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Analytical Analysis and Performance Characterization of Hexagonal Grid Configuration of Wet Cell Battery

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ABSTRACT: The batteries are efficient energy storage devices and help to stabilize electricity networks. The wet cell batteries are successfully applied for industrial & automotive applications and for utility energy storage. One of the major limitations associated with wet cell batteries is the lower charge acceptance rate, which results in the increase in time to recharge battery. In batteries, grids are used to provide structural support for the active material and serve as current distributor during recharge and current collector during discharge. In this paper a unique hexagonal grid structure configuration for positive plate is proposed with composite material of Graphene (1.5%) and Lead (98.5%) to enhance the charge acceptance rate, grid conductivity and to reduce the grid resistance. This paper presents a systematic analytical analysis and performance characterization of structural grid with the hexagonal shape to improve the energy storage efficiency. The 3D model is simulated using COMSOL Multiphysics, to study the effect of hexagonal grid configuration and performance of a positive electrode in wet cell batteries. The modified design of hexagonal grid is compared with existing rectangle design and result shows that conductivity of hexagonal grid is increased by 4 times, the hexagonal grid has low resistance as compared with rectangular grid, which also increase the charge acceptance rate.

Keywords: battery structure grid, energy storage devices, energy storage materials, grid configuration.

I. INTRODUCTION

The demand of energy storage devices is increasing and becoming essential in electricity networks, as more power generating capability uses intrinsically intermittent renewable-energy sources. The batteries, which store electrochemical energy is easy to utilize, compact, economical and offers immediate response both first, input to the battery and second, output from the battery. Different battery chemistries are available and wet cell batteries offer a cost-effective and consistent solution which can be applied in different types of energy storage applications [1-5]. The researchers are still working and proposing different methods and techniques to improve efficiency of batteries. Performance of batteries is adversely affected with the passage of time and usage [6-8]. Adverse effects on the battery capacity and power are not necessarily interdependent and do not completely describe the state of health [9-11].Energy storage is a stationary or standby service and wet cell type batteries can provide this service, which offers high efficiency for limited time period backup and their utilization for local systems, smart grids support, and domestic & small business-related energy systems is increasing [12]. The change in geometry of grid cells can change the conductivity and performance of batteries, where, increased conductivity leads to a more consistent current distribution and better performance [13–15]. The energy storage devices (batteries) with massive capacities are achievable, with different chemistries as they have energy producing cells which utilize active materials. [16]. The lead acid batteries gradually sulphated after continues running, and due sulphate efficiency decreased in terms of capacity and charge acceptance [17–19].

Grid performs two function, first current collector and second current carrier. Enhancing the grid configuration and employing additives to both (1) battery electrolyte and (2) active material to enhance effectiveness and performance of lead acid batteries [20-21]. Electric current (in/out) moves in opposite directions through both lug and grid during the charge or discharge processes [22].

The battery grid is a base for active material and penetrable for mechanical stress caused by peripheral forces, it is also for current distribution through the plate [23]. The configuration of grid minimizes the ohmic drop and stabilize the current distribution through the electrode. The grid design also introduces reaction spots on the electrode [24]. Several investigations have been made for grid configuration for current distribution and potentials, but hexagonal configuration is not considered yet [23, 25].

The aim of this study is to improve the grid design and increase the battery performance. In present study, the numerical methods are used to simulate the effects and impacts of such parameters to analyze the battery performance.

The 3D mathematical model is simulated using COMSOL Multiphysics, to study the effect of hexagonal grid configuration and performance of a positive electrode in wet cell batteries. The effect on hexagonal grid with composite material is investigated on the performance of the positive plate by considering the current and potential distribution in 3D model to optimize positive plate grid design.

II. GRID OF LEAD ACID BATTERY

Lead acid batteries consists of positive and negative grids (shown in Fig. 1) are designed and manufactured in different forms and shapes. Positive grids deliver electrical energy whereas corrosion occurs on negative grid. The increment in adhesion between paste mixture and grid can improve the efficiency as well as life cycle of battery. However, there are different methods to increase the efficiency and life cycle, changing material or by changing design of grid, it is one of the easiest ways. In different types of batteries grids are constructed in different shapes and sizes of different materials. It is known that in lead acid batteries most of them failure occurs because of corrosion of the grid surface.

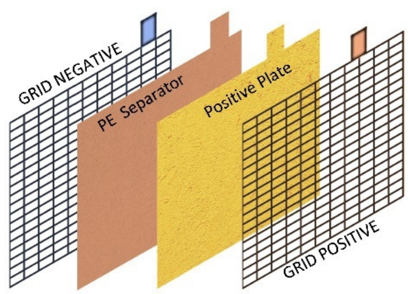


Fig. 1. Lead acid Battery with, negative grids, PE separator, Positive plate and positive.

III. GRID STRUCTURE DESIGN

Grids are used to provide structural support for the active material and serve as current distributor during recharge and current collector during discharge (shown in Fig. 2). Grids are designed by considering electrochemical reactions and because of that variation occurs in size where as to enhance the fundamental characteristics of any battery interior shape such as hexagon, octagon, rhomboid and many more are designed, it is necessary to design grid interior structure in such a way that the wires orientation must be other than 90 degrees because of active material, then the change paste flow would be continuing and provide better results.

IV. GRID PROPERTIES

Grid properties varies because of design and material, mostly grids are made of alloys and composite of different material such as lead aluminum alloy or lead graphene composite.

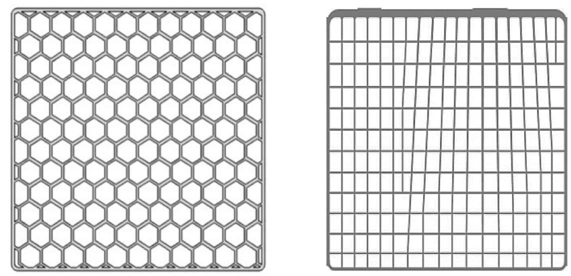


Fig. 2. Grid structure design as (a) Hexagonal and (b) Rectangular.

Properties of alloy or composite various in manufacturing method such as stamping and embossing method is much more efficient then batch casting. However, change in shape also has great influence on properties, such as rhomboid can conduct more current then rectangular grid.

Grids are designed in such a way that active material and grid formed plate and these plates are tested for different properties. By changing material and design structure of grid we can increase the rate of charge acceptance of a battery. In lead acid battery rectangular as well as square shape of grids are used by changing that grid shape into the Hexagon shape grid or simply honeycomb structure, which provide more current as compare to other designs. The angle between interior structure of grid is 120 degrees of each hexagon cell, these angles provide continues flow of paste material that is electrolyte and it also increase the flow of electrons.

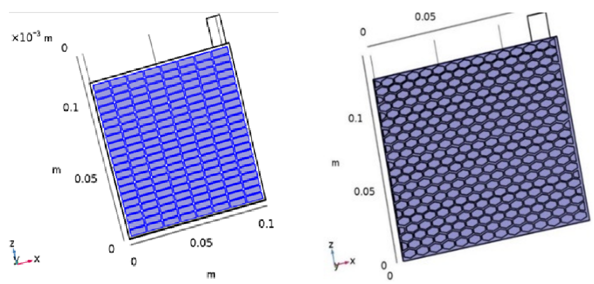
Table 1: Comparative study between passive and active systems.

Name	Expression	Value	Description
H	125[mm]	0.125 m	Cell height
W	142[mm]	0.142 m	Cell width
H_lug	18[mm]	0.018 m	Lug height
W_lug	14[mm]	0.014 m	Lug length
s_grid	4[mm]	0.004 m	Grid thread width
s_frame	5[mm]	0.005 m	Frame width
N_x	14	14	Number of porous electrodes, x-direction
N_z	18	18	Number of porous electrodes, z-direction
H_porous	(H - 1*s_frame-(N_z - 2)*s_grid)/N_z	0.0031111 m	Porous electrode height
W_porous	(W - 1*s_frame-(N_x - 2)*s_grid)/N_x	0.0063571 m	Porous electrode width
d_electrode	1.7[mm]	0.0017 m	Thickness of porous electrodes, grid and lug
d_electrolyte	1[mm]	0.001 m	Thickness of electrolyte
sigma_metal	4.8e6[S/m]	4.8E6 S/m	Conductivity of grid and lug
sigma_porous	9500[S/m]	9500 S/m	Conductivity of electrode material

To know the rate of charge flow we made theoretical analysis which are done in COMSOL Multiphysics 5.0, there design is constructed, and simulation is done.

V. GRIDDESIGN PARAMETERS

Table 1 shows the list of parameters, used to design the hexagonal grid in COMSOL Multiphysics. The same height and weight of grid frame and lug size are taken for rectangular grid and proposed grid. The only changing occurs in interior mesh, that is number of porous electrodes. In rectangular grid number of porous electrodes have 90-degree angle where is in hexagon it is regular 120-degree is taken. These are sigma properties of metal for lead acid batteries and can be varied with sigma properties. Fig. 3 shows the hexagonal and rectangular grid shapes of positive plate and pasted with electrolyte material. The material is used for grid is lead & graphene composite with lead 98.5% and graphene 1.5%. The proposed hexagonal grid structures simulation is done in COMSOL Multiphysics.



(a) (b)

Fig. 3. Grid structure design as (a) Hexagonal and (b) Rectangular.

In Fig. 3, Electrode current density that is current conduction per meter in grid and lug is simulated, it can be seen current conduction occurs through porous electrodes and current is conducted only in grid not in lug.

VI. ELECTRODE CURRENT DENSITY & ELECTROLYTE POTENTIAL

Current density is measure of current conduction per unit area. By applying current at grids, maximum and minimum current on different voltage ranges are found. The maximum current gained is far from lug, the reason is that the current cannot conduct at lug because it is outer side of grid and there no paste material is added. Comparing both designs of grid having same design parameters applying voltage from 0.1 V to 0.5V it is found that hexagonal grid can conduct $1.19x10^7$ A/m^2 far from the lug at the potential difference of 5V and near the lug it is $0.2x10^{-6}$ A/m^2 at 0.1V as shown in Fig. 4 and the average current is $5.9x10^6$ A/m^2 at average 0.2 volt.

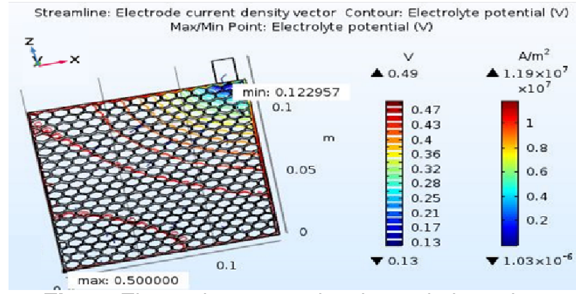


Fig. 4. Electrode current density and electrolyte potential of hexagon plate.

But in rectangular grid the current conduction is very low as shown in Fig. 5. The conducted maximum current is is$1.81x10^{-7}$ A/m^2 at voltage of $4.3x10^{-14}$ V and minimum current that is $1.83x10^{-9}$ A/m^2 at voltage of $-9.51x10^{-14}$ V.

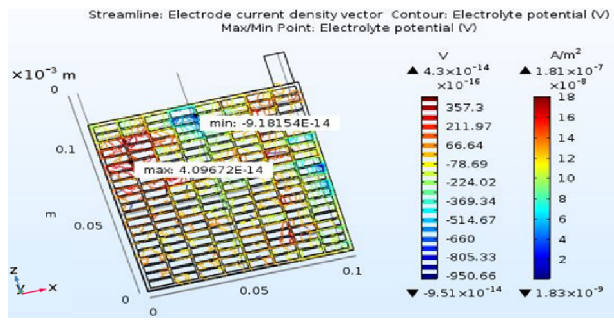


Fig. 5. Electrode current density and electrolyte potential of rectangular plate.

From the Fig. 4 and 5, by applying 0.1V to 0.5V the potential difference that is 0.2V is used for flow of charges. By changing internal mesh, the conduction of current increases 7 times more than the normal rectangular grid. In Fig. 6, electrolyte is used on hexagonal grid and variation occurs in conduction of current. In hexagonal plate, heat notices and increase in temperature can cause these changes due because of high current conduction. Fig. 6 shows the areas in which conduction occur.

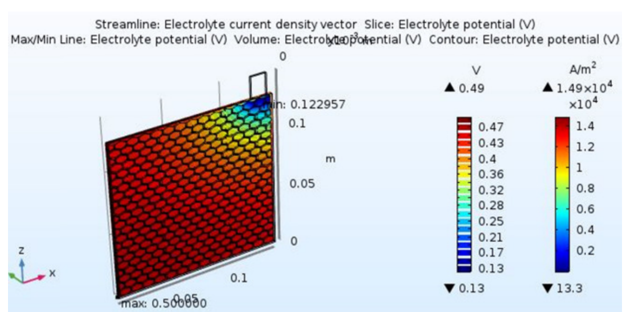


Fig. 6. Heat production during electrode current density and electrolyte potential of hexagon plate.

By adding electrolyte, the current decreases and maximum current it can conduct $1.49x10^4$ A/m^2 at same 0.5V, whereas in flat plate grid current also decreases at same voltage range, as shown in Fig. 7. The maximum current it can conduct $4.2x10^{-9}$ A/m^2 at 0.5V.

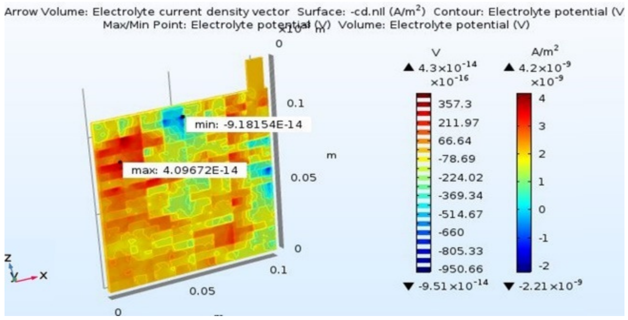


Fig. 7. Heat production during electrode current density and electrolyte potential of rectangular plate.

It has been noted from Fig. 6 and 7 that increasing in current conduction at same voltage ranges can cause very low resistance, flat plate batteries have high resistance whereas hexagonal plate have very less resistance but with this amount of conduction of current heat could be generated in hexagonal grid and it can damage the internal mesh as well it can evaporate electrolyte easily.

VII. ENERGY IMPEDANCE SPECTROSCOPY OF COMPOSITE

Different energy impedance measurement techniques are widely used in material sciences to analyze the resistivity of material at different frequencies [26-28]. In this research, the composite material of Graphene (1.5%) and Lead (98.5%) are used for grid. Some tests have been carried out to find the proper composition of lead and graphene. The electrochemical impedance tests have been done by using proper concentration of oxidation and reactants. Impedance spectroscopy (IS) is a common technique in which a small oscillating perturbation is applied to an electrochemical system to interrogate kinetic and transport properties. This example model of IS for a range of electrode reaction rates. The bode plots illustrate the transition between the reaction proceeding under kinetic or transport control. Here the transition in lead and graphene is under observation. The parameters by which impedance test has been carried out are listed in Table 2. It is found that the internal change in composition which occurs due to the applied voltage and above parameters by using lead and graphene composite. Fig. 8 shows the impedance absolute value verses frequency at different heterogeneous rate. Bode plot (Fig. 8) showing the magnitude of impedance as a function of frequency for a range of electrode kinetic heterogeneous rate constants.

Table 2: Parameters of Impedance.

Name	Expression	Value	Description
D	2e-10[m^2/s]	2E−10 m^2/s	Diffusion coefficient
c_bulk	1[mol/m^3]	1 mol/m^3	Bulk concentration
Cdl	20[uF/cm^2]	0.2 F/m^2	Double layer interfacial capacitance
k0	0.001[cm/s]	1E−5 m/s	Heterogeneous rate constant
freq_min	1[Hz]	1 Hz	Minimum frequency
freq_max	997[Hz]	997 Hz	Maximum frequency
log_freq_min	log10(freq_min[1/Hz])	0	Log of min frequency
log_freq_max	log10(freq_max[1/Hz])	2.9987	Log of max frequency
xdiff_max	sqrt(D/(2*pi*freq_min))	5.6419E−6 m	Mean diffusion layer thickness at minimum frequency
xdiff_min	sqrt(D/(2*pi*freq_max))	1.7868E−7 m	Mean diffusion layer thickness at maximum frequency
L_el	xdiff_max*10	5.6419E−5 m	Electrolyte length
A_el	0.002916[mm^2]	2.916E−9 m^2	Electrode area
V_app	2.2[mV]	0.0022 V	Applied perturbation potential

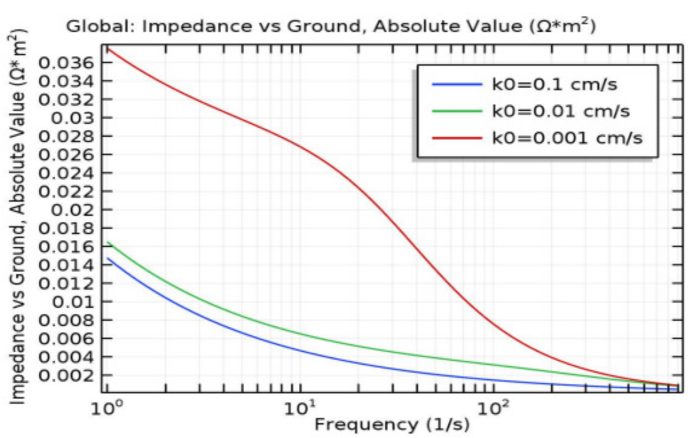


Fig. 8. Absolute impedance

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In Fig. 9, bode plot showing the phase of the impedance as a function of frequency for a range of electrode kinetic heterogeneous constants rate.

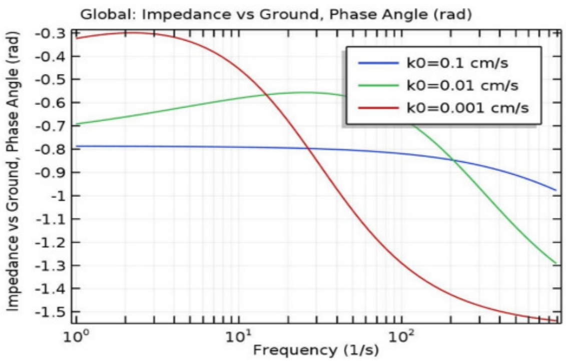

Fig. 9. Impedance phase angle.

From Fig. 8 and Fig. 9, it is found that under heterogeneous rate constant kinetic and transport control regime occurs. In both graphs the real component of impedance is on x-axis. It shows resistance and another component that is reactant on y-axis. From both bode plot, it is found that at given voltage 2.2V with 977 Hz and feed rate of 0.001 m/s the transportation of material (mass) occurs in safe region, and mixed completely, whereas changing speed rate that is kinetic constant rate mass of material can't have mixed properly or they can break immediately at higher frequency.

VIII. CYCLIC VOLTAMMETRY

This is analytical electrochemistry technique, where current is recorded by swept the potential up and down at a working electrode to analyze electrochemical redox reactions [29]. The current and voltage waveform (the voltammograms) gives the information about the mass transport and reactivity properties of the analytic objects. The cyclic voltammetry at an electrode of 1 mm in dimensions is carried out.

By testing composite of graphene and lead and applying current of 19 A/m^2 at sample, the maximum current, minimum current, peak current and potential differences were recorder, as mentioned in Table 3.

Table 3: Parameters of Impedance.

Variable	Recorded Value
max_curr (Anodic peak current density [A/m^2])	0.17682310547272087
min_curr (Cathodic peak current density [A/m^2])	-7.585105587237775E-9
pot_max_curr (Anodic peak potential [V])	0.13600000000000012
pot_min_curr (Cathodic peak potential [V])	1.1120625000000002
delta_pot (Peak potential difference [V])	-0.9760625

From Table 3, the maximum and minimum current of composite can conduct at applied voltage range of 0.1V to 2.2V can be plotted, as shown in Fig. 10.

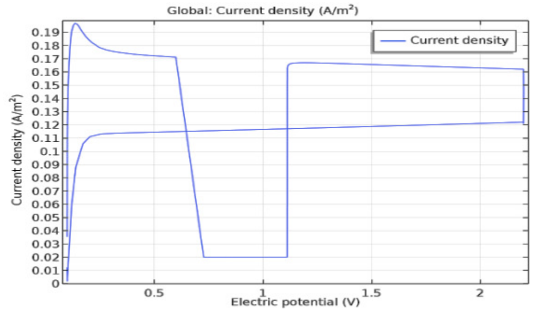

Fig. 10. Cyclic voltammetry current vs electrolyte potential.

The cyclic voltammetry results show that lead-graphene composite has high conductivity at different potential intervals.

IX. LEAD AND GRAPHENE COMPOSITE

In this paper a hexagonal grid configuration is recommended with lead graphene composite. In proposed configuration the current conductivity and charge acceptance rate increase, along with increase in heat generation at the same time.

If the pure lead material is used for the proposed grid configuration, it can easily breakdown the internal geometry due to high temperature and low conductivity. Similarly, if the pure graphene material is used for the proposed grid configuration, it can easily be dissolved with electrolyte due to high temperature and high conductivity.To overcome this issue a composite of lead and graphene can be used. Lead can withstand dissolving and graphene can maintain the rate of conductivity. The proposed composite is lead 98.5% and graphene 1.5%.

X. CONCLUSION

In this paper, the structural shape of grid is changed from rectangular to hexagonal, which helps to reduce the distance between nodes as compared to rectangular. The COMSOL Multiphysics simulation software is used to analyze the modified and existing designs.

The result of both structural configurations was compared and found that by changing the grid design, conductivity of grid increased by four times, which helps to increase the charge acceptance rate, but also increase heat rate. In this study graphene and lead composite is used as grid material, to decrease the heat. The use of graphene and lead composite as grid material for positive electrodes can enhance the performance of lead–acid batteries as well as decrease the weight of the battery. Results show that the proposed configuration of grid is optimized and enhances the battery performance.

XI. FUTURE SCOPE

The significance of wet cell batteries is not expected to diminish in near future. Among various types of energy storage devices, the wet cell batteries are affordable, provide high number of charge-discharge cycles. However, the wet cell batteries have higher weight and lower charge acceptance rate.

In future, rectangular grid can be replaced by hexagonal grid to improve the current conductivity and charge acceptance rate. The manufacturing of wet cell batteries with recommended lead graphene composite material and grid design can result in reduction of weight and increase in charge acceptance rate.

Conflict of Interest. This is to certify that research with title "Analytical Analysis and Performance Characterization of Hexagonal Grid Configuration of wet cell battery" is being attested by authors that they have no conflict of interests, regarding financial concerns and other kind of related disagreements with any organization, institutes, research labs and educational grants.

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