



Optimization of grid configuration by investigating its effect on positive plate of lead-acid batteries via numerical modeling



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ABSTRACT

With increasing the applications of lead-acid batteries, the demand for efficient, low resistant and inexpensive batteries has increased drastically. As discharge rates increase, ohmic voltage losses in current collecting system become more important. In this study, numerical methods are employed to investigate the effect of grid configuration, lug position, diagonal wire angles and tapering wires towards the plate's lug on the performance of positive electrode of lead-acid batteries via modeling the current and potential distribution through grid wires, active material and adjacent electrolyte to the surface of each grid. 18 distinct grid designs with same weights are designed to achieve this task. The results indicate that double-diagonal configuration offers up to 43% increased current distribution uniformity. It is also shown that locating the lug near the midpoint of the frame, increasing the degree of parallel diagonal wires and tapering the wires towards the lug increases the uniformity of the current distribution up to 14%, 1.6% and 5.6%, respectively. It is noteworthy that manufacturing and practical limitations has been taken into account in this work as well.

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1. Introduction

Applications of lead-acid batteries have increased significantly during the last decades. Most of these applications require batteries to work on partial state of charge (PSoC) status and deliver high currents in short periods more frequently [1]. It is well known that as the discharge rate increases, ohmic losses in current collecting system become more important and even dominant in some cases [2]. Therefore optimization of grid configuration may contribute to enhance the overall performance of the lead-acid batteries (LAB) for these new and more demanding applications with reducing ohmic losses through the current path.

Many attempts have been exerted during the last 9 decades to investigate the effect of different parameters on current and

potential distribution through electrodes of LABs [3]. Puzey and Orriel were one of the pioneers in this field, who considered the battery electrodes a two dimensional structure. They assumed uniform current distribution and based on this assumption, investigated the effect of some design parameters with measuring equipotential lines in the both electrodes for 16 different designs and highlighted the effect of negative active material (NAM) to its corresponding electrode's conductivity [4]. Few years later they developed a distinct two dimensional mathematical model which applied to same grid designs and predicted cell voltage, current density distribution, grid potential losses, the distribution of local active material utilization, and cell capacity as a function of the depth of discharge, discharge rate, and grid design variations. They emphasized that with increasing the discharging current, grid losses becomes more important in determining the total capacity [5].

Complexity of three dimensional models made it impractical for researchers before 1990 and therefore it was preferred to reduce this complexity by developing a two dimensional model

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either by examining the electrode plane and neglecting the effect of polarization, electrolyte resistance, and counter electrode or in the alternative approach by taking into account inhomogeneity of the current density and ignoring the width of electrode [2].

In 2000, Milan Calabek et al. [6] determined the current distribution over the surface of a lead-acid cell experimentally. Two grids were interconnected with parallel, thin wires which stood for electrolyte and active material (AM) ohmic resistance. With applying a DC current of 2A and measuring ohmic drop the current distribution was found for each of eight models. Afterwards, they claimed that the locating lugs in the middle of the grid and one in the top and the other in the bottom of the each grids provides the most uniform current distribution over the whole current collecting system.

Two years later and in 2002, Ball et al. [7] observed an increase in the corrosion layer thickness near the grid lug more than the rest of the grid during cycling of a 40 Ah VRLA. To investigate the idea of increasing corrosion layer thickness with increasing the current density, they solved Laplace equation by using finite element package (ANSYS) for the simplified assumed two dimensional geometry. The obtained results were in line with their experiment and also indicated that with optimizing the grid design, current density and therefore corrosion layer thickness could be significantly reduced.

3 years later, Keizo Yamada et al. [8] took a different approach for optimization of grid configuration and weight for LABs. They assumed a pair of differential equations to be valid for the optimum design and with defining proper boundary conditions, they were solved to obtain a low resistance grid design. It seems that although this approach will reduce the number of required designs and therefore the simulation time, the equations may not be ideal for the optimum case.

In 2014 [9], one of the authors of this paper investigated the effect of grid configuration on the performance of the battery by modeling the current and potential distribution through grid wires and its adjacent active material and electrolyte and introduced numerical modeling as a fast, effective and inexpensive way to optimize the grid configuration of the LABs, however as it was emphasized in the paper, only four designs were evaluated to prove the effectiveness and validity of the model and further investigation on the detailed design parameters was postponed to future works.

In this paper the effect of lug position, conventional, diagonal, or double-diagonal grid design, wire angels and the level of tapering currents as well as the starting point of tapering current were investigated on the performance of the positive plate of LABs through modeling the current and potential distribution in a three dimensional model to offer the optimize grid design of the LAB's positive grid, which is vital in minimizing the ohmic drop for the high rate performance of nowadays LABs.

2. Theory

As mentioned in the previous chapter, ohmic losses in current collecting system become more important with increasing the discharge current, and may even be dominant in some cases. As the objective of this work is to investigate the effect of grid design on the LABs performance and this effect is more profound in high rate discharges, therefore it seems logical to evaluate grid designs, based on their respective ohmic drop losses in their current collecting system.

The equations used in this work is quiet similar to the ones in the previous work [9]. Therefore herein only a brief summary of equations are presented. With having the abovementioned reasons

in mind, mass transport and kinetic limitations can be ignored with the assuming no ionic concentration gradient and perfectly reversible faradic reactions, respectively.

The total ionic current density (i) is expressed in the following equation:

$$i = -F^2 \nabla \Phi \sum_j Z_j^2 \mu_j C_j - F \sum_j Z_j D_j \nabla C_j + F \nu \sum_j Z_j C_j \quad (1)$$

Definitions of the used parameters are listed in Table 1.

With applying the electroneutrality condition in the solution and assuming no ionic gradient in the electrolyte, the second and third terms of Eq. (1), become zero and it yields the ohm's law:

$$i = \sigma \nabla \Phi \quad (2)$$

$$\sigma = -F^2 \sum_j Z_j^2 \mu_j C_j \quad (3)$$

With assuming the net effect of ionic species in the reactions occurring in the electrolyte (if any) is zero. Applying this assumption to Eq. (2) results in Laplace equation:

$$\nabla^2 \sigma = 0 \quad (4)$$

The overall overpotential at the electrode is expressed as:

$$\eta = E - E_e - \Phi \quad (5)$$

Proper boundary conditions should be considered for solving Eq. (4).

At insulator boundary:

$$\nabla \Phi = 0 \quad (6)$$

The second required boundary condition is:

$$\Phi_0 + \Phi_m = \text{Constant} \quad (7)$$

This indicates that the potential on the electronic conductor is equal to the potential in the solution adjacent to it.

3. Model and recruited design

To investigate the effect of different design parameters on the performance of positive plates of LABs, a three dimensional model was developed which pave the way to evaluate the effect of highly detailed design parameters on current and potential distribution through grid wires, active material and its adjacent electrolyte. In this section, initially some key parameters for comparison of different grid designs are introduced, then recruited designs are presented and finally simulation procedure is described.

Table 1
Definition of all equations parameters.

Parameter	Definition
N_j	Ionic flux
Z_j	Charge
μ_j	Ionic electrochemical mobility
F	Faraday's constant
C_j	Concentration
∇	Differential operator
Φ	Electrostatic potential outside the electric double layer
D_j	Diffusion coefficient
ν	Bulk average fluid velocity

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