ISSN: 2250–3676

[IJESAT] INTERNATIONAL JOURNAL OF ENGINEERING SCIENCE & ADVANCED TECHNOLOGY Volume-2, Issue-5, 1210 – 1217

IMPROVEMENT OF LIFE TIME AND RELIABILITY OF BATTERY

E. Suresh Kumar[1], Dr. Bijan Sarkar[2]

[1]*Research Scholar, Production Engineering, Jadavpur University, Kolkata, India,* ***sureshconference@gmail.com***
[2]*Professor, Production Engineering, Jadavpur University, Kolkata, India,* ***bijon_sarkar@email.com***

Abstract

Determining battery lifetimes is beset with difficulties. Performance data are not generally available and costly to generate since large numbers of batteries must be tested to destruction. Furthermore, the required test period to verify the predictions is often greater than commercial decision lead time. While the reliability predictions in the following section are very useful, they are designed for applications involving constant controlled environments, operating conditions and loads. Many batteries however, operate under a wide variety of operating conditions with wide variations in the loads they must supply. Predicting the lifetime of these batteries is much more complicated. One problem with predicting battery lifetimes is that several failure modes exist, each with its own characteristic shape and lifetime, and this requires a different expression for each failure type. The Weibull failure distribution does not apply to every failure mechanism but it is useful tool for analysing many of the most common reliability problems. This paper is an insight into the issues encountered in the battery during operational life time and based on the sample data doing a Weibull analysis and suggesting the ways to improve the life time and the reliability of a battery.

Index Terms: *Peukert Law, Weibull life distribution, Characteristic life, MTBF, operating Depth of Discharge.*

---***---

1. INTRODUCTION

Battery life, reliability, and life-costs has always been a primary concern where they are needed in photovoltaic systems, telephone and telecommunications, computers, Uninterruptible Power Supplies (UPS) or backup and emergency power to the AC power line, electric vehicles (EVs), etc. The life costs can make or break a products success, and false trust in a defective battery can be catastrophic. The first step in long battery life is the proper selection of the battery chemistry and size for the application. This requires consideration of the fault and safety protection, the worst case discharge current-vs-time profile requirements that fit the battery including the derating factors [1], plus charging techniques and charge/discharge cycles if applicable. Manufacturers rate the capacity of a battery with reference to a discharge time.

Peukert's law [2] describes an exponential relationship between the discharge current (normalized to some base rated current) and delivered capacity (nomalized to the rated capacity), over some specified range of discharge. The Law takes into account the internal resistance and recovery rate of a battery. A value close to one (1) indicates a well-performing battery with good efficiency and minimal loss; a higher number reflects a less efficient battery. The Peukert Law of a battery is exponential and the readings for lead acid are between 1.3 and 1.4. Nickel-based batteries have low numbers and lithium-ion is even better. The lead acid battery prefers intermittent loads to a continuous heavy discharge.

2. ESTIMATING BATTERY LIFETIMES

Determining battery lifetimes [3] is beset with difficulties. Performance data are not generally available and costly to generate since large numbers of batteries must be tested to destruction. Furthermore, the required test period to verify the predictions is often greater than commercial decision lead time. Charge – discharge times for high capacity batteries are very long and using accelerated life testing to determine battery lifetime is most likely to lead to misleading results since battery life depends on temperature, rate and depth of discharge and the test conditions used to accelerate the occurrence of failures are quite likely to introduce new and unrepresentative failure modes.

While the reliability predictions in the following section are very useful, they are designed for applications involving constant controlled environments, operating conditions and loads. Many batteries however, operate under a wide variety of operating conditions with wide variations in the loads they must supply. Predicting the lifetime of these batteries is much more complicated. Latent defects [4] in the components used in the construction of the battery or manufacturing and workmanship defects may cause early failures or "wear in" faults, more commonly called "infant mortalities". Other latent defects such as the contamination of the active materials may cause a series of random failures which could result in the sudden death of the battery rather than gradual wearout. These failures are more difficult to characterise and tend to be random in nature and thankfully occur with a very low frequency. Of particular concern is the occurrence of internal short circuits which could result in fires. Wearout failures [5] are due to the gradual deterioration of the cell chemicals which may be caused by the breakdown or loss of active chemicals causing a reduction in cell capacity. These failures may in turn result in a fatal condition, such as a short circuit, or they may simply cause out of tolerance performance of the cell. Wearout failures may be initiated or accelerated by the usage pattern to which the battery is subject. The diagram below shows cell failure distributions due to a variety of failure modes.

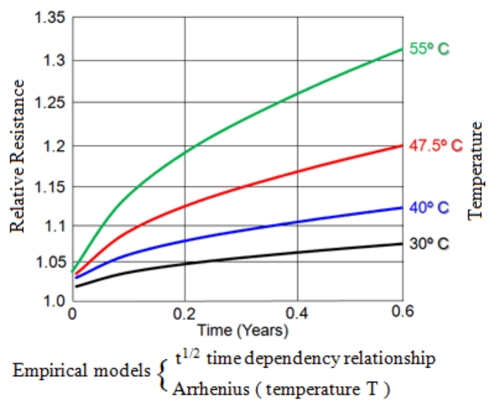

Figure 1: Increasing internal resistance with time and temperature.

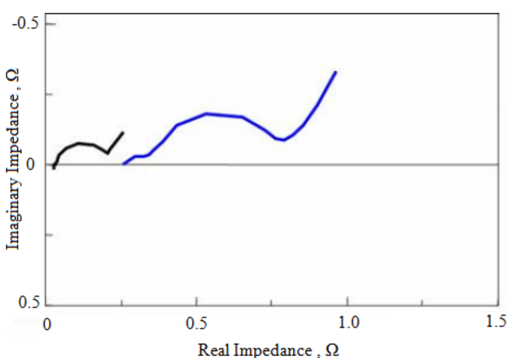

Figure 2 : Nyquist plots for a lead acid battery before (black) and after (blue) 450 aging cycles.

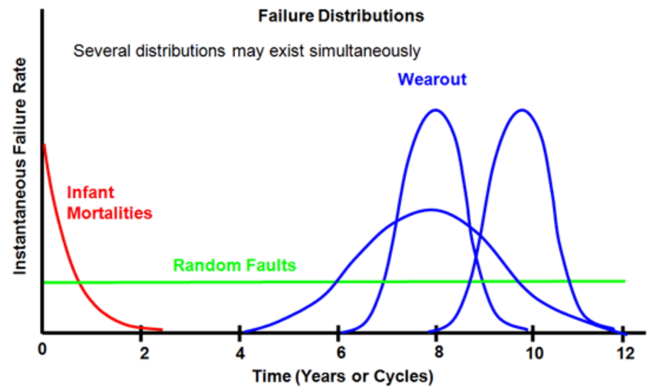

Figure 3 : Several distributions existing simultaneously.

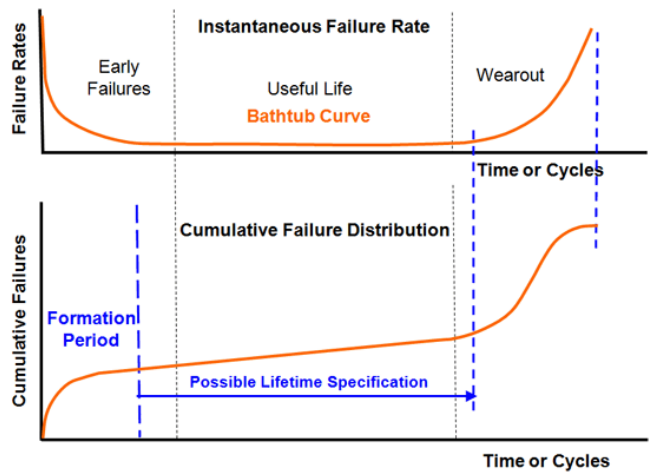

Figure 4 : Cumulative failure over time.

Components designated for high reliability applications are often subject to "burn in" [6] to weed out the infant mortalities [6]. In cell manufacturing, all cells must go through one or more charge–discharge cycles as part of the formation process and this can serve the dual purpose of identifying early failures.

3. WEIBULL LIFE DISTRIBUTION MODEL

One problem with predicting battery lifetimes is that several failure modes exist, each with its own characteristic shape and lifetime, and this requires a different expression for each failure type. The Weibull failure distribution [7] does not apply to every failure mechanism but it is useful tool for analysing many of the most common reliability problems. For statistically independent failures of a given type the Weibull distribution is given by

$F(t) = 1 – \exp[-(t/\alpha)^{\beta}]$

Where F(t) is the cumulative percent failing after time t, α is the Characteristic life of the components (Also known as the

Scale factor) , β is the Shape parameter describing the failure distribution curve. The parameters α and β are determined graphically from measured data gathered from life tests on a relatively small number of samples (see below). The expression is simply a mathematical model representing the shape of the distribution and does not imply any cause and effect. The characteristic life is defined as the time when the cumulative failure percent of the population reaches 63.2%. It is given by making t = α in the above equation. Thus when t = α the cumulative failure percent is given by $F(t) = 1 - e^{-1} =$ 63.2% regardless of the value of β. If more than one failure mechanism exists within the population, each with different characteristics, the appropriate α and β corresponding to each failure mode must be applied separately to obtain the total failure percent. Using the shape and scale parameters developed for similar products is not justified and is likely to lead to erroneous results. More complex Weibull distributions have been developed with more variables to allow for other factors such as γ (gamma), known as the Location factor [8] , which represents the time delay before the effect of the failures becomes manifest.

More generally the Weibull distribution is given by: $F(t) = 1 – \exp[-((t-\gamma)/\alpha)^{\beta}]$ Replacing the time duration t, in the two variable Weibull equations with (t-γ) effectively moves the Weibull lifetime distribution curve to a new location γ periods the right. Unfortunately, unlike the practical determination of α and β, the determination of a reliable value for γ is much more difficult. Fortunately the location factor γ is zero for most cases since failures may start occurring immediately at time zero so that the two variable distribution is usually sufficient for analysing most common problems. The distribution of component lifetimes within the

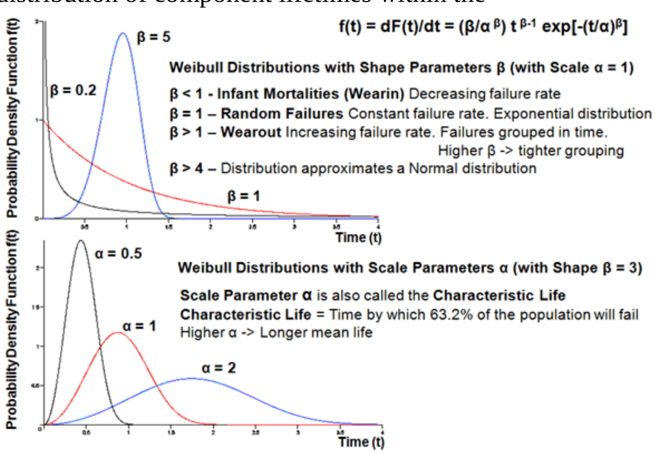

Figure 5 : Weibull Probability Density Function f(t)

Total population is given by the time derivative of the cumulative failure distribution. Thus
$f(t) = dF(t)/dt = (\beta/\alpha^{\beta})\, t^{\beta-1} \exp[-(t/\alpha)^{\beta}]$
In batteries which are constructed from a series string of "N" components from the same distribution with independent failures, where the failure of one component causes the failure of the string, the shape and scale factors for the string are given by
$\beta_N=\beta_1$
$\alpha_N=\alpha_1 / (N)^{1/\beta}$

For random failures (β = 1), the characteristic life of a battery with a string of N cells is 1/N times the characteristic life of the cells, or conversely, the failure rate of the battery is N times the failure rate of the individual cells. The hazard rate h(t), also called the failure rate, is given by
$h(t) = f(t)/R(t) = (\beta/\alpha^{\beta})\, t^{\beta-1}$

For a constant failure rate, β = 1, the mean time between failures (MTBF) [9] is equivalent to the characteristic life and can be deduced from the above equation. B=1 and α=MTBF and MTBF=1 / h. Thus the MTBF is the reciprocal of the failure rate.

4. WEIBULL PROBABILITY PLOT

To determine the α and β parameters for independent failures of a given type within a given population, it is necessary to conduct a life test on a small representative sample of units. The cumulative percent of the sample failing is then plotted against the time of failure, or number of cycles completed, on Weibull probability paper [10]. The characteristic life α of the population is defined as the time when 63.2% of the sample or population has failed and this is obtained directly from the graph. The slope β of the graph is given by drawing a parallel line on the β scale outlined on the graph and corresponds to the shape factor of the distribution. If the results of the sample tests do not show a distinct trend line, but instead are scattered across the chart, then the Weibull distribution is unsuitable for modeling the failure characteristics of the products concerned.

The curves represent the cumulative percentage of failed cells for the three types of cells with different failure characteristics [11]. The cumulative percentage of failed cells in time **t** is given by $F(t) = 1 – \exp[-(t/\alpha)^{\beta}]$

(If α and β are known, the curves can be drawn using the Weibull function provided in the Excel spreadsheet). For each cell type, the cumulative percent which have failed when the elapsed time corresponds to the characteristic life of the cell is 63.2%. The curves could also represent 3 (or more) separate, simultaneous failure mechanisms active in the same battery.

ISSN: 2250–3676

[IJESAT] INTERNATIONAL JOURNAL OF ENGINEERING SCIENCE & ADVANCED TECHNOLOGY Volume-2, Issue-5, 1210 – 1217

For example, one for failures due to dendrite growth, another for electrode plating and another for electrolyte breakdown. In such cases the cumulative cell failures in any year would be the sum of the failures due to each factor.

Differentiating the above function with respect to time gives the corresponding distribution of cell lifetimes shown in the curves below.

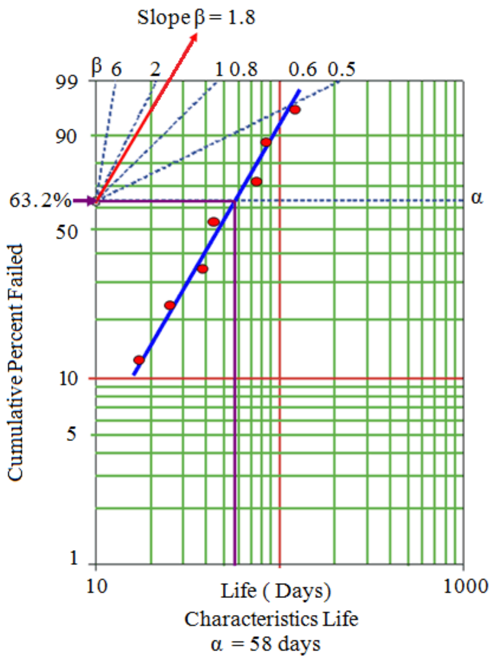

Figure 6 : Weibull plot for the estimation of shape parameter and characteristics life.

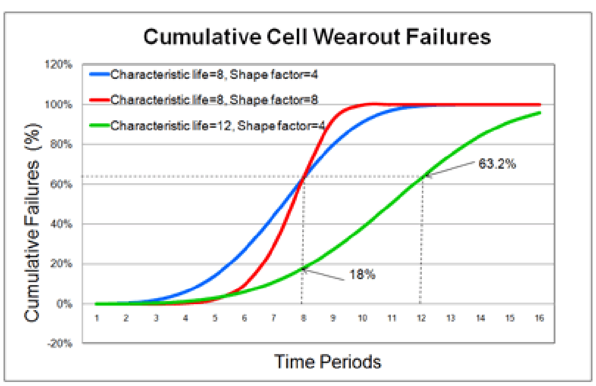

Figure 7 : Cumulative wearout failures of cell.

5. LIFE TIME DISTRIBUTIONS

The curves opposite show the distribution of lifetimes [12] for the above three cell types, that is, the percentage of cells failing in each period. The blue and red curves show the distribution of lifetimes for cells with an eight year characteristic cell life (α=8). The blue curve indicates components with a wide spread of production tolerances (β=4) which cause a high number of early failures. The red curve shows that the initial failure rate can be reduced by using tighter production control to produce components with a narrower tolerance spread (β=8) but in this case the failure rate increases later and all the cells fail relatively quickly. Note that in all cases, more than half of the cells (63%) fail before the characteristic life.

To reduce the number of cells failing within a desired period such as the eight year example above, it would be necessary to use cells with a longer characteristic life. The green curve shows the lifetime distribution of cells with a characteristic life of 12 years. At the same time the the shape factor shows that the cells have a more manageable (wider) production spread. In this case the cumulative percentage of cells failing in eight years will be reduced to 18% (See above diagram). Whether this is practical or not is another matter.

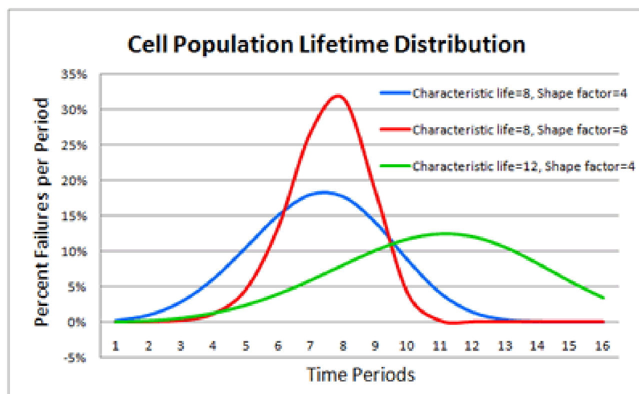

Figure 8 : Population life time distribution.

The wearout failure of a single cell will not itself result in a battery failure since all the cells in the battery, including the "failed" cell, will continue to function and the gradual effect of reduced capacity, or increased impedance, of a single cell on the battery will not show until many of the cells are below the rated capacity or above the impedance tolerance. This does not apply to fatal cell faults which will always cause a battery failure. The example below shows two scenarios of the effect of cell failures on the corresponding lifetime of batteries built from 80 cells, each with a 12 year characteristic life as in the green example above.

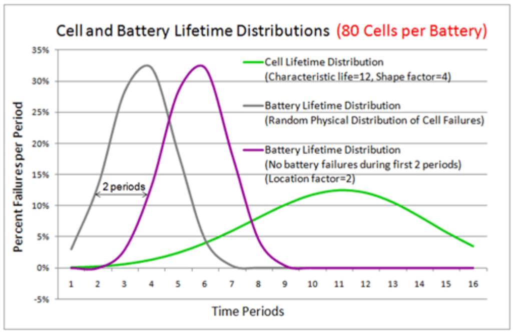

Figure 9 : The cell and battery lifetime distribution .

The green curve shows the cell lifetime distribution. The grey curve shows the battery lifetime distribution resulting from the failure of the cells. It assumes that the presence of a single failed cell in a battery chain is sufficient to cause the battery to fail. The cell failures occur randomly throughout the batteries so that some batteries will have more than one failed cell (but can only fail once) while other batteries have no failed cells. The purple curve shows the more likely case when early cell failures due to ageing will have minimal effect on the overall battery performance. In this case there are no battery failures during the initial periods. The Weibull location factor (γ = 2) represents the delayed onset of the failures and essentially moves the lifetime distribution to the right by 2 periods.

6. BATTERY LIFETIME MODEL

From the test results a composite ageing characteristic or lifetime model for the battery [13] can be developed by combining all the lifetime graphs of capacity fade or internal impedance rise for both calendar and cycle life, due to each of the identified stress factors, into a single curve. The example below shows how the capacity fade results due to two stress factors, one mild and one severe, can be combined into a single graph by applying each stress factor for the estimated percentage of the battery lifetime for which it applies. The process can be repeated until all the test results have been incorporated.

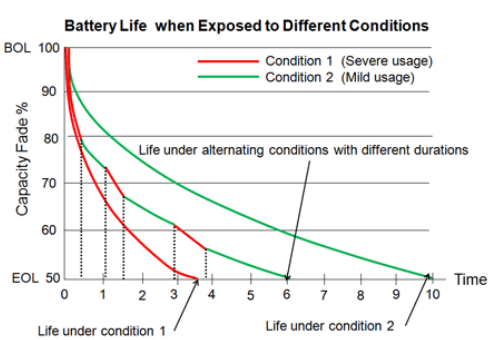

Figure 10 : Battery capacity fade for severe and mild usage.

During the extended period necessary for testing the batteries, it would be expected that the vehicles in which the batteries will be used will also undergo performance testing in a parallel series of tests. By monitoring battery performance of these field test vehicles in practical daily use and comparing the results with the model's predictions, the validity of the model can be verified or refined if necessary. Random faults are amenable to simpler analysis. They tend to demonstrate a fairly constant failure rate, not time varying as in wearout faults.

Consider a multi-component system such as a series chain consisting of n components in which the failure of any component n results in the failure of the system [14]:

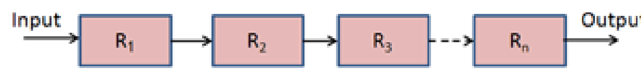

Figure 11 : Reliability block diagram of series connected components.

If the probability of survival of each component after time t is $R(t)_n$ and the failure rate per hour of each component is λ_n, the system reliability $R(t)_{system}$ is given by:

$R(t)_{system} = R(t)_1 \times R(t)_2 \times R(t)_3 \times \ldots R(t)_n$. For components with constant failure rates in which λ_n= the failure rate per hour of component n, then $R(t)_n = e^{-\lambda nt}$ and the system reliability is given by $R(t)system = e^{-\lambda 1t} \times e^{-\lambda 2t} \times e^{-\lambda 3t} \times \ldots e^{-\lambda nt} = e^{-(\lambda 1 + \lambda 2 + \lambda 3 + \ldots \lambda n)t}$. Thus the system failure rate λ_{system} is given by: $\lambda_{system} = \lambda_1 + \lambda_2 + \lambda_3 + \ldots \lambda_n$.
In a battery the components (cells) making up the series chain are identical so that: $\lambda_1 = \lambda_2 = \lambda_3 = \ldots \lambda_n$ and the system failure rate is given by: $\lambda_{system} = n \times \lambda$. The system reliability is then given by: $R_{system} = R^n$

7. SYSTEM RELIABILITY IMPROVEMENTS

The overall system reliability can be improved by adopting design and operating principles to minimise the stress on the battery. The obvious policy is to use the most reliable cells available.

Burn in can improve cell reliability by ensuring that the infant mortalities occur in the cell or pack maker's plant and not in the customer's battery. In general, lower voltage designs will be more reliable than high voltage designs. This applies at the cell level and the system level. At the cell level, operating cells slightly below their maximum specified level reduces the stress on the cell and can significantly increase the cell life time. At the system level, reliability can be increased by reducing the system voltage but maintaining the system power by increasing the corresponding current. This allows fewer cells in the series chain but it needs cells with higher current carrying capacity or more parallel cells. The system reliability is inversely proportional to the number of cells in the series chain.

Another way of increasing cycle life by reducing the stress on the cells is by specifying cells with a slightly higher capacity than absolutely necessary. This small capacity reserve reduces the effective maximum operating Depth of Discharge DOD [15]. Instead of large cells, use parallel strings of smaller cells in . This has the following benefits. Smaller cells tend to be less stressed and consequently have a lower failure rate. Because less energy is stored in smaller cells, the energy released in case of the catastrophic failure of an individual cell will be less. Any failure will thus be easier to contain and less likely to cause fault propagation throughout the battery. The failure of an individual cell in a parallel configuration will not cause the failure of the whole battery which could possibly continue functioning at lower power. In multi-cell batteries, manufacturing tolerance spreads of cells tend to increase as the cells age causing the weaker cells to fail. Sorting the cells to be used in each battery into narrower tolerance bands before assembly can help to minimise these premature failures.
Control the operating environment. Both high and low temperatures are cell killers. The system should incorporate thermal management with heating and cooling circuits, where necessary, to keep the cells operating within their temperature sweet spot. Provide redundancy so that the failure of a single cell does not incapacitate the battery allowing it to continue working in emergency situations. Use parallel cell strings
Provide standby or cycling redundancy. Divide the battery into two or more sections, each with bypass paths which can be switched in to enable a section with a failed cell to be circumvented allowing the battery to continue to function at low power. In any system constructed from independent and identical components, each with the same reliability rate of R in a given period , if the failure of any one of the components causes the failure of the system, then the system reliability R_{system} is given by:
$R_{system} = R^n$ where n is the number of components in the system.

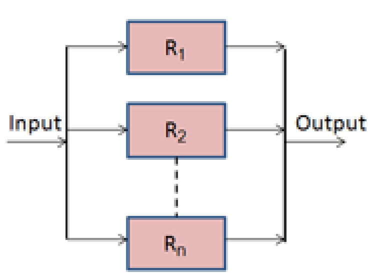

Figure 12 : Reliability block diagram of parallel components.

If however the system is designed with more components than strictly necessary to ensure normal functionality, the life of the system can be prolonged by arranging that any of the surplus components can take the place of failed components. The principle of incorporating one or more extra "back-up" components which only come into play when another component has failed is called redundancy and the extra components are called redundant components. The greater the number of redundant components, the greater the reliability improvement, enabling a dramatic improvements in system reliability to be achieved.
A system with n identical components of which only k are necessary for normal functionality thus has (n - k) redundant components. The reliability of such a system with redundancy is given by:

$$R_{system} = \sum_{i=k}^{n} \binom{n}{i} R^i (1-R)^{n-i} \text{ where}$$

$$\binom{n}{i} = \frac{n!}{i!} \text{ the binomial coefficients}$$

Consider a system built from k essential components each with a reliability R of 0.85 per unit time. (Constant failure rate). In a system built from 4 identical components, all of which are required to deliver full functionality, k=4 and the system reliability R_{system} will be given by: $R_{system} = 0.85^4 = 0.5220$ With 2 redundant components added to improve the reliability, the total component count is increased to n = 6 and the system reliability is given by:

$$R_{system} = \sum_{i=4}^{6} \binom{6}{i} 0.85^i (1-0.85)^{6-i}$$

$$R_{system} = \binom{6}{4} 0.85^4 \times 0.15^2 + \binom{6}{5} 0.85^5 \times 0.15^1 + \binom{6}{6} 0.85^6 \times 0.15^0$$

$$R_{system} = \frac{6x5}{1x2} \times 0.85^4 \times 0.15^2 + \frac{6}{1} \times 0.85^5 \times 0.15^1 + \frac{6}{6} \times 0.85^6$$

$$R_{system} = 0.1762 + 0.3993 + 0.3771. R_{system} = 0.9526 = 95.26\%$$

Thus in this case, by adding 2 redundant components, the reliability of the bare system of 4 components without redundancy will be almost doubled.

The table 1 presents the data derived from the above example in a slightly different way showing how reliability improves as

Minimum System Components k	Redundant Components (n-k)	System Reliability
6	0	0.377150
5	1	0.776480
4	2	0.952660
3	3	0.994110
2	4	0.999600
1	5	0.999989

Table 1 : Reliability Improvement with Redundancy.

The level of redundancy increases. Starting with a total of n=6 available components, each with a reliability of 0.85, it shows the system reliability of 6 different system configurations where **k** is the minimum number of components necessary to keep the system functioning and the balance of the components are used to provide redundancy. When all 6 components are required for system functionality, the system has no redundancy and the the reliability is only 0.37715. At the other extreme, a system consisting of a single component with 5 possible back-up components would have a reliability of 0.999989.

8. CONCLUSION AND FUTURE SCOPE

The overall system reliability can be improved by adopting design and operating principles to minimise the stress on the battery. The obvious policy is to use the most reliable cells available. Carry out thorough cell qualification. Burn in can improve cell reliability by ensuring that the infant mortalities occur in the cell or pack. In general, lower voltage designs will be more reliable than high voltage designs. This applies at the cell level and the system level.

At the cell level, operating cells slightly below their maximum specified level reduces the stress on the cell and can significantly increase the cell life time. At the system level, reliability can be increased by reducing the system voltage but maintaining the system power by increasing the corresponding current. Another way of increasing cycle life by reducing the stress on the cells is by specifying cells with a slightly higher capacity than absolutely necessary. This small capacity reserve reduces the effective maximum operating DOD. Instead of large cells, use parallel strings of smaller cells. The system should incorporate thermal management with heating and cooling circuits, where necessary, to keep the cells operating within their temperature sweet spot.

REFERENCES

[1] Dr. Kusum Sahu (2003) - EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating, NASA/TP—May, 2003–212242, National Aeronautics and Space Administration, Goddard Space Flight Center , Greenbelt, Maryland 20771.

[2] A.A.K. Vervaet, D.H.J. Baert (2002) - The lead acid battery: semiconducting properties and Peukert's law, Pergamon- Electrochimica Acta 47 (2002) pages : 3297_ 3302

[3] Henrik Bindner, Tom Cronin, Per Lundsager, James F. Manwell, Utama Abdulwahid, Ian Baring-Gould (2005) - Lifetime Modelling of Lead Acid Batteries, Risø-R-1515(EN),April 2005, Risø National Laboratory, Denmark.

[4] M. Meniconi, (1997) "Electrostatic discharge: Perhaps the most problematic phenomenon in the manufacture of products involving electronic devices and assemblies", International Journal of Quality & Reliability Management, Vol. 14 Iss: 3, pp.301 – 308.

[5] Nakagawa, Toshio (1980) - Replacement Policies for a Unit with Random and Wearout Failures, IEEE Transactions on Reliability , Oct. 1980, Volume: R-29 , Issue: 4 , Pages : 342 – 344.

[6] Cooper, M.(2008) -Observations on Component Infant Mortality and Burn-In Effectiveness, IEEE Transactions on Components and Packaging Technologies, Dec. 2008, Volume: 31 , Issue: 4 , Pages**:** 914 – 916.

[7] G.R Pasha, M. Shuaib Khan, Ahmed Hesham Pasha (2006) - Empirical Analysis of The Weibull Distribution for Failure Data, ISSN 1684 – 8403 Journal of StatisticsVol: 13, No.1.

[8] Evans, James W.; Johnson, Richard A.; Green, David W.(1989) - Two- and three-parameter Weibull goodness-of-fit tests. Res. Pap. FPL-RP-493. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1989. Pages : 1-27.

[9] Michlin, Y.H., Grabarnik, G.Y. ,Leshchenko, E. (2009) - Comparison of the Mean Time Between Failures for Two Systems Under Short Tests, IEEE Transactions on Reliability, Dec. 2009, Volume: 58, Issue: 4 , Pages: 589 – 596.

[10] C. D. Lai, Min Xie, D. N. P. Murthy*(2003)* - A Modified Weibull Distribution, IEEE transactions on reliability, VOL. 52, NO. 1, March 2003, Pages : 33-37.

[11] http://www.mpoweruk.com/reliability.htm

[12] B.Malarkodi, B.Prasana and B.Venkataramani(2010) - A battery power scheduling policy with hardware support in mobile devices , International journal on applications of graph theory in wireless ad hoc networks and sensor networks (GRAPH-HOC) Vol.2, No.3, September 2010.

[13] Wei Jun Gu, Ze Chang Sun, Xue Zhe Wei, Hai Feng Dai (2010) - Review of Methods for Battery Life Modeling and Their Applications, Journal of applied mechanics and materials Volumes 29 – 32 Applied Mechanics And Mechanical Engineering, Pages 2392 – 2397.

[14] Dey, D.K., Jaisingh, L.R.(19880 - Estimation of system reliability for independent series components with Weibull life distributions, IEEE Transactions on

Reliability, Oct 1988, Volume: 37 , Issue: 4 , Pages: 401 – 405.

[15] Chengke Zhou, Kejun Qian, Allan, M., Wenjun Zhou (2011) - Modeling of the Cost of EV Battery Wear Due to V2G Application in Power Systems. IEEE Transaction Transactions Energy Conversion, Dec., Volume: 26 , Issue: 4, Pages: 1041 – 1050.

BIOGRAPHIES

Dr. Bijan Sarkar is a Professor and Former Head of the Department of Production Engineering at the Jadvapur University, Kolkata. He is a specialist in the field reliability, terotechnology, tribology and operations management. He guide more than a decade doctoral thesis and an internationally reputed reviewer of for many journals.

E Suresh Kumar is a Research Scholar at the Jadavpur University Kolkata and an Assistant Professor at the College of Engineering, Trivandrum, India.