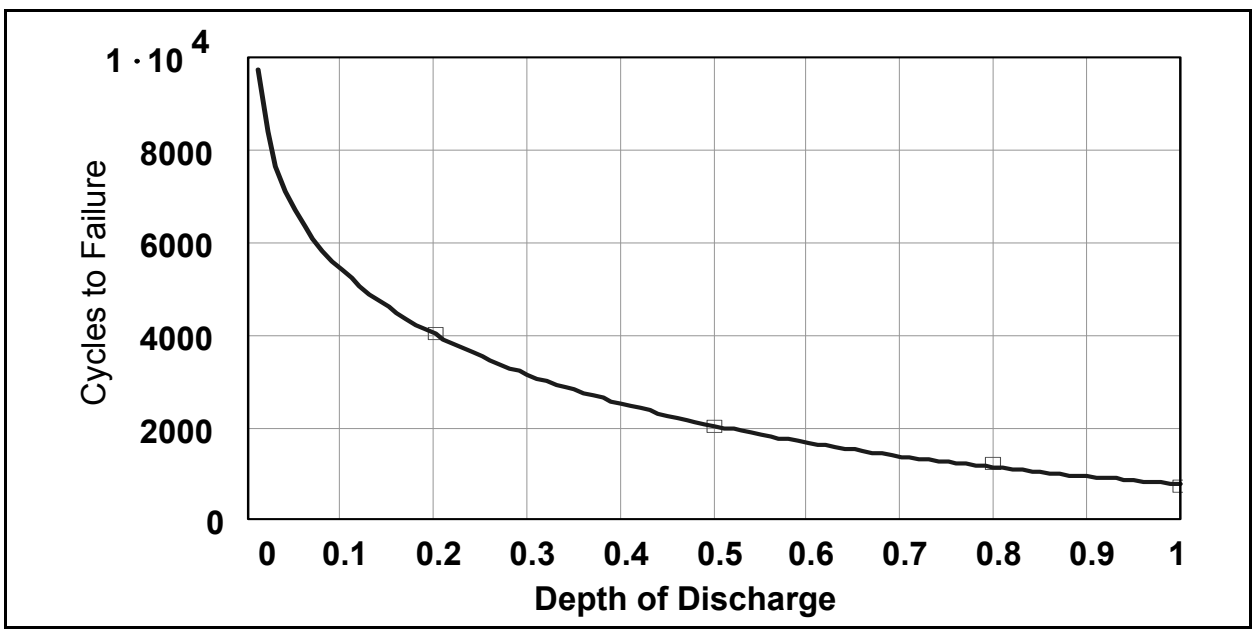

Figure 3 Best fit curve to manufacturer's cycle life data for glass-mat VRLA cells. Equation 3 parameters are u_0 =0.19, u_1 =1.69, and u_2 =765.

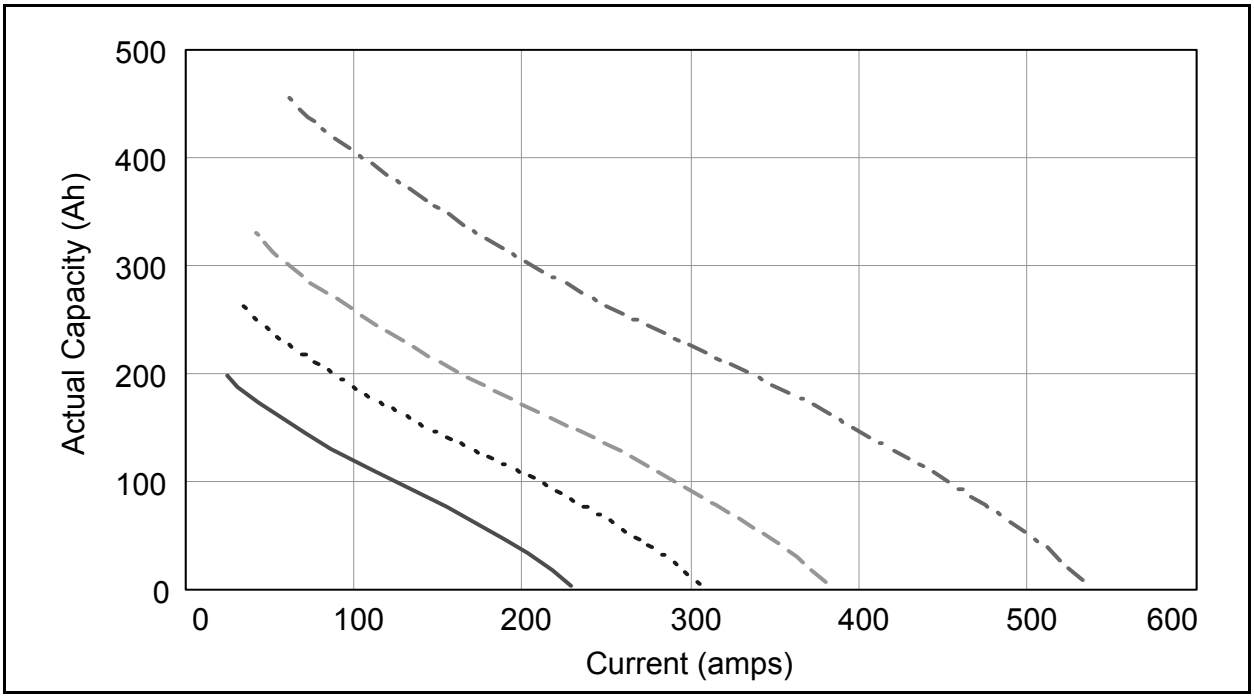

Figure 4 Actual Capacity versus Discharge Current for Four Different VRLA cell sizes. (Nominal capacities of cells shown are 198, 264, 330, and 462 Ah.)

4.1 Input File Preparation

4.1.1 Battery Cycle Life and Capacity

The battery cycle life and capacity data used for the NiCd cells is as appears in Figure 1 and Table 1 respectively. The cycle life and capacity data used for the VRLA cells is shown in Figures 3 and 4.

4.1.2 Cell Discharge Profile

The discharge profile input consists of a series of approximately 600 discharge events of specified current and duration. This series was obtained through an analysis of measured time series data of available wind power and village load at an Alaskan village. As shown in Figure 5, a discharge event is defined at a distinct period where the village load continuously exceeds the available wind power. Due to the strategy of using battery storage for short term peak shaving, only discharge events of less than 30 minutes were included in the data set. The battery bank has a nominal voltage

of 240 volts. For each discharge event, the average discharge current is determined from the average discharge power assuming a battery discharge voltage of 210 volts. The discharge isolated in Figure 4 has a current of 36.7 A and a duration of 14 minutes. The complete discharge data set, which represents a system operating period of 7 days, is shown in Figure 6.

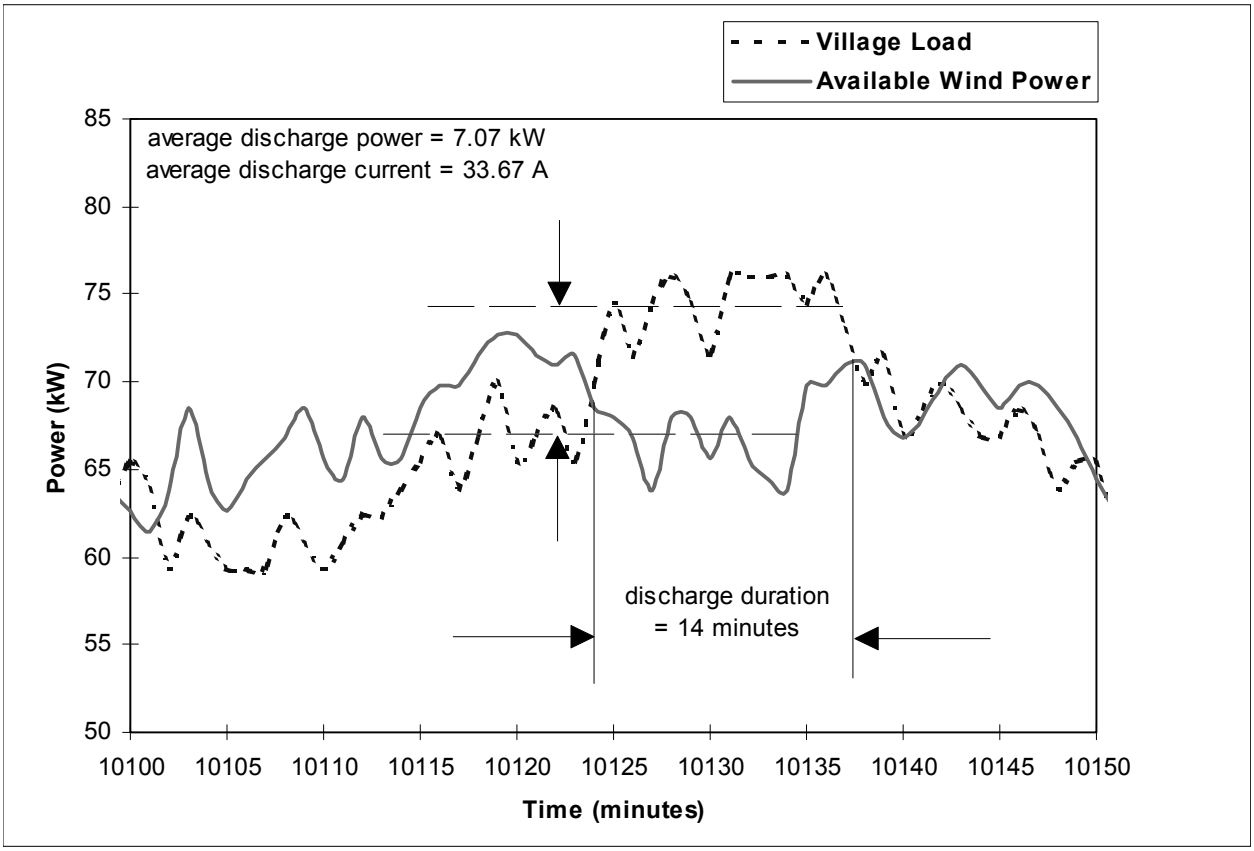

Figure 5 Determination of Current and Duration of Each Discharge Event

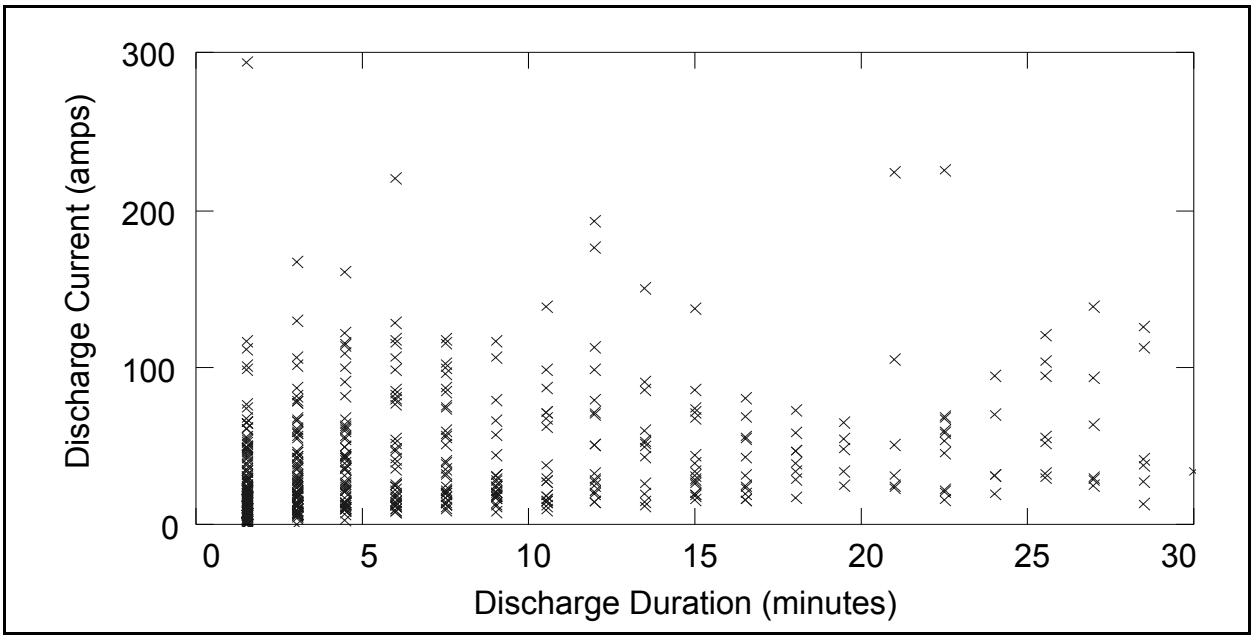

Figure 6 The Complete Data Set of Discharge Events used in the Analysis Example

4.1.3 Final Discharge Voltage

When sizing a battery for a given application, it is important to verify that the cell size chosen can actually deliver the required current for the required length of time without dropping below a certain minimum voltage. The minimum acceptable voltage per cell will depend on the specific battery type and on the voltage window tolerable by the load. So, in addition to the effective discharge and cell life calculations, our computer model determines the final discharge voltage for each discharge event. Knowing the minimum cell voltage that would be reached based on the prescribed discharge profile will help prevent an inappropriate battery choice made strictly based on predicted life time. The final discharge voltage computation is done by interpolating the cell manufacturer's discharge voltage versus DOD data for each discharge event. This method requires that we assume an initial state of charge for each discharge. In our analysis we assumed that the cell would begin each discharge at 80% state of charge, which will not of course be exactly true. It is however, a desirable operating target. The manufacturer's data for the NiCd cells of the example analysis is shown in Figure 7. The final discharge voltages calculated for a 111 Ah NiCd cell subjected to the set of discharge events represented in Figure 6 is shown in Figure 8.

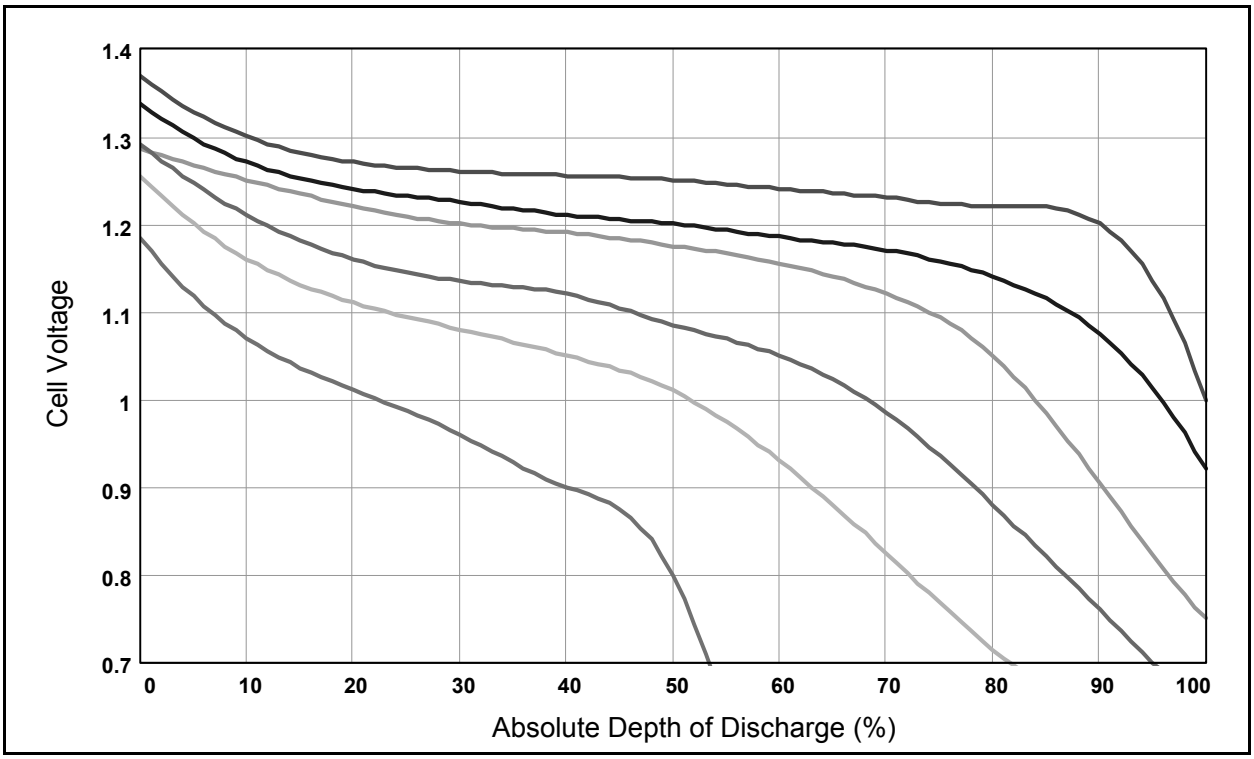

Figure 7 Discharge Voltage versus Depth of Discharge for Various Discharge Currents Based on Manufacturer's Data for Pocket Plate NiCd Cells.

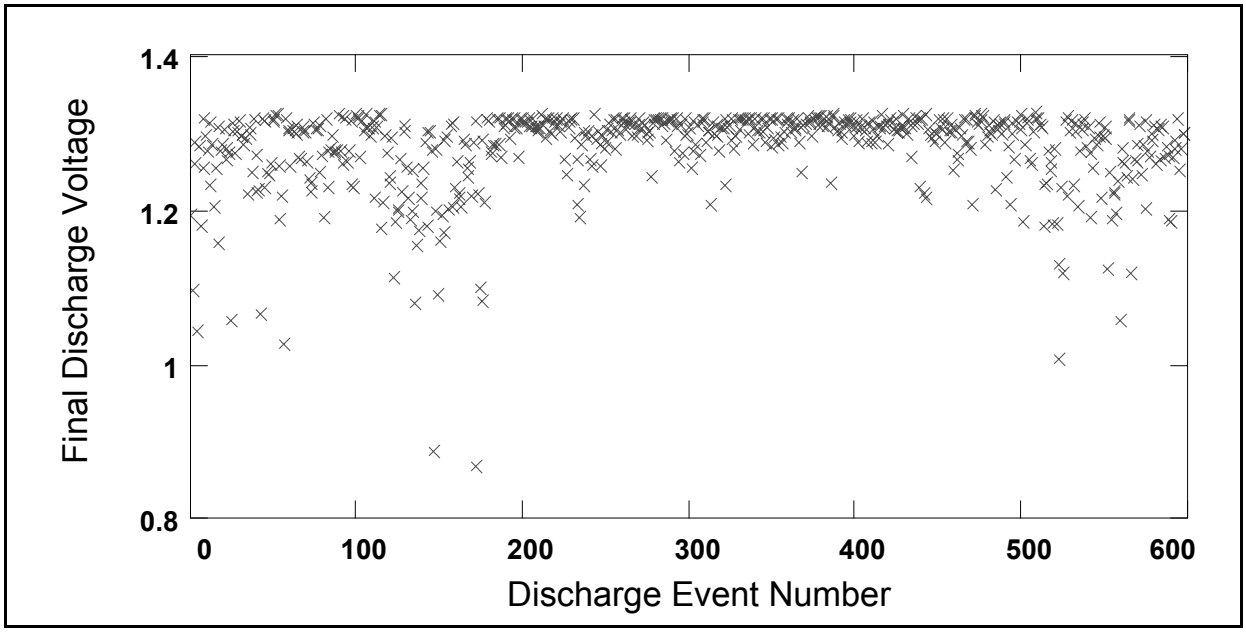

Figure 8 Final Discharge Voltages for each Discharge Event on a 111 Ah NiCd cell.

4.2 Results of the Example Analysis

The results of the analysis are shown in Table 2. The minimum acceptable discharge voltage for the NiCd cells is about 0.8 volts. Therefore we can eliminate from consideration all but the two largest NiCd cells. We did not have sufficient discharge voltage versus DOD data for the VRLA to compute the minimum discharge voltage that would be caused by our prescribed discharge profile. As one would expect, the predicted cell life time increases with increasing nominal capacity, because the larger cells are not working as hard and thus not wearing as rapidly as the smaller ones. The annualized cost of a 240V battery bank is computed using purchase prices of $1,100/kWh nominal capacity for the NiCd cells and $250/kWh for the VRLA cells. The larger sizes of the VRLA cells appear to offer a more economical battery for this application than either of the NiCd cells. However, several things would have to be verified before making a final selection, for example: 1) Is it reasonable, given battery aging processes, to expect a VRLA battery to last 11 or 19 years? 2) Can the VRLA cells handle the rapid charge rates (which would be about equal to the maximum discharge rates) called for in this application? 3) Do the minimum final discharge voltages for the VRLA cells fall within the acceptable range?

Cell Type	Nominal Capacity (Ah)	Nominal Charge Life (Ah)	Effective Discharge (Ah per 7 days)	Predicted Life (years)	Minimum Discharge Volts per Cell	Annualized Cost of 240V Battery
NiCd	58	119000	1805	1.3	<0	--
NiCd	67	138000	1307	2.0	<0	--
NiCd	85	175000	798	4.2	<0	--
NiCd	93	191000	672	5.5	.39	--
NiCd	102	210000	574	7.0	.59	--
NiCd	111	228000	496	8.8	.69	--
NiCd	128	263000	386	13.1	.84	$2,580
NiCd	137	282000	344	15.7	.92	$2,304
VRLA	198	152000	1713	1.7	NA[d]	$6,988
VRLA	264	212000	578	6.7	NA	$2,364
VRLA	330	253000	455	10.6	NA	$1,868
VRLA	462	354000	357	19.0	NA	$1,459

Table 2 Results of the Comparative Battery Life Analysis

5. Conclusions

We have presented a method for estimating the life of battery cells subjected to a specified pattern of discharge cycles of varying depth and rate. The method relies largely on battery cycle life and capacity data commonly available from battery manufacturers, but its accuracy could be enhanced by test data on the effect of discharge rate on cycle life. We have demonstrated the potential utility of the method if it proves to be valid, but we cannot yet verify the validity of the method, because we do not have sufficient life cycle data. Obtaining cycle life data over a wide range of discharge rates and for different battery types should be a focus of future work.

If battery cell life testing shows the model to be accurate, and as the parameters of Equation 4 are determined for a variety of cell types, the method could be combined with one of the excellent battery performance models that exist[5] to make it less dependent on the availability of detailed capacity data from battery manufacturers.

[d]Final discharge voltage data not available for the VRLA cells.

List of Symbols

Γ_A amp-hour life of a cell subjected under actual operating conditions

Γ_R amp-hour life of a cell under repeated discharges of rated DOD and rated discharge current

C_A amp-hour capacity of a cell at a given discharge current

C_R amp-hour capacity of a cell at rated discharge current

D actual discharge as a percentage of rated capacity

D_R percent depth of discharge at which rated cycle life was determined

d_{actual} actual amp-hour discharge

d_{eff} effective amp-hour discharge as adjusted for depth and rate of discharge

I discharge current

L cycle life of cell at a given percent discharge and discharge current

L_R cycle life at rated depth of discharge and rated discharge current

L_{time} life time (years) of the cell under actual operating conditions

T time period corresponding to the series of discharge events used as input data

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