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Magnetic tomography for lead acid batteries

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This paper explores the inverse problem approach for finding the current distribution within an electrochemical cell from magnetic field measurements. Current distribution is shown to be a useful measurement for diagnosis of cells and development of cell design. Existing current distribution measurement methods are discussed to provide context and motivation for the work. Magnetic field measurements can be obtained non-invasively and contain information about the current distribution, which is extracted using an appropriate solver. Experimental results are presented which test the effectiveness of a particular inverse problem solver, using both simulated and real magnetic field measurements. The solver presented is based upon one found in literature, but with novel problem-specific modifications. Errors in conductance values in the forward model definition are simulated in order to quantify their effect on solution quality. A modification to the solver is proposed to improve robustness against these model errors. This results in improved solution quality when using real measured data from a resistor-wire model of a cell, and simulated data from a model which more accurately represents the conductance of the cell plate grid and active mass.

1. Introduction

The hybridisation and electrification of vehicles requires high performance batteries in terms of energy density and specific energy [1], high current delivery (cold and warm cranking) [2], long service life [3], and dynamic charge acceptance [4]. In addition, cost of the batteries must be minimised [1] to bring the price of electric vehicles and hybrid electric vehicles to a level that is competitive with internal combustion engine vehicles. It should be noted that the wide variety of levels of hybridisation (plug-in hybrid, mild hybrid, micro-mild hybrid *etc.*) yields an equally wide variety of battery requirement specifications [4,5]. Even in purely internal combustion engine-powered vehicles, stop-start functions as well as more sophisticated power management place more demand on the battery than in the traditional starting-lighting-ignition application [4]. Uniformity of current distribution has been shown to be a factor contributing to various measures of battery performance, which are described in Section 2.

For the purposes of this paper, current distribution refers to the current leaving or entering the plate due to the cell reaction. Furthermore, distribution over the whole area of the cell plate (mesoscopic) is of interest, as opposed to what happens at the microscopic level, or how current may be shared between multiple cells within a battery or batteries within a battery pack (macroscopic). In other words the goal is to produce a diagram showing the regions of greater and lesser magnitude of current over the whole area of the cell plate (see Figs. 3, 5, 7, 8). This does not imply that the micro- or macro- scopic models of the battery system are not related, but the mechanisms at those levels are beyond the scope of this paper.

We investigate the use of magnetic measurement for imaging the current distribution within lead acid cells. Using magnetic measurements to obtain current distribution is applicable to many battery chemistries, but automotive lead acid cells are a convenient choice for experimentation due to their relatively large plate size and the fact that they are available dry-charged, allowing safe construction of a test cell. Despite being a mature technology, research into lead acid batteries is ongoing. This is because they are commercially relevant due to their low cost [6,7], but have limited dynamic charge acceptance [4] and poor specific energy. Firstly, the motivation for the research is explained in Section 2, and a very brief description is provided of the ways in which current distribution impacts on some battery performance metrics. Then, a review of the existing methods for measuring the current distribution in lead acid cells is provided (Section 3). This includes some related methods, with comment on their applicability. The

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review also includes some background for magnetic imaging as a method. Finally, some experimental work is presented (Section 4) which is concerned with finding the current distribution from magnetic field measurements using an inverse problem approach.

2. Current distribution, cell performance and state of health

2.1. Dynamic charge acceptance

Inhomogeneous current density distribution has been linked with reduced dynamic charge acceptance [8]. It is offered as an explanation for the dependence of dynamic charge acceptance on the recent charging/discharging history of the battery, which has also been reported in [9]. Acid stratification is suggested as the cause of the inhomogeneous current distribution, since it is dependent on recent history of the battery. Acid stratification also causes premature sulphation in localised areas of the battery plate, even at modest overall depth of discharge for the whole cell [10]. This is acknowledged as a failure mechanism in lead acid cells [8,11,12] Sunu and Burrows use potential non-uniformity around the plate as a figure of merit for cell performance [13].

2.2. Active mass utilisation

One factor determining the specific energy of a battery is the active mass utilisation – lead acid batteries in practice perform poorly in this regard compared to other battery chemistries (such as nickel metal-hydride (NiMH) and lithium ion (Li-Ion)), and also compared to the theoretical maximum specific energy for a lead acid battery [14–16]. Active mass utilisation is typically measured by taking the time integral of the current at the battery terminals, and measuring the mass of the active material, giving a capacity in units of Ah kg_{AM}^{-1} [17]. The theoretical capacity of a given mass of active material is obtained by considering the atomic weights of Pb and/or PbO_2 and the number of atoms needed to exchange an electron at each electrode [18]. By measuring localised current density, a localised measure of active mass utilisation is possible [19]. A non-uniform active mass utilisation means that some parts of the plate are underutilised (resulting in poor specific energy) and some parts are over-utilised (resulting in damage due to deep discharge [20]). In addition, the mechanisms themselves which limit active mass utilisation are current-dependent; it has been found that the dominant process limiting active mass utilisation depends on the rate of charge/discharge (at high rates transport of acid through the active mass limits its utilisation [21] whereas at low rates it is the electronic conductivity of the active mass [15,16]). Therefore knowledge of current distribution will give greater insight into the mechanisms governing the active mass utilisation at different locations around the cell plate. Gyenge et al. [17] develop a novel current collector for lead acid batteries with improved active mass utilisation compared to a standard grid. They acknowledge that current distribution measurements could aid optimisation of active mass thickness.

2.3. State of health

As well as optimising performance, information on current distribution of a cell could be used to identify damage or wear to the cell. Active mass shedding, where the active mass falls from the plates and pools in the bottom of the battery case, is one failure mechanism for lead acid batteries. A summary of aging and failure of lead acid batteries by Ruetschi [10] gives examples of a plate which has shed its active mass over part of its area. Areas where active mass are not present would not be able to participate in the cell reaction and so there would be no current leaving the plate in these areas. Two other failure modes from the same paper are firstly, capacity loss due to poor contact between the active mass and supporting grid and secondly, short circuiting between plates due to movement of active mass. If the former occurs initially in one part of the plate area, then a reduced current density would be expected in that part of the cell, and so a current distribution measurement may be useful for showing the degradation of the plate by this method. In the latter case, short circuits occur towards the bottom of the cell due to shedding, or elsewhere around the plate if dendrites are formed [10]. Identifying the path of the short circuit current would differentiate between these two cases. Sulphation is another cause of capacity loss and failure, which may occur non-uniformly on battery plates, with a distribution that is dependent on charge/discharge rate [11,22,23].

3. Existing current distribution measurement methods

There is relatively little experimental (as opposed to simulation) work on the current distribution of lead acid batteries. However, similar research into fuel cells is much more active. Kalvyas et al. [24] provide a review of methods for measuring current distribution in polymer electrolyte fuel cells. Some techniques used in fuel cells are applicable to lead acid batteries, but not all. This is because the geometry of a fuel cell or flow battery can be more complex than a lead acid battery – it may include multiple layers, and a convoluted flow channel to transport the fuel around the electrode [25,26]. By contrast, the cell of a parallel plate lead acid battery, such as those used for starting, lighting and ignition of an internal combustion engine vehicle, consists of two opposing faces of adjacent plates of approximately similar geometry with an absorbed aqueous or gelled electrolyte in between. The cell is then simply repeated and connected in series/parallel to increase the battery voltage/current. One plate may form part of either one or two cells, since the active mass may be pasted onto both faces of the plate, but the geometry of each cell is simple and repeating.

3.1. Modelling

Lead acid batteries have been modelled as electrochemical and as purely resistive systems. Newman and Tiedemann [27] develop a macrohomogeneous theory of the cell reactions, which is used by Kowal et al. in their study into current inhomogeneity and recent cycle history of a lead acid cell [8]. Sunu and Burrows incorporate a resistive model of the plate grids into an electrochemical model of the battery in order to predict potential and current density distributions [13,19] and the effect of altering grid design. Due to the relative ease/speed of creating models compared to building a real grid, the authors were able to make comparisons between various proposed grid designs and dimensions in order to plot capacity against grid weight – aiding optimisation of specific energy. Král et al. [28] developed an equivalent circuit incorporating resistances of constituent parts of a lead acid cell as well as the state of charge-dependent local polarisations to simulate non-uniformity of current distribution for different battery current take-off tab configurations.

3.2. Sense wires

One direct way to measure potential distribution around the plate (and thereby estimate current distribution by making assumptions about the resistivity of the electrolyte) is to attach sense wires to the grid. Calabek et al. constructed a purely resistive model from a pair of unpasted lead acid cell plate grids, connected together by uniformly spaced resistance wires to simulate the electrolyte resistance. Using this apparatus they found that the uniformity of the current distribution can be improved by correct