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State of Health Estimation of VRLA Batteries Using Vibration Tools.

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Abstract—VRLA batteries are widely accepted primary source of energy for electrical vehicles due to their cost efficiency and will remain in the near future. Despite this advantage, VRLA batteries are prone to acute as well as chronic defects due to continual usage, and they may develop various faults during their use such as reduction of electrolyte, sulphonation, etc. These faults degrade the battery performance. To sustain battery performance we must continuously measure and monitor state of health and state of charge of the battery. Various methods to measure state of charge have been discussed. And to monitor the health of batteries a vibration sensor is attached to the external surface of the cell. Real time data from the vibration sensor is used to non-destructively evaluate the internal condition of vital interfaces inside the cell. Hence pre-emptive measures are taken against any incipient faults and defects to prevent any further damage to the battery. A regular data of the vibration for batteries used in vehicles may prove to be helpful in realizing the need of repair or replacement. To collect this data a set of vibration sensors are used along with a set-up placed around a battery and a microcontroller for data acquisition from the sensors. This data is then plotted on a graph which is then matched with previously made graphs to understand the type defect that has taken place in the battery or the period of its life it is going through.

Keywords— *Battery management system, Lead Acid, battery, battery health monitoring, State of Health, State of Charge,*

I. Introduction

The lead-acid battery industry has been in existence for more than 150 years. With a proven arrangement for reliable and low-cost energy storage, lead-acid battery plays an important role in our day-to-day life. The next wave of lead-acid battery adoption could come from EVs, but it would mean auto manufacturers opting for lead charge batteries over lithium-ion batteries.

While lithium-ion batteries have built a remarkable presence, lead-acid batteries are still decades ahead in terms of production costs, adoption and recycling because lead-acid batteries are 99% recyclable-making them the biggest contender for EVs and renewable energy storage solutions.

With the phased adoption of electric vehicles, the entire supply chain of the automobile industry is expected to be affected. All the major value drivers such as battery, motor, controller, chargers, and other electronics are currently being imported from other countries. India also does not have reserves of key raw materials for all the major components such as lithium, cobalt, permanent magnets etc. Sustained policy support to bridge large cost gap and improve consideration for initial customers.[8] Followed by achieving the critical mass demand and supporting EV research, supply chain localization and value retainment has to be taken care by the State of Health of Batteries, its condition monitoring and economical to EV users. Finally, leading to higher scale of domestic production has the potential sustainably reduce the vehicle cost for customers. The value chain comprises raw material processing, and manufacturing of separators, cathodes, electrolyte, anode, cell and finally the battery storage packs.

With India only manufacturing battery storage packs and relying on Chinese imports for the rest, the aim is to become self-sufficient across the value chain by 2025. So, in order to become self-sufficient, lead-acid batteries will again take over the Indian market. Indian lead-acid battery market is projected to reach $7.6 billion by 2025. So researching and developing the Battery Monitoring System of lead-acid batteries becomes essential to help them penetrate into the Indian market and make the country completely self-reliant in manufacturing of Electric Vehicles.

The number of vehicles registered is estimated using the [8] reports which has done a survey at national level as shown in below table :

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Table 1 Surveyed number of Vehicles [8]

Year	2W	3W	Cars –Jeeps	Buses
2004-08	9.8%	7.6%	10.5%	16.8%
2008-12	11.3%	9.9%	11.3%	4.1%
2012-16	10.0%	10.8%	9.3%	1.2%

The automotive industry produced a total of 29.86 million vehicles including commercial vehicles, passenger vehicles, tractors, three-wheelers, two wheelers and quadricycle in the Financial Year (FY) 17–18. The two wheelers are the dominant automobile manufactured in India, accounting for 79.7% of the total vehicles manufactured in the FY 2017–18, followed by passenger vehicles (13.7%), three-wheelers (3.5%), and commercial vehicles (3.1%).

The below two graphs shown in figure 1 & figure 2 shows number of 2W (Two Wheeler) and 3W (Three Wheeler) Electric Vehicles Vs year shows a linear increase of purchase of Non-transport Electric Vehicles every year. It is predicted that in the coming years this linear relation of buying EVs would transform into an exponential function and there would be a steep rise in the EV mobility on Indian roads. The formula for calculation of a Day purchase of EVs:

$$\text{Therefore } Nevs = \frac{Np\ X0.1\ xNm\ x\ X20\ X\ 12}{No.of\ days\ X\ Span\ of\ Year} \quad \ldots\ldots\ldots\ldots(1)$$

Here,
Nevs = Total Nnumber of EVs,
Np =Number of Purchased Vehicle So Far,
Nm = Number of Models of Electric Vehicles
(NOTE – The data from which the graphs are plotted are of Gujarat State)

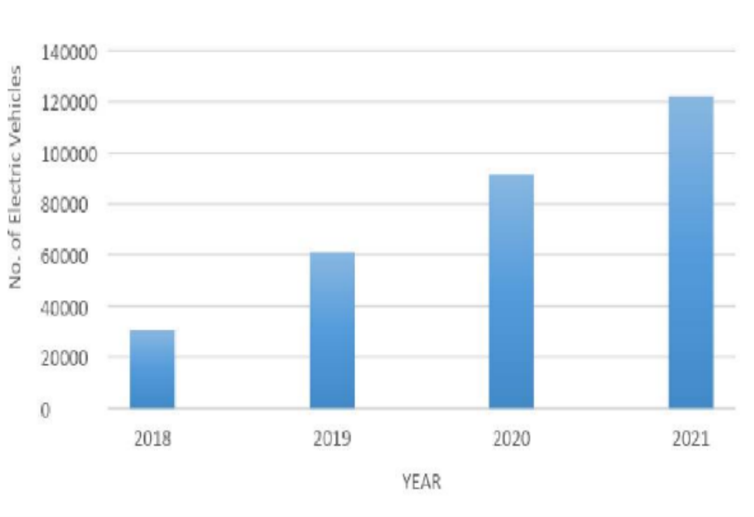

Figure 1. 3W EVs with LA Battery

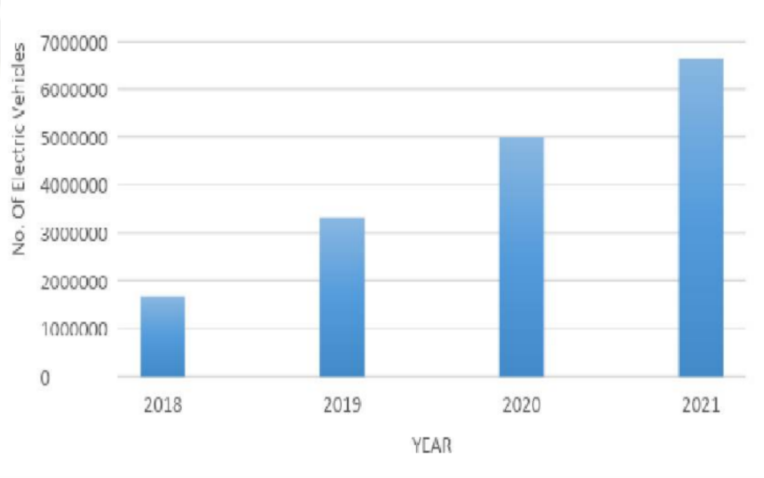

Figure 2. 2W EVs with LA Battery

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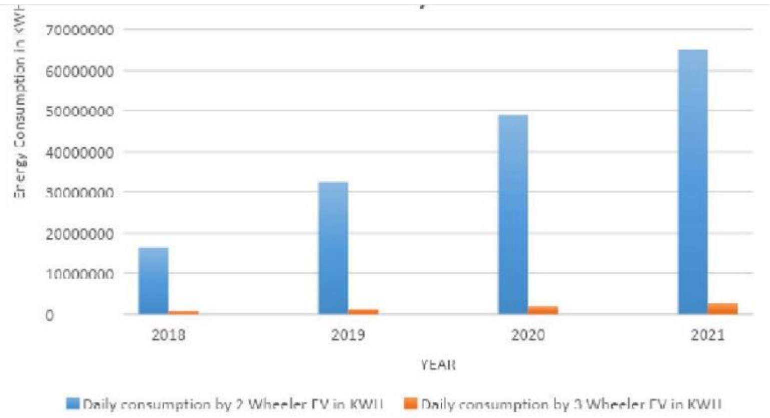

Figure 3. Daily Energy Consumption by EVs with LA Battery

From the above shown graph if the demand of Electric Vehicles increases as predicted then there will be huge demand for electrical energy in giga Watt hours. So to meet this demand, As per TERI report [8], Battery amounts to almost 40~50% of the EV cost. Localization of cell manufacturing will therefore help in reducing EV costs, and achieving self-sufficiency to ensure

a sustainable EV growth. Therefore, the use of renewable energy resources comes in the picture to meet the booming demand of power due to the increase in EVs and in turn there will be a need of renewable energy storage systems which will further increase the use of Lead-acid batteries not only in India but in the other parts of the world too due to its easy availability and its cost- effectiveness.

Formula for calculating Daily Energy consumption,

$$Energy = Nevs \text{ X } Eratev \ldots\ldots\ldots\ldots (2)$$

Nm = Number of Models of Electric Vehicles

(NOTE – Here the addition of battery capacity(in kWh) of all the EV models available in the market is to be taken for the above formula)

II. LA Battery:

This research work is focused on use of VRLA batteries (LABs). LABs has been around for over 100 years and will be a market force for the foreseeable future due to its low cost, established manufacturing base and wide acceptance due less complexity and better safety [2]. The significance of LABs is evident from the extensive use in automobiles as start-lighting-ignition (SLI), with power inverters in form of stationary power backup, and recently in Electric Vehicles (EVs) like e-rickshaws, Mahindra Reva, Hero 2-wheelers and several others. The electrodes are made of lead grids to maximize its surface area. The anode grid is filled with finely divided spongy lead (Pb) and the cathode grid is packed with lead dioxide (PbO_2). Both electrodes are submerged in sulfuric acid solution having a specific gravity of about 1.25 that acts as the electrolyte. Anode and cathode grids are separated by insulators like strips of wood, rubber or glass fiber. Overall Reaction in LAB is given below:

$$Pb(s) + PbO_2(s) + 4H^+(aq) + 2SO_4^{2-}(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l) \quad (3)$$

III. SIGNIFICANCE OF TEMPERATURE

The performance, life and cost of any EV are strongly affected by its battery pack. Operating temperature of the battery is critical to its performance and influences the availability of discharge power (for start-up and acceleration), energy, and charge acceptance during energy recovery from regenerative braking. These affect vehicle drive-ability and driving range. Higher operating temperature is responsible for degrading the battery life.

Therefore, ideally, batteries should operate within an optimum temperature range for the best performance and life. Various operational parameters that may be observed by battery monitoring equipment used in stationary applications, and the relative value of such observations can be helpful in finding the condition of battery. It does provide a means for establishing specifications for the desired parameters to be monitored [11]. The desired operating temperature depends on electrochemistry, for a LA Battery, it is 25°C to 45°C. However, since an EV will operate in a much wider temperature range (icy winters up to hot summers), therefore a smart Battery Monitoring System plays a crucial role and must be designed to take into account temperature effects while SoC estimation and charging process.

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IV. State of Charge Estimation

To estimate the performance analysis of a battery, like how much energy is stored in the battery and how quickly one can extract it we must know the state of charge and state of health of the battery. In general, the SoC of a battery is defined as the ratio of its current capacity (*Q(t)*) to the nominal capacity (*Qn*). The capacity of a battery shows the maximum amount of charge that can be stored in the battery and is stated by the manufacturer [5]. The SoC can be defined as follows:

$$SoC\ (t) = \frac{Q(t)}{Qn} \quad \text{.............................} (4)$$

There are various methods used for determining the SoC of the battery. These methods are mainly classified into the following categories– Direct measurement, Book- keeping estimation, Adaptive systems and Hybrid method[3,9].

A. Direct Measurement

Direct measurement methods refer to some physical battery properties such as the terminal voltage and impedance. There are many different direct methods have been employed to determine the SoC such as: terminal voltage method, open circuit voltage method, impedance measurement method, and impedance spectroscopy method. [7]

B. Book-Keeping Estimation

Book-keeping estimation method uses battery discharging current data as input. This method permits to include some internal battery effects as self-discharge, capacity-loss, and discharging efficiency. Two kinds of bookkeeping estimation methods have been employed: Coulomb counting method and modified Coulomb counting method. In Coulomb counting method we literally perform counting of coulomb which can be described by given formula:

$$SoC\ (t) = SoC(0) - \frac{1}{Q_n}\int_{t_0}^{t} \eta' i(\tau) d\tau \ \text{..............................} (5)$$

C. Adaptive System

Recently, with the development of artificial intelligence, various new adaptive systems for SoC estimation have been developed. The new developed methods include back propagation (BP) neural network, radial basis function (RBF) neural network, fuzzy logic methods, support vector machine, fuzzy neural network, and Kalman filter. The adaptive systems are self-designing ones that can be automatically adjusted in changing systems. As batteries have been affected by many chemical factors and have nonlinear SoC, adaptive systems offer good solutions for SoC estimation.

D. Hybrid Methods

The object of hybrid models is to benefit from the advantages of each method and obtain a globally optimal estimating performance. Since the information contained in the individual estimating method is limited, hybrid methods can maximize the available information, integrate individual model information, and make the best use of the advantages of multiple estimating methods thus improving the estimation accuracy. The literature shows that the hybrid methods generally produce good SoC estimating results compared to individual methods. The hybrid methods combine different approaches such as direct measurement method and book-keeping estimation method. In this paper, Hybrid method is used, in which booking-keeping estimation method is used for finding the static SoC based on OCV & temperature and direct estimation for determining the dynamic SoC based on charge flow.

The vibration stress has impact on the cell polarization resistance, while it significantly affects the ohmic resistance, OCV recovery, thermal measurement, and capacity of cells, respectively [12]. Thus the result of vibration of the batteries can be utilized for the SoC as well as SoH.

V. State Of Health Estimating

Battery health is one of the crucial parameters to be maintained because the state of health of the battery can directly affect the performance of the battery. One way to determine SOH of the battery is using Vibration analysis and Vibration estimating. [3,4,9]

A. Vibration Analysis and Vibration Monitoring

Vibration analysis is a method of looking for anomalies and monitoring change from the established vibration signature of a system. The vibration of any object in motion is characterized by variations of amplitude, intensity, and frequency. These can correlate to physical phenomena, making it possible to use vibration data to gain insights into the health of equipment

B. Vibration Measurement Technique

Although a number of sophisticated techniques can be used, the two most fundamental methods for presenting vibration data are the time waveform (amplitude as a function of time) and the frequency spectrum (amplitude as a function of frequency). Vibration analysis follows the general flow as described below.

C. Calculate the Expected Vibration Spectrum

Based on the features of a system, it is possible to model its vibration spectrum. For a given rotating asset, this would

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include an expected peak at the fundamental rotational frequency of the shaft, synchronous peaks (harmonics) based on additional components. In particular, electronic tools can be used to very effectively model expected system behavior.

D. Establish a Baseline

In order to effectively use vibration data for condition monitoring, it is important to establish a baseline. After all, not all vibration is sinister. There are many vibrations that are benign in nature and have no impact on the lifetime or performance of machinery. A baseline vibration spectrum makes it possible to identify these features.

D. Time-Waveform Analysis

Time-waveform analysis can enhance vibration analysis. It should not be considered a primary tool but rather as a tool to provide additional insights. It can be useful for low-speed applications because it reveals the way the machine is moving. Time-waveform analysis is frequently used for analyzing gears, for example. There is a crossover point at around 100 RPM – below that speed, time-waveform analysis provides better results and frequency analysis is not effective.

VI. VIBRATION SENSOR

Accelerometers are the preferred motion sensors for most vibration monitoring. They measure low to very high frequencies and are available in a variety of general purpose and application specific designs. The piezoelectric accelerometer is reliable, versatile, unmatched for frequency and amplitude range, and popular for machinery monitoring.

Figure 4. Vibration Sensor

VII. SET-UP

Six sensors are placed on four sides of one set of a battery. Two are placed on the wider side of the set and one on each of the narrower sides with the help of a Velcro belt. Each sensor has a cylinder comparator for vibration input. Whereas it has three pins: one for digital output, two for Vcc and ground. All the Vcc and ground pins are brought together using a breadboard and connected to the 5V and GND port of ARDUINO respectively. The digital output from the sensors is connected to the ARDUINO ports D2 to D7. This setup is placed on a motorized two wheeler to measure real-time vibrations of the battery set. The amplitude data is obtained from SERIAL MONITOR in ARDUINO IDE. The data is obtained for two paths, namely GO and RETURN. This data is then copied into a MICROSOFT EXCEL sheet for further analysis. This process is repeated for various battery sets.

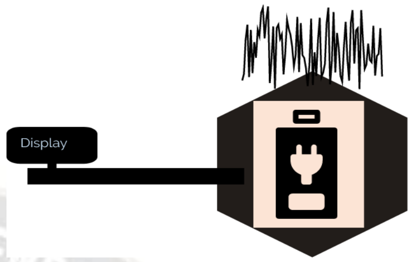

Figure 5. Block representation of setup

Figure 6. Vibration Analysis setup Actual

VIII. RESULT

The result has been captured using a standard and the unique path drive of the 2W and 3W vehicle. The path which was under test is common for all the test – full go, half go, empty go, and common for full return and empty return. The distance covered during this test is 300 meter. Other physical conditions were kept same during the test.

The test setup is shown in figure 5 which is having the memory to store the readings and later the readings were transferred to the system for plotting the graph.

A. Result for LA 2W Battery (12V & 2.5 A)

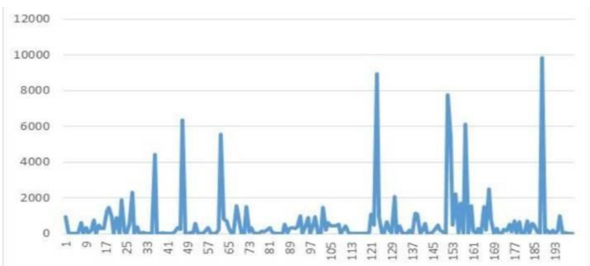

Figure 7. LA Battery of 2W_full_go

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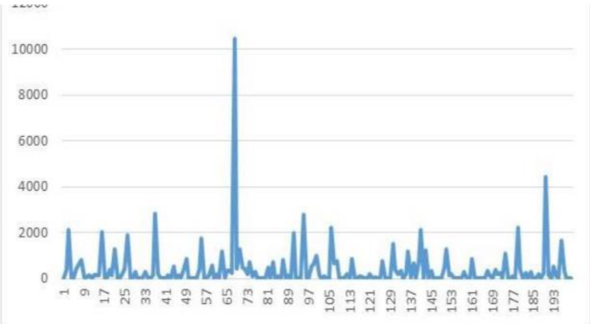

Figure 8. LA Battery of 2W_empty_go

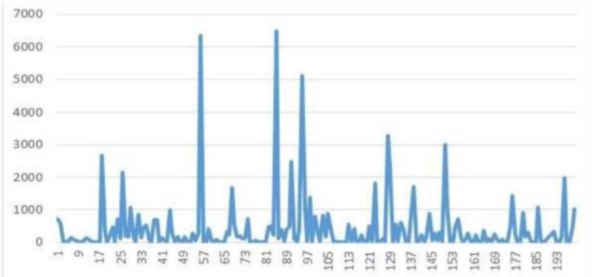

Figure 9. LA Battery of 2W_full_return

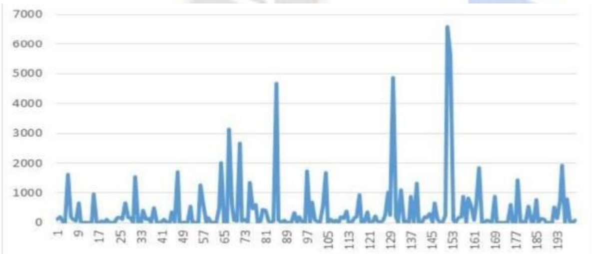

Figure 10. LA Battery of 2W_empty_return

B. LA Battery Sample(12V & 36 Ah)

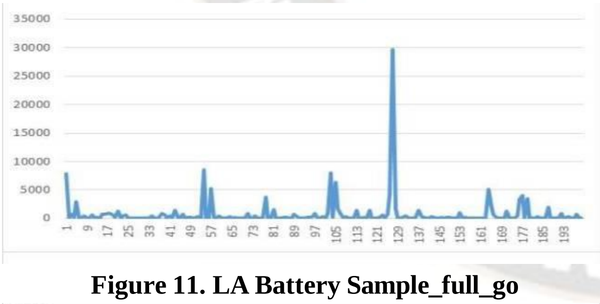

Figure 11. LA Battery Sample_full_go

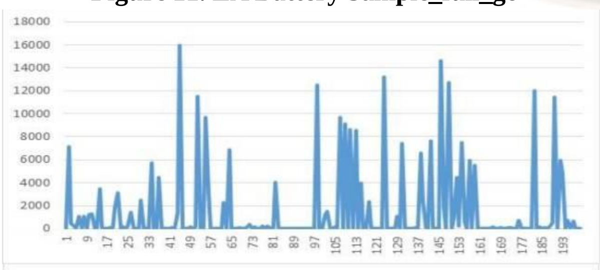

Figure 12.LA Battery Sample_half_go

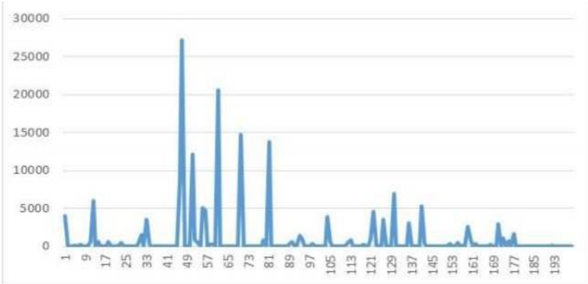

Figure 13.LA Battery Sample_empty_go

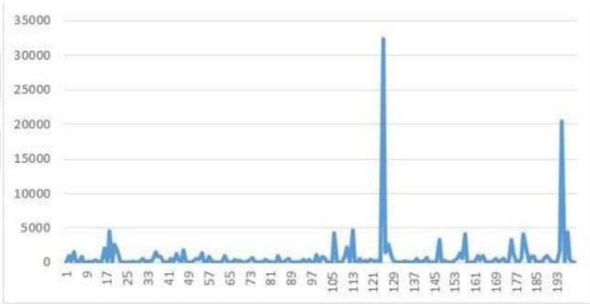

Figure 14. LA Battery Sample_full_return

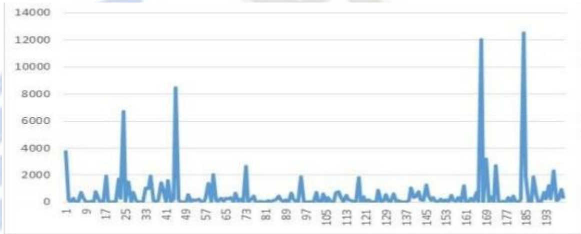

Figure 15. LA Battery Sample_half_return

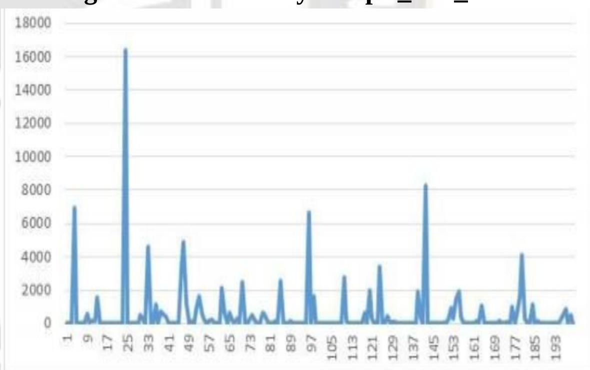

Figure 16. LA Battery Sample_empty_return

C. VRLA-SMF Battery (12V & 42Ah)

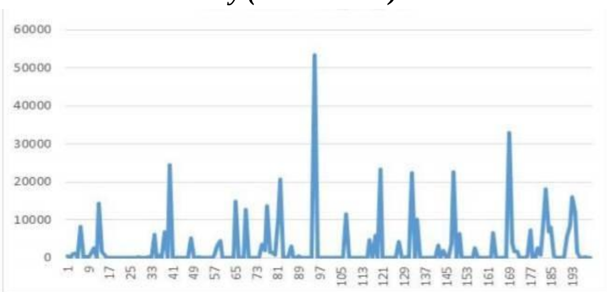

Figure 17. SMF charged 9V_go

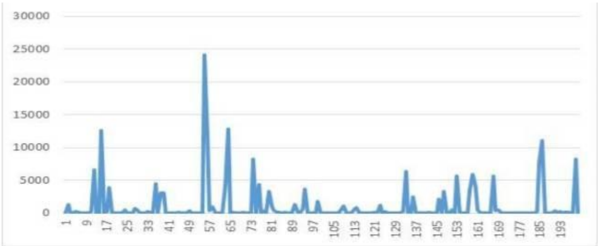

Figure 18. SMF Discharged 5.73V_go

The VRLA _SMF battery is used and tested with full charge and full discharge state under the same test conditions. All the graphs shown figure 6 to 17 are time (sec) Vs µm.

CONCLUSION

It is to conclude after an experimental setup on 2W and only batteries with healthy and unhealthy state. Using a novel vibration tool for the State of Health (SoH) of VRLA batteries, it is almost predictive for the level of acid and any other health issues of the LA Battery. There should be the signature of the battery to be saved during the healthy condition and which is referred later on the different interval to identify the unhealthy condition. The battery is analyzed as per the standard cycles available of the power train testing. Even charging and discharging of the VRLA SMF results shows the prediction of the charge – SoC level using the signature analysis. This vibration tool predicts the health level of the VRLA batteries.

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