Capacity Optimization and Energy Management in Rechargeable Lead Acid Batteries using Response Surface Methodology

Aatif Jawad Khan, Salman Hussain

Abstract— The rechargeable or secondary battery is such battery where electrical energy delivered by source can be stored in the form of chemical energy and this chemical energy is then be consumed by load in the form of electrical energy according to the requirement. Batteries are being used for the backup purpose from more or less one century. The usage of a battery for the purpose of off grid power supply can increase the overall efficiency of the system and also provides the economic savings across the whole system life cycle. Reliability of the power supplied from renewable as well as conventional sources can be improved by using the battery as energy storing device or medium. Typical Battery can be charged by using the solar energy for the use of renewable energy or by power supply for the purpose of conventional energy supply. Different type of batteries shows different behavior of current, voltage and capacity characteristics when charged by using traditional power supply. This paper focuses and outlines the discharging characteristics of Lead acid batteries under different operating conditions such as discharge rate, time and battery capacity. The main aim of this particular paper was to optimize the operating conditions of any battery which leads to the improved battery efficiency and capacity as well as reduced power losses associated with battery the storage system.

Index Terms— Capacity optimization, Discharge characteristics, Energy management, Lead acid batteries, Optimization, Reachargeable batteries, Response surface methodology.

1 Introduction

RECHARGEABLE or secondary batteries play an important roles in many daily life applications, such as in power tools, portable power products, and, most especially in automobiles. The technical characteristics of the batteries are difficult to predict as compared to other electric or mechanical devices due to the complexity of the chemical and physical processes involved in it. Technically a battery is a device which converts the chemical energy stored in it into electrical energy; but in case of a rechargeable system, the battery is further recharged by reversing the same process under different operating conditions. Therefore, battery energy efficiency represents the utilization rate of its energy, including both the chemical energy as well as the electric energy, during charging & discharging processes. Unlike those of small scale batteries, the technical parameters and characteristics of large-scale batteries, especially the power batteries used in transportation system actually require deep analysis, not only with respect to basic properties such as voltage, current, capacity and energy, but also the properties related to the vehicle side, such as environment temperature, power and energy efficiency. The current and latest studies on batteries energy efficiency aims to (1) improve the utilization rate of energy to save the electric energy by optimizing the working parameters; (2) estimate the discharge time of the batteries used in pure electric vehicles and portable devices, (3) judge the batteries whether these are excellent by using the measured energy efficiency and density as an evaluation parameter; and finally (4) the contribution to the thermal management, because thermal energy is also related to the loss of electric or chemical energy, based on law of conservation of energy [1].

1.1 Need of Electrical Energy Management

In most of the industrial and domestic sectors, high reliability of power supply is required in case of critical loads. Uninterruptible power supplies some times are used to improve the power quality and guarantee the availability of backup power. During voltage fluctuations or sometimes complete breakdown of the power supply, the energy has to be supplied by traditional energy storage systems. Conventional energy storage system for UPS is basically relying on the selection of good rechargeable batteries like lead acid batteries. However, there are some disadvantages also associated with these batteries such as less power density as well as limited charge &/discharge cycles [2].

1.2 Aims and Objective

The main aim of current research is to optimize the output power, capacity and energy of the secondary lead acid batteries using the proper selection of ranges for the particular working parameters like discharge rate and battery state of charge.

Objectives of this particular research are

- To carry out extensive literature review in the field of Lead Acid Batteries.
- To investigate the major causes of power losses associated with the secondary batteries.
- To develop an optimized model for the batteries power system optimization.
- To validate the model by the experimental results.

1.3 Scope of the Research

Area of research has been selected on rechargeable lead acid batteries for this particular research. As the battery is fundamental source of electrical energy storage and retrievel as well. The major issue and problem statement in this particular case is output capacity as well as energy losses during the electro-mechanical energy conversion processes. The scope of this particular research covers the area of the industrial devices and domestic loads which are relying on lead acid batteries for their smooth functioning.

2 Literature Review

In recent years, uninterruptible power supply (UPS) system is extensively being used as an alternative for power shutdown as well as for stabilization. For this particular reason, a UPS system has been effectively applied for variety critical loads such as computers, portable devices and life support equipment. A battery pack is used along with conventional UPS system assembled in a number of series connected cells [3]. The most commonly used energy storage technologies now a days are Lead acid batteries, Nickel based batteries and Lithium ion batteries. Li-ion batteries are a comparatively new technology devices, first marketed in the start of 1990's where as the lead acid battery is conventional used technology since 1980's. Nickel based batteries are in service since 1950, due to memory effect issue, they are less popular technologies [4].

Presently, the most commonly used secondary batteries in market are Li-Ion batteries, NiCd batteries, NiMH batteries and lead-acid batteries whose technical comparison has been shown below in Table I. Amongst these, NiMH battery and NiCd battery is mostly used in hybrid type vehicles and cordless power tools. Lead acid batteries are extensively being used in the automobile vehicles, industrial power equipments & also in energy storage setup. Finally the lithium ion batteries are widely used portable electronics equipments like laptops, android phones and tablets. Technically, the lead (Pb) and cadmium (Cd) both are harmful for humans as well as for the environment also, due to this reasons those batteries which contain these elements have been gradually replaced by NiMH batteries. But the major disadvantage for these types of batteries is efficiency and memory effect. Hence these batteries are also being replaced by lithium ion battery. Amongst all these batteries, the lead acid battery is relatively safe, affordable, and reliable having a long history associated with them. In the recent years of batteries life, a new type of battery containing $LiFePO_4$ has been developed having its higher security and discharge power, so its cycle life is greater than other batteries **[5].**

TABLE 1
Technical Comparison b/w Different Rechargeable Batteries

Type	Lead Acid battery	NiCad battery	NiMH battery	$LiCoO_2$ battery	$LiMn_2O_4$ battery	$LiFePO_4$ battery
Rated Voltage	2V	1.2V	1.2V	3.7V	3.7V	3.3 V
Security	Good	Good	Good	Bad	Middle	Good
Energy eff.	60%	75%	70%	90%	90%	95%
Cycle life	400	500	500	>500	>500	>2000
Charge time	8hours	1.5hours	2hours	2-4hours	2-4 hours	<2 hours
Self Discharge	20%/Month	30%/Month	35%/Month	10%/Month	10%/Month	8%/Month

As a matter of fact, there is no single energy storage device or technology that can meet the requirements of the all types of power system appliances and applications. Detailed analysis of electrical energy storage technologies have been conducted by [6] which has been tabulated below providing the comprehensive technical aspects, performance parameters and characteristics of these battery technologies.

Different optimization, programming and analysis techniques have extensively been employed in the field of energy storage technologies. A brief study of recent developments in this field has been tabulated below indicating significant operating factors, output objective functions, methods and techniques used by different authors and finally the conclusions of these studies have been presented. The literature review proposes that the batteries output power and efficiency can be optimization and improved in much better way if we apply the latest programming and optimization techniques like simulation, multicriteria decision making, response surface methodology etc in these energy storage technologies.

TABLE 2
TECHNICAL CHARACTERISTICS OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Technology	Energy density (Wh/L)	Specific energy (Wh/kg)	Power rating (MW)	Daily self-discharge (%)	Lifetime (years)	Discharge efficiency (%)
PHS	0.5–1.5, 1–2	0.5–1.5	100–5000,	Very small	40–60	87
Large–scale CAES	3–6 , 2–6	30–60	Up to 300	Small, Almost zero	20–40, 30, 20+	70–79
Overground small CAES	higher than large scale CAES	140 at 300 bar	0.003–3	Very small	23+	75–90
Flywheel	20–80	10–30 , 5–100	<0.25	100, >20% / hour	15, 15+,20	90–93
Lead–acid	50–80, 50–90	30–50, 25–50	0–20	0.1–0.3 , <0.1 , 0.2	5–15,	85
Li-ion	200–500, 200–400	75–200,90,120-200	0.05–10	0.1–0.3	5– 15, 14–16	85
NaS	150–250, 150–300	150–240, 100-174	0–0.1	Almost zero	10–15, 12–20	85
NiCd	60–150, 15–80	50–75, 45–80	<8	0.2–0.6,0.3,	10–20, 3–20	85
VRB	16–33, 25–35	10–30	0–40	Small , very low	5–10, 20	75–82
ZnBr	30–60, 55–65	30–50,80	0.03–3	Small	5–10, 8–10	60–70
PSB	20–30	15–30	0.05–2 , 1–10	Almost zero	10–15, 15	–
Capacitor	2–10, 0.05	0.05–5 ,<0.05	1–15	40,	5, 1–10	75–90
Super- capacitor	10–30, 10–30	2.5–15, 0.05–15	0–0.05	20–40	10–30, 10–12	95
SMES	0.2–2., 6	0.5–5, 10–75	0–0.3	10–15	20+, 30	95
Solar fuel	500–10,000	800–100,000	0.1–10	Almost zero	–	–
Hydrogen Fuel cell	500–3000	800–10,000	<50	Almost zero	5–15, 20	59
TES	80–120, 120–200, 200	80–120, 80–200	0.1–300	0.05–1	10–20, 5–15,	–
Liquid air Storage	4–6 times than CAES	214	10–200	Small	25+	–

Fig 1 presented below comprehensively describes the overview of past researches being done in the field of rechargeable batteries. It clearly explains the relationship between battery types, significant factors and objective or goals of the researchers. According to the past research being shown in the figure, most of the researchers have focused their research on lead acid and Li-Ion batteries or all type of batteries. Similarly the mostly used significant factors were discharge rate, temperature and voltage. From objectives point of view, it can be seen that most of the researchers have focused to optimize and manage the energy as well as the capacity of the rechargeable batteries.

In continuing the above scenario, figure 2 describes the methods and techniques being applied by the same researchers in their respective research paper. The trend in these studies shows that various optimization and management techniques or algorithms have been used in the field of rechargeable batteries. The most common techniques being used were programming [15], simulation [11], [17], [19], [27], optimization [9],[20], [26], fuzzy logic [16],[22], mathematical modeling [10], [24] and algorithms [3].

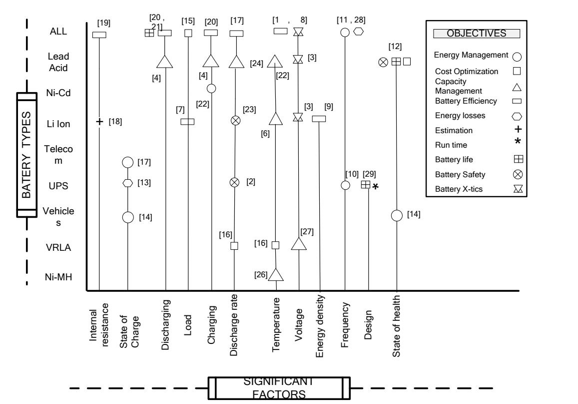

Fig. 1. Graphical Literature Review of Lead Acid Batteries operating parameters.

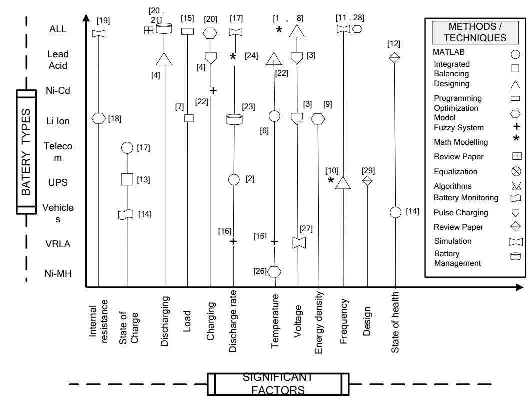

Fig. 2. Graphical Literature Review of Lead Acid Batteris performance opmtimization techniques.

3 Experimental Setup

3.1 Technical Specifications of Batteries

After the comprehensive literature review of different types of rechargeable batteries. Sealed deep cycle lead acid batteries have been selected for this particular research on the basis of following reasons.

a. Inexpensive and simple to manufacture; low cost per watt-hour
b. Low self-discharge; lowest among rechargeable batteries
c. High specific power, capable of high discharge currents
d. Good low and high temperature performance

TABLE 3
Technical Specifications of Lead Acid Batteries

Type	20 Hrs Rating	Plates Per Cell	Dimensions (mm) L	W	H	Terminal	Terminal Type	Acid Vol/ Cell (ml)	Dry Weight (Kg)
N65Z	65	11	257	170	204	228	B	800	12
N65ZL	65	11	257	170	204	228	B	800	12
T-15	100	15	365	168	204	228	B	980	16
6X15	100	15	365	168	204	228	B	980	16
N145	150	23	503	180	211	237	B	1450	24.5
LV200D	200	27	503	221	211	237	B	1570	29.1
UPS200	200	27	503	220	237	255	B	1570	29.1
N200	220	31	502	218	210	232	B	1580	30

Eight different brands of lead acid batteries have been selected for experimentation purpose. These batteries were most commonly used in residential sector for backup purpose as well as in transportation for ignition purpose. The technical specifications of these batteries being chosen are as shown in Table-3.

3.2 Experimental Procedure

First of all this section explains the details regarding lead acid batteries composition, experimental samples & setup, output response parameters calculation and other assumptions being made. The technical compositions of the lead acid batteries which have been used for the experimentation process are mentioned in Table # 4 below which explains its manufacturing components as well as conditions for its safe operational use.

• *Aatif Jawad Khan has currently completed masters degree program in engineering management from UET Taxila Pakistan, PH-+923360938599. Enrolment # 14-UET-MSc-EM/FT-01, E-mail: aatif.uet115@gmail.com*
• *Salman Hussain is currently teaching in bachelors degree program at UET Taxila Pakistan, PH-+92519047828. E-mail: salman.hussain@uettaxila.edu.pk*

The technical composition of these lead acid batteries have been verified from a leading lead acid batteries manufacturer in Pakistan named as Pakistan Accumulators Private Limited ISO 9000-14000 certified. The experiment was performed on lead acid batteries having the brand name of VOLTA/OSAKA. Fully charged batteries have been completely discharged at different current and temperature levels. Then their delivered output capacity and electric energy have been measured.

The main objective of this research is to optimize the operating parameters so that the maximum utilization of these batteries could be obtained. The operating parameters have been finalized after the detailed literature review of past relevant papers, the response variables were output capacity and electrical energy deliver by the stationary battery. The design space have been finalized and reviewed on the basis of literature review whereas the experimental runs were performed on UPS lead acid batteries.

TABLE 4

TECHNICAL SPECIFICATIONS OF LEAD ACID BATTERIES

Pb	Sb	Acid Gravity	Acid gravity	Upper voltage limit	Lower voltage limit	Battery age limit	Battery manufacturer	Container type
%	%	full charged level	full discharge level	volts	volts	months	Company name	material
97	03	1.275	1.125	13.5	10.5	03	PAL	Polypropylene

Experimental runs have been performed by maintaining the above mentioned levels. The first output response of delivered capacity was measured using digital multimeter and temperature sensor, whereas the second response of electrical energy delivered has been calculated by developing a regression model between output power delivered at any instant and total time consumed during discharge. Then the area under the curve have been calculated which gave us the overall energy consumed by the load.

TABLE 5

OPERATING PARAMETERS WITH THEIR DESIGN SPACE

Operating Parameters	Units	Lower Level	Central Level	Upper Level
Discharge Rate	Ampere	10	20	30
Temperature	Centigrade	15	25	35
Battery Rating	Amp Hour	100	150	200

3.3 Experimental Design

Response Surface Methodology (RSM) technique has been used for the analysis, modeling and optimization of our response variables under different operating conditions. The operating parameters of discharge rate **[A],** battery rated nameplate capacity **[B]** and temperature **[C]** have been used to evaluate and analyze our response variables. As it is known that in RSM method when all the input parameters are controllable as well as measureable with negligible variation or residuals, then the response surface can be explained using the following expression.

$$Y = f(A, B, C) \quad (1)$$

Practically it is desirable to construct the actual response of that particular model under those operating conditions. Either linear first order or quadratic second order model predict the closer response with minimum residual depend upon the nature of experiments being conducted. The equation representing the first and second order model is expressed respectively as below.

$$Y = \beta 0 + \beta 1 X1 + \beta 2\, X2 + \beta 3\, X3 + \varepsilon \quad (2)$$

$$Y = \beta 0 + \beta 1\, X1 + \beta 2\, X2 + \beta 3\, X3 + \beta 4\, X1\, X2 + \beta 5\, X2\, X3 + \beta 6\, X1\, X3 + \varepsilon \quad (3)$$

Where $\beta_{0\rightarrow6}$ are the coefficient or approximating functions of the parameters, $X_{1\rightarrow3}$ are input parameters whereas "Y" is response of this model.

3.4 Central Composite Design

Experiments performed in this research are then analyzed using faced central composite design. In central composite design, if there are "n" no of factors under consideration, then the total number of experiments in Central Composite Design becomes:

$$N = 2^n + 2n + C \quad (4)$$

In the relation mentioned above, 2^n are the factorial points, 2n are the axial points and "C" are the number of centre points. The first factor of discharge rate has been varied from 3.2A to 36.8A, the battery rating have been varied from 66AH to 234AAH whereas the ambient temperature has been varied from 8^0C to 42^0C. As in our case there were 03 numbers of factors, the total number of 20 experiments have been obtained. The complete design matrix of all the experimental runs along with their responses in given below in table.

Table 6
Design Matrix

Run	Factor 1	Factor 2	Factor 3	Coded Values			Response 1	Response 2
	Discharge Rate	Batery Rating	Temperature	Amp	AH	^0C	Capacity Efficiency	Energy Delivered
	Amp	AH	^0C	A	B	C	%	KWh
1	20.0	150	25	0	0	0	77.00	1.38
2	20.0	150	25	0	0	0	75.67	1.36
3	10.0	100	35	-1	-1	+1	77.90	0.93
4	30.0	200	15	+1	+1	-1	61.25	1.46
5	20.0	066	25	0	-1.68	0	53.94	0.44
6	03.2	150	25	-1.68	0	0	92.20	1.66
7	30.0	100	35	+1	-1	+1	63.70	0.76
8	10.0	100	15	-1	-1	-1	67.30	0.80
9	36.8	150	25	+1.68	0	0	59.53	1.07
10	20.0	150	8	0	0	-1.68	55.73	1.01
11	20.0	234	25	0	+1.68	0	79.36	2.13
12	30.0	100	15	+1	-1	-1	55.20	0.66
13	30.0	200	35	+1	+1	+1	78.45	1.88
14	10.0	200	35	-1	+1	+1	90.30	2.18
15	20.0	150	25	0	0	0	71.93	1.30
16	10.0	200	15	-1	+1	-1	80.20	1.92
17	20.0	150	42	0	0	+1.68	83.00	1.41
18	20.0	150	25	0	0	0	73.00	1.31
19	20.0	150	25	0	0	0	75.00	1.35
20	20.0	150	25	0	0	0	73.67	1.32

4 Results & Discussion

4.1 Development of Mathematical Model

In order to properly analyze the output response and develop a mathematical model of this response, Design Expert Software has been used to formulate the model whereas validity of the proposed model has been verified using analysis of variance (ANOVA) technique.

4.2 Capacity Efficiency

The fit summary for the first response of delivered capacity shows the quadratic behavior as the best fit model. The results of ANOVA showed that A, B, C & B^2 were the significant model terms. Values of "Prob > F" less than 0.05 indicate that these model terms are significant whereas other terms are insignificant. The values of R^2, adjusted R^2 and predicted R^2 are much close to 1 indicating the strong relationship between actual and predicted values of the given model. The final mathematical term representing the 2FI model considering the actual input factors is given in below equation as:

Capacity Efficiency
= 33.848 -1.135 * Discharge Rate +0.394 * Battery Rating +0.982 * Temperature -0.001125 * Discharge Rate * Battery Rating +0.00625 * Discharge Rate * Temperature +0.00205 * Battery Rating * Temperature +0.020008191 * Discharge Rate^2 -0.0009758 * Battery Rating^2 -0.0147 * Temperature^2 (5)

Table-7 Model Summary (Capacity Efficiency)

Std. Dev.	**2.90**	**R-Square**	**0.9641**
Mean	**72.22**	**Adj R-Squared**	**0.9318**
C.V. %	**4.02**	**Pred R-Squared**	**0.7656**
PRESS	**550.16**	**Adeq Precision**	**20.911**

ANOVA for Response Surface 2FI Model (Capacity Utilization)

Source	Sum of Squares	df	Mean Square	F Value	P Value P>F
Model	**2262.72**	**9**	**251.41**	**29.83**	**< 0.0001**
A-Discharge Rate	***919.15***	**1**	***919.15***	***109.04***	***< 0.0001***
B-Battery Rating	***578.05***	**1**	***578.05***	***68.58***	***< 0.0001***
C-Temperature	**623.23**	**1**	***623.23***	***73.93***	***< 0.0001***
AB	***2.53***	**1**	***2.53***	***0.30***	***0.5957***
AC	***3.13***	**1**	***3.13***	***0.37***	***0.5562***
BC	***8.41***	**1**	***8.41***	***1.00***	***0.3416***
A^2	**9.67**	**1**	**9.67**	**1.15**	**0.3093**
B^2	**85.78**	**1**	**85.67**	**10.18**	**0.0097**
C^2	**31.52**	**1**	**31.52**	**3.78**	**0.0819**
Residual	**84.29**	**10**	**8.43**		

4.3 Energy Consumption

The fit summary for the second response of Energy Consumption shows the quadratic behavior as the best fit model. The results of ANOVA showed that A, B, C, AB, BC and C^2 were the significant model terms. Values of "Prob > F" less than 0.0500 indicate that these model terms are significant whereas all other terms are insignificant. The values of R^2, adjusted R^2 and predicted R^2 are much close to 1 like in previous case indicating again the strong relationship between actual and predicted values of the proposed model. The final mathematical term representing the quadratic model considering the actual input factors is given in below equation as. The final mathematical term representing the mathematical relationship betwwen input and reponse vriable is:

$$\text{Energy Delivered} = -0.297 - 0.01 * \text{Discharge Rate} + 0.01 * \text{Battery Rating} + 0.01 * \text{Temperature} - 0.0001112 * \text{Discharge Rate} * \text{Battery Rating} + 0.000178 * \text{Discharge Rate} * \text{Temperature} + 0.000107 * \text{Battery Rating} * \text{Temperature} + 0.000182 * \text{Discharge Rate}^2 - 0.000003671 * \text{Battery Rating}^2 - 0.0003663 * \text{Temperature}^2 \quad (6)$$

Table-8 Model Summary

Std. Dev.	**0.050**	**R-Squared**	**0.9941**
Mean	**1.32**	**Adj R-Squared**	**0.9888**
C.V. %	**3.82**	**Pred R-Squared**	**0.9611**
PRESS	**0.17**	**Adeq Precision**	**49.264**

ANOVA for Response Surface Quadratic Model (Energ Delivered)

Source	S.S	df	Mean Square	F Value	P Value P>F
Model	4.30	9	0.477	187.62	< 0.0001
A	*0.31*	1	*0.31*	*122.68*	*< 0.0001*
B	*3.72*	1	*3.72*	*1463.20*	*< 0.0001*
C	*0.18*	1	*0.18*	*72.35*	*< 0.0001*
AB	*0.02*	1	*0.02*	*9.71*	*0.0110*
AC	*0.002*	1	*0.002*	*1.00*	*0.3420*
BC	*0.02*	1	*0.02*	*9.00*	*0.0134*
A2	*0.004*	1	*0.004*	*1.87*	*0.2009*
B2	*0.001*	1	*0.001*	*0.48*	*0.5057*
C2	*0.019*	1	*0.019*	*7.59*	*0.0203*
Residual	0.025	10	0.0025		

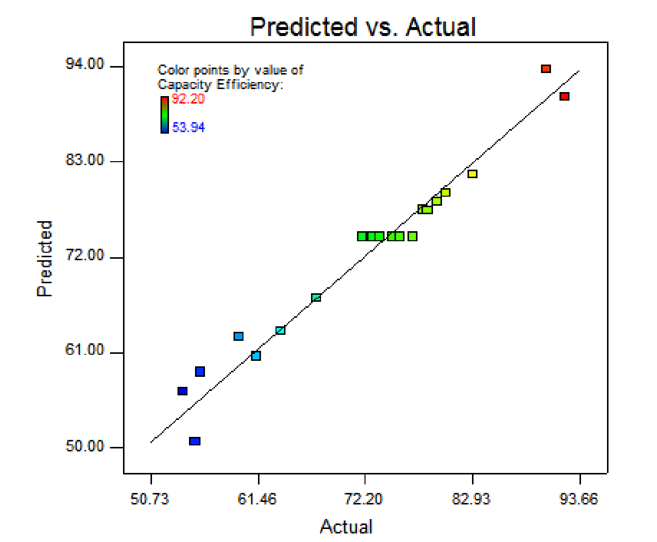

Fig. 3. Actual and predicted values for first response variable (capacity efficiency).

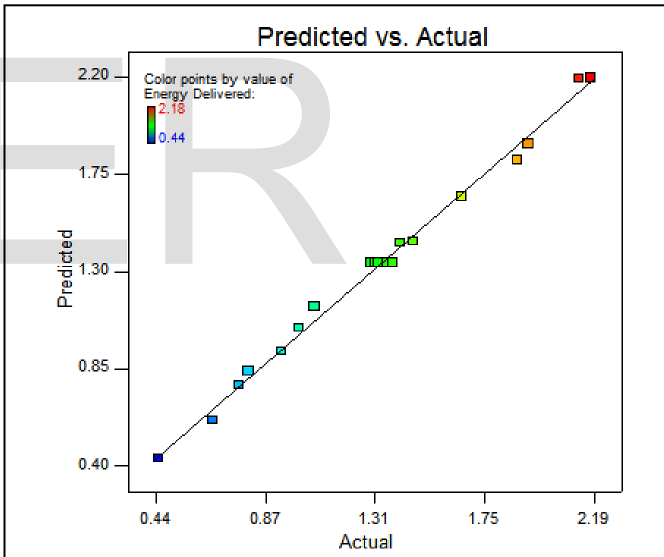

Fig. 4. Actual and predicted values for second response variable (energy delivered).

4.3 Adequacy measure and validation of the developed model

After statistical analysis of the proposed model, the mathematical model developed has been verified. Results analysis of the proposed model presented below in figures indicates that there is a strong relationship between the predicted regression line and actual values taken from experiments, minors errors are also distributed normally. This model indicates that the model proposed is adequate for predicting the delivered capacity as well as energy under different operating conditions.

In order to validate our model experimentally, five confirmation tests have been conducted randomly on different lead acid batteries manufactured by the same company. The values of operating parameters have been chosen randomly from out of the domain which has been taken in our case. Then the results of these experiments have been tabulated and compared with the predicted results of our proposed model. In order to compare the results, the percentage error has been calculated using the expression;

Percentage error = (pred. values-actual values)*100/pred. values (7)

TABLE 9
COMPARISON B/W ACTUAL & PREDICTED RESPONSES

Experiment No.	Parameters			Predicted responses		Actual responses		Percentage Error	
	Discharge rate	Battery rating	Temperature	Capacity utilization %	Delivered Energy KWH	Capacity utilization %	Delivered Energy KWH	Capacity utilization	Delivered Energy
1	25	175	11	66.8	1.03	62.55	1.1	6.36	6.79
2	18.4	115	25	73.87	0.856	78.47	0.91	6.22	6.54
3	10.1	60	12	55.77	0.305	53.78	0.33	3.56	8.19
4	7.5	50	13	55.52	0.242	52.29	0.25	5.81	5.37
5	2.3	45	15	60	0.257	58.6	0.28	2.33	8.94
6	12.5	75	12	58.24	0.422	55.99	0.41	3.86	2.84

The results of this comparison model showed that there is less error between actual as well as predicted values (less than 10%) within a certain limit of operating parameters. By increasing the discharge rate level more than 50 Amps and reducing the battery rating below 10 AH level, the model remains no more useful and significant. Within these boundary conditions, this model predicts the delivered capacity as well as energy in an acceptable and feasible way with minor level of tolerance.

4.4 3-D Response Surface

3D graphs analysis of response surface for both output variables have been shown in figure 4 & 5. Figure 4 (a, b & c) represents the response graph for the delivered capacity between two variables by taking the third variable at fixed and constant level. The response graphs represents the behavior of output variable w.r.t any two of the operating parameters effecting simultaneously by keeping the third parameter at its centre level. Our objective in this particular study was to maximize the response variable under defined operating parameters. It can be easily observed from these graphs that the delivered capacity of the lead acid batteries maximizes with the increase in temperature and battery rating but it decreases with increase in discharge rate.

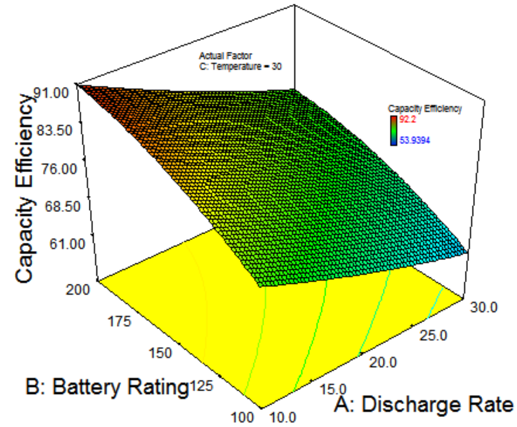

Fig. 5. 3-D analysis of response surface graph for delivered capacity under constant temperature.

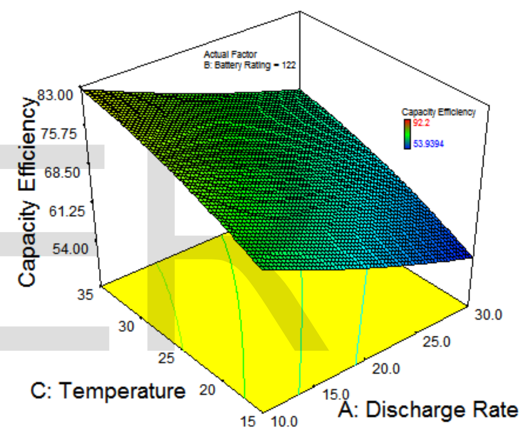

Fig. 6. 3-D analysis of response surface graph for delivered capacity under constant battery rating.

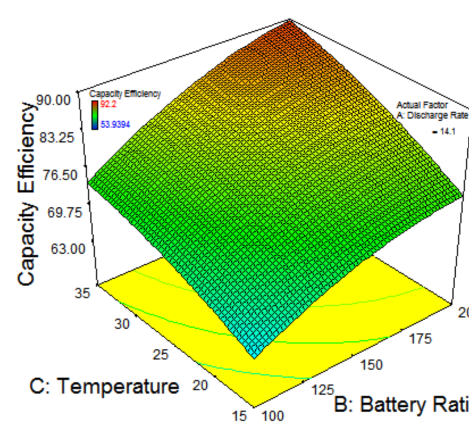

Fig. 7. 3-D analysis of response surface graph for delivered capacity under constant discharge rate.

We can also define and adjust our response variable to a desired range in order to analyze and calculate the particular level of operating conditions in order to attain that desired value of that output response. Figure 4-d is explaining this scenario in which we for example desire to obtain the output capacity in the range of 100 to 110 AH region, then we have to set our operating parameters in this feasible region in order to achieve our objective.

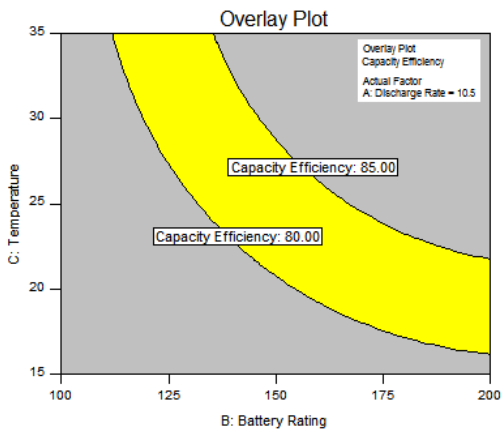

Fig. 8. 2-D overlay plot of adjusted output response indicating specific area of operations (Factor A; discharge rate is constant).

In the same manner, analysis has been made on the second response variable of Energy Consumption. The response graphs indicating the behavior of energy delivered under the operating conditions of discharge rate, battery rating and temperature. Two parameters have been analyzed simultaneously by making the third variable constant. From the 3D graph plots, it can be observed that energy delivered by the lead acid batteries maximizes with the increase in temperature and battery rating but it decreases with increase in discharge rate.

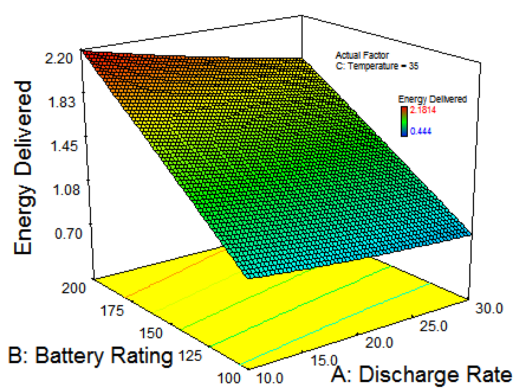

Fig. 9. 3-D response surface graph for Energy Consumption under constant temperature.

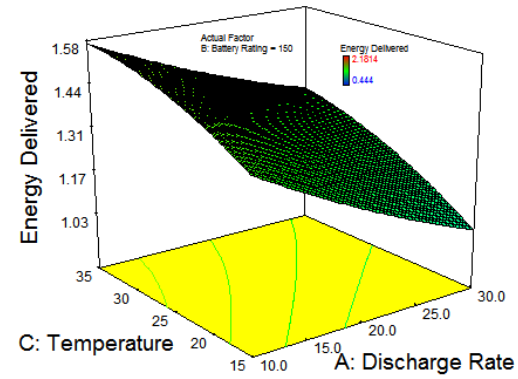

Fig. 10. 3-D response surface graph for Energy Consumption under constant battery rating.

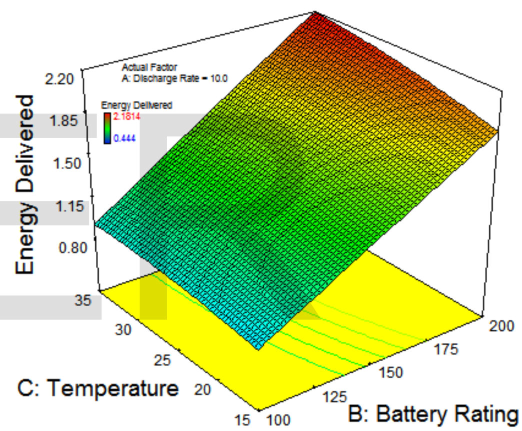

Fig. 11. 3-D response surface graph for Energy Consumption under constant discharge rate.

As previously analyzed, we can also define and adjust our output response variable to a desired certain range in order to find the level of operating conditions to attain that particular desired value of output response. Next 2D graph plot is explaining this scenario in which we for example want to obtain the output energy from the batteries in the range of 1000 Wh to 1100 Wh region, then we have to set our operating parameters in a particular feasible region in order to achieve our objectives. In the below mention plot, the third factor of enironment temperature have been kept at constant level and the other two parameters have been analysed under the given condition.

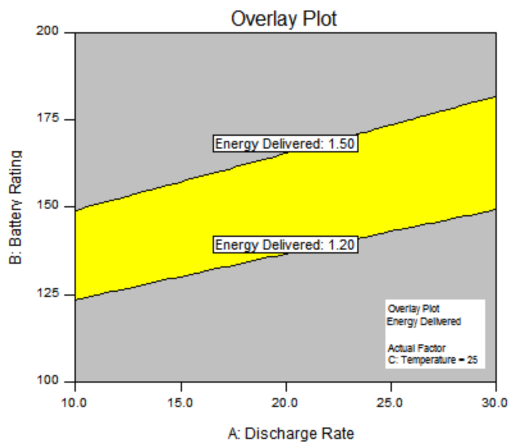

Fig. 12. 2-D overlay plot of adjusted output response of energyconsumption; indicating specific area of operations.

5 Conclusions

Battery is a product which is sold for certain period of warranty time and after this time it has to be expired. The customer's requires proper education as it is consider being an electronic product and has long service life as T.V, Refrigerator, Cell phones, etc. But they are unaware of the fact that if battery handled with care, it also gives good service life. It is impossible to bring battery's defects to 0 % but can be minimize to acceptable limit with joint co-operation of production department, quality control, dealer's & customer's proper training and education. .

Battery is a device which shows different characteristics and behaves differently under different operating conditions. Hence like other electronic and control equipments, the battery can also be controlled and managed up to a certain limit to obtain better results from it. Overcharging, undercharging, and overheating, under heating as well as long duration of standby use effects on its performance. Within these limitations there is a certain feasible region of operation where the battery performs in a much better way by saving the energy being consumed as well as longer service life.

These models are same like battery management system which is an electronic system to manage and control the rechargeable battery by protecting it from operating outside the given operating conditions. A BMS can monitor the state of the battery by measuring its various characteristics like voltage, current, temperature, State of charge and state of health etc. Additionally a BMS can also calculate the maximum level of charge and discharge current, energy and charge deliver to the load or taken from the source. Finally a BMS may also be used to protect the battery from overcharge, undercharge, over voltage, under voltage, over temperature and under temperature.

Acknowledgement

The authors feel great pleasure and thanks to the management of the Volta Batteries (Private) Limited Pakistan company for providing valueable information and assistance regarding experimentation phase.

References

[1] Kang, J., et al., *A novel way to calculate energy efficiency for rechargeable batteries*. Journal of Power Sources, 2012. **206**: p. 310-314.

[2] Lahyani, A., et al., *Battery/supercapacitors combination in uninterruptible power supply (UPS)*. Power Electronics, IEEE Transactions on, 2013. **28**(4): p. 1509-1522.

[3] Lee, S.-R., et al. *Battery balancing algorithm for serial multi-module UPS system*. in *Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014 IEEE Conference and Expo*. 2014. IEEE.

[4] Meena, N., et al. *Charging and discharging characteristics of Lead acid and Li-ion batteries*. in *Power and Energy Systems Conference: Towards Sustainable Energy, 2014*. 2014. IEEE.

[5] Syue, B. *Charge and discharge characteristics of lead-acid battery and LiFePO4 battery*. in *Power Electronics Conference (IPEC), 2010 International*. 2010. IEEE.

[6] Luo, X., et al., *Overview of current development in electrical energy storage technologies and the application potential in power system operation*. Applied Energy, 2015. **137**: p. 511-536.

[7] Muenzel, V., et al., *Battery Management using Secondary Loads: A Novel Integrated Approach⋆*. Cell, 2014. **6**(S5): p. S7.

[8] Pavkovic, D., et al. *Battery current and voltage control system design with charging application*. in *Control Applications (CCA), 2014 IEEE Conference on*. 2014. IEEE.

[9] Golmon, S., K. Maute, and M.L. Dunn, *A design optimization methodology for Li+ batteries*. Journal of Power Sources, 2014. **253**: p. 239-250.

[10] Zhan, Y., et al., *Power and energy management of grid/PEMFC/battery/supercapacitor hybrid power sources for UPS applications*. International Journal of Electrical Power & Energy Systems, 2015. **67**: p. 598-612.

[11] Oudalov, A., D. Chartouni, and C. Ohler, *Optimizing a battery energy storage system for primary frequency control*. Power Systems, IEEE Transactions on, 2007. **22**(3): p. 1259-1266.

[12] Goodenough, J.B., *Rechargeable batteries: challenges old and new*. Journal of Solid State Electrochemistry, 2012. **16**(6): p. 2019-2029.

[13] Erdinc, O., B. Vural, and M. Uzunoglu. *A dynamic lithium-ion battery model considering the effects of temperature and capacity fading*. in *Clean Electrical Power, 2009 International Conference on*. 2009. IEEE.

[14] Thyagarajan, A., R.R. Prabu, and G. Uma, *Battery Monitoring and Power Management for Automotive Systems*. American Journal of Energy Research, 2014. **2**(1): p. 1-8.

[15] Riffonneau, Y., et al., *Optimal power flow management for grid connected PV systems with batteries*. Sustainable Energy, IEEE Transactions on, 2011. **2**(3): p. 309-320.

[16] Pascoe, P.E. and A.H. Anbuky. *VRLA battery capacity estimation using soft computing analysis of the Coup de Fouet region*. in *Telecommunications Energy Conference, 2000. INTELEC. Twenty-second International*. 2000. IEEE.

[17] Carter, R., A. Cruden, and P.J. Hall, *Optimizing for efficiency or battery life in a battery/supercapacitor electric vehicle.* Vehicular Technology, IEEE Transactions on, 2012. **61**(4): p. 1526-1533.
[18] Zhang, Q. and R.E. White, *Capacity fade analysis of a lithium ion cell.* Journal of Power Sources, 2008. **179**(2): p. 793-798.
[19] Johnson, V., *Battery performance models in ADVISOR.* Journal of Power Sources, 2002. **110**(2): p. 321-329.
[20] Chiasserini, C.-F. and R.R. Rao, *Improving battery performance by using traffic shaping techniques.* Selected Areas in Communications, IEEE Journal on, 2001. **19**(7): p. 1385-1394.
[21] Benini, L., et al., *Discharge current steering for battery lifetime optimization.* Computers, IEEE Transactions on, 2003. **52**(8): p. 985-995.
[22] Surmann, H., *Genetic optimization of a fuzzy system for charging batteries.* Industrial Electronics, IEEE Transactions on, 1996. **43**(5): p. 541-548.
[23] Kitoh, K. and H. Nemoto, *100 Wh Large size Li-ion batteries and safety tests.* Journal of Power Sources, 1999. **81**: p. 887-890.
[24] Casacca, M.A. and Z.M. Salameh, *Determination of lead-acid battery capacity via mathematical modeling techniques.* Energy Conversion, IEEE Transactions on, 1992. **7**(3): p. 442-446.
[25] Casacca, M.A., M.R. Capobianco, and Z.M. Salameh, *Lead acid battery storage configurations for improved available capacity.* Energy Conversion, IEEE Transactions on, 1996. **11**(1): p. 139-145.
[26] Heacock, D. and D. Freeman. *Capacity monitoring in advanced battery chemistries*. in *Battery Conference on Applications and Advances, 1995., Proceedings of the Tenth Annual*. 1995. IEEE.
[27] Anbuky, A.H. and P.E. Pascoe, *VRLA battery state-of-charge estimation in telecommunication power systems.* Industrial Electronics, IEEE Transactions on, 2000. **47**(3): p. 565-573.
[28] Dougal, R.A., S. Liu, and R.E. White, *Power and life extension of battery-ultracapacitor hybrids.* Components and Packaging Technologies, IEEE Transactions on, 2002. **25**(1): p. 120-131.
[29] Essig, B. and G. Braun. *Selecting batteries for uninterruptible power supply systems*. in *Applied Power Electronics Conference and Exposition, 1991. APEC'91. Conference Proceedings, 1991., Sixth Annual*. 1991. IEEE.