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Multiple Battery Systems for Electric Vehicles

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Abstract

Battery electric vehicles are finding increased application in niche market sectors where higher vehicle capital cost and range are not constraining specification criteria. These applications can be relatively high power demanding, thus a number of high energy traction batteries need to be connected in parallel. Here, inequality in the individual battery characteristics can lead to significant degradation of vehicle performance. This paper presents results of a study investigating the parallel operation of 2xZEBRA batteries and the impact of battery cell failure on vehicle operating performance. The paper will give an overview of the battery model, potential failure modes, ride-through capability and battery management.

Keywords: ZEBRA battery, Multi-battery server, Battery cell failure

1 Introduction

Increasingly stringent demands for cleaner vehicular energy conversion and lower energy consumption are motivating the development in alternative power-trains for vehicles [1]. One technological solution is to replace the conventional mechanical power-train with an electrical based propulsion system, for example a battery electric vehicle. Such vehicles are finding increased application in niche market sectors where higher vehicle capital cost and range are not constraining specification criteria, for example in delivery type vehicles of 2-tonne up to buses for urban transportation of 9-tonne [2]. These applications require relatively high peak powers for example 80 to 200kW respectively for the 2 and 9 tonne vehicles. This necessitates the connection of a number of high-energy traction batteries in parallel to obtain the required energy and power. Here, each battery is controlled by a battery management interface.(BMI) monitoring the battery characteristics to keep the battery in a safe operating condition. Any inequality in the individual battery characteristics can lead to significant degradation of vehicle performance. In the case of parallel connected batteries,, a multi-battery server (MBS) is used to manage the operation of the individual BMIs according to the operational condition for each battery.

Mantovani et al [2] reviewed the problems associated with the inevitable differences in battery state-of-charge (SOC) when operated in parallel and arising from the difference in charge or discharge currents, and cell failures.

This paper presents results of a study investigating the parallel operation of ZEBRA batteries in electric vehicle applications considering the impact of battery cell failure on vehicle operating performance. The paper will give an overview of the battery model, potential failure modes, ride-through capability and intelligent management of the energy source combination.

2 Electrochemical batteries

The electrochemical battery is one alternative energy source considered for vehicle propulsion. Traditionally, lead-acid technologies have been the preferred technology; however, their energy storage capability, particularly in the presence of highly dynamic loading regimes and thermal ambient typical of vehicle applications, is poor compared to Lithium based technologies or the ZEBRA (Sodium Nickel Chloride) battery technology [1].

Among a various type of batteries used in electric vehicles the, ZEBRA battery shows a good all round performance and is the candidate battery technology for this paper study. The high temperature sodium-sulphur and sodium-nickel-chloride battery (ZEBRA) operates at a nominal temperature of 280ºC in a thermally managed chamber such that the battery external casing never exceeds 40ºC above ambient. Hence, the battery is less prone to environmental ambient changes than any other battery technology.

The ZEBRA battery has a good energy density, no self-discharge (i.e. is 100% Columbic efficient), has relative low operating costs and good energy conversion efficiency. A cooling plate, where ambient air is circulated, is provided between every second cell for cooling power. . Double walled vacuum insulation surrounds the cells for thermal insulation and mechanical support. Light plates made out of foamed silicon oxide take the atmospheric pressure load. This configuration has a heat conductivity of only 0.006W/mK and stable for up to 1000ºC [3].

Furthermore, the ZEBRA battery has passed many vehicle related safety tests, including crash at 50km/h, overcharge, over discharge, short circuit, vibration, external fire, and submersion in water,, have been specified and performed [3]. The ZEBRA battery has passed all of these tests because it has four safety barriers related to the cell chemistry, cell case, thermal enclosure, and the battery controller [3, 4, 5].

Currently, the ZEBRA technology has a cell failure tolerance of up to 10% of the total battery cells, though thus may be increased by the inception of improved battery management and power electronic controllers. In the event of failure, the battery cells progress to short-circuit [3, 4, 5] favouring series cell connections. Thus, the ZEBRA battery technology is particularly suited to high voltage (400-1000V) applications. For high energy series strings of ZEBRA cells can be connected in parallel. Different battery types have been made with one to five parallel strings, as required by vehicle platforms.

In the case of multiple battery systems, the ZEBRA multi-battery server (MBS) controls the unbalancing that occurred due to a cell failure. The MBS detects that a failure has occurred and adjusts all operative parameters, such that the batteries may be kept in step with each other.

3 Modelling and analysis

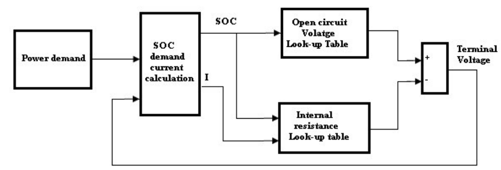
3.1 ZEBRA Battery model

The ZEBRA battery is modelled in the Matlab/Simulink environment based on experimental test data [6]. The battery open circuit voltage and internal resistance data is stored in look-up table. The model is used to assess the battery dynamics and to understand the interconnection issues in terms of energy flow, voltage, and current transients.

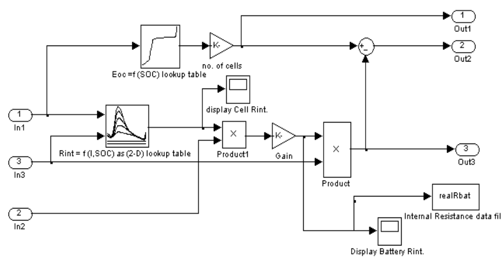
Fig. 1 shows an overview of the battery model implementation (a) and the Simulink presentation (b). The look-up tables calculate the internal resistance as function of state-of-charge (SOC) and charge/discharge current, and the open circuit voltage (E_{oc}) as a function of SOC. Fig.2 illustrates the look up table functions for ZEBRA battery internal resistance (a) and open circuit EMF (b).

3.2 Battery management unit (BMI)

The ZEBRA battery has a battery management interface (BMI) that controls the internal heater and cooling fan, and the main circuit breaker that isolates the positive and negative poles of the battery [7]. The BMI also acts to control the battery operating limits, for example, when the battery terminal voltage exceeds maximum during regenerative braking or when the terminal voltage drops under the minimum level during high rates of discharge, i.e. vehicle acceleration. The BMI unit controls these extreme voltage limits by disconnecting the battery via contactors. Moreover, other operating limits are implemented in the MBI, such as the charging and discharging current and SOC, and terminal data to avoid battery damage [7].

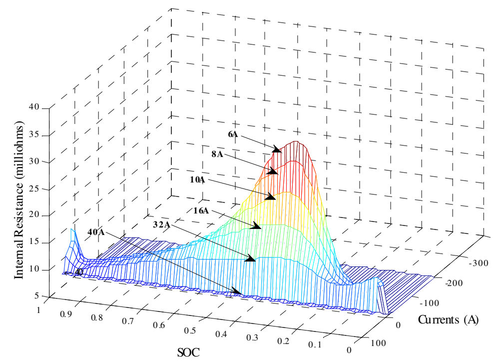


(a) Overview of the model implementation

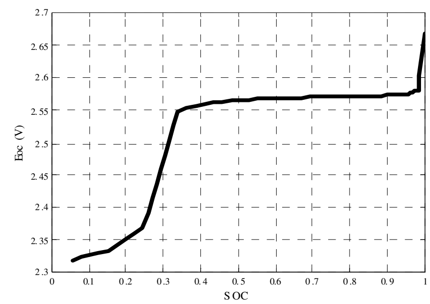


(b) Simulink presentation

Fig. 1 ZEBRA Battery model



(a) Internal resistance function

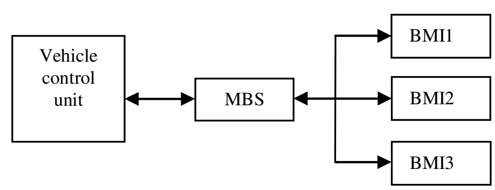


(b) Open circuit voltage vs. SOC

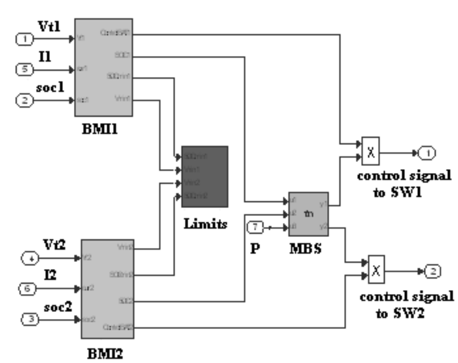
Fig. 2. Look-up-table functions for ZEBRA battery

3.3 ZEBRA Multi-battery system

In high energy/power applications, a number of batteries may be connected in parallel to obtain the required energy levels or satisfy and the peak power demands. In these multi-battery applications, a controller is needed to supervise the BMIs of each battery, here, this controller is called multi-battery server (MBS), and operates as an interface between the individual battery systems via their BMIs to the vehicle energy management unit. Fig. 3 illustrates an overview of the multiple battery server in the vehicle energy management hierarchy (a) and an example Simulink model for the case of two parallel batteries (b). As discussed, the ZEBRA battery could be operated in with failed cells, though with a reduced energy capacity and open circuit voltage. However, it parallel batteries have a different number of failed cells, the terminal voltage of the batteries will be unbalanced and hence their individual SOC. The Simulink model takes into account possible variation between batteries, and can be used to analyse the performance of the multiple battery systems in the case of various unbalance operating scenarios.



(a) Overview of multi-battery server (MBS)



(b) MBS scheme.

Fig. 3. Simulink MBS model for two parallel batteries.

3.4 MBS algorithm

The MBS manages the unbalanced system to maintain vehicle functionality by disconnecting the faulty battery or the lower SOC battery in order to discharge other batteries to an equitable level.

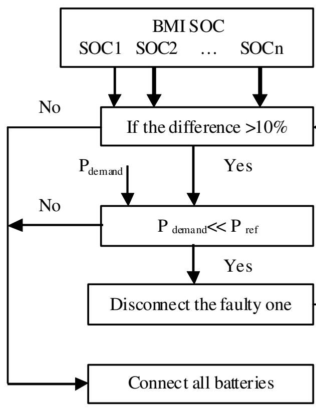


Fig. 4. Flowchart of MBS operation

The algorithm reported here maintains the SOC of each battery at within a variation not more than 10% SOC. If the vehicle demand power could be provided without the faulty battery, the MBS will disconnect the faulty battery, and the power will thus be developed from the remaining healthy batteries, however, they still disconnect until the difference in SOCs is less than 10%. Nevertheless, if the vehicle demand is high, the MBS keeps all batteries connected to supply the demand. Fig.4 illustrates a flow chart of the MBS algorithm.

4 Simulation results

Some results of simulation of various percentage of cell failure are presented in this section, Table1 provides a result obtained with two zebra batteries with full cell capacity for London taxi over repetitive NEDC driving cycles. The total distance travelled in this case of simulation is 94 km, the profile of the power demand during NEDC are illustrated in Fig.5.

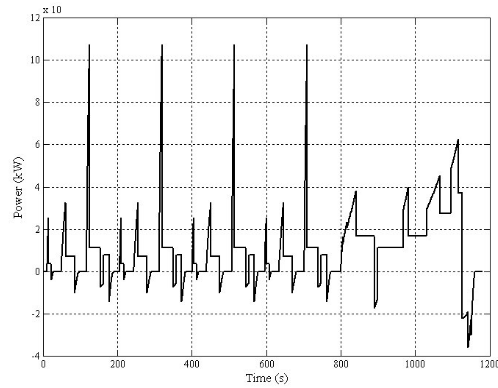


Fig.5 Battery power demand over NEDC driving cycle.

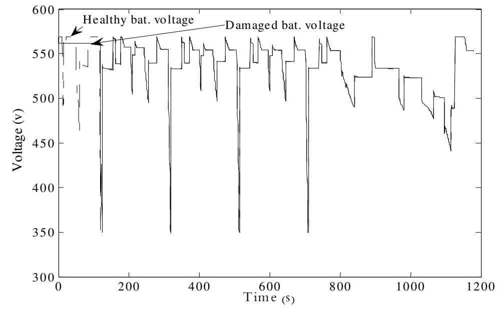
The first case studied is for 2 cell failures in one battery. It is clear from Fig. 6 that in first 150 second, the damaged battery is switched OFF in order to discharge the healthy battery to a voltage level equitable to that of the damaged one. It can be noted that the MBS keeps battery OFF when two things are valid; (i) the state of charge of the healthy battery is greater than the damanged battery and (ii) the healthy battery can provide the load demand. The range of the vehicle is slightly affected, as shown in Table 1.

Fig. 7 shows the second case when the number of failed cells increases to 5. The performance of the vehicle is consequently greater affected than the first case. The healthy battery has the to supply the demand power for 250 seconds.

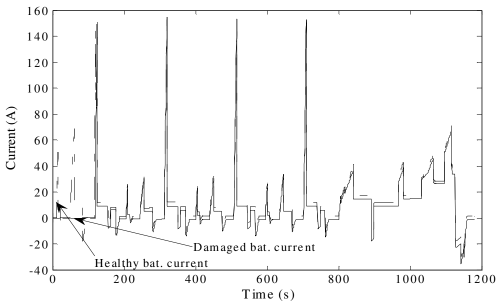
Fig.6(d) and 7(d) shows the state of charges of the two batteries in the two cases. It is clear that the MBS switches the contactors to ON as shown in the Fig.6(c) and 7(c). The contactors are ON during the driving cycle unless they are outside of the battery parameter limits that can be controlled from the BMI. Table 1 shows the impact of cell failure on vehicle range.

Table 1: Impact of cell failure on vehicle range.

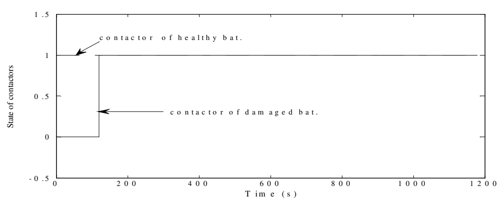
Battery 1	No. of failed cells in Battery 2	Range (km)
Full capacity	0	94.0
Full capacity	2	92.0
Full capacity	5	86.5



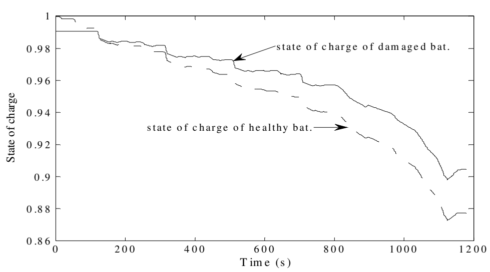
(a) Terminal voltages of two batteries



(b) Currents of two batteries

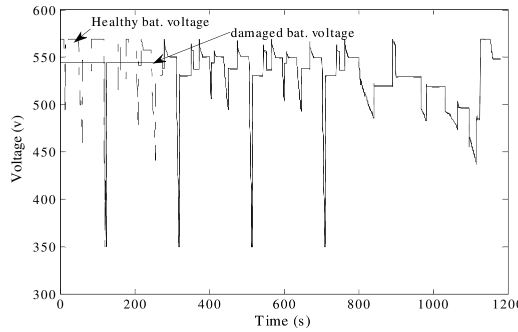


(c) States of the battery contactors

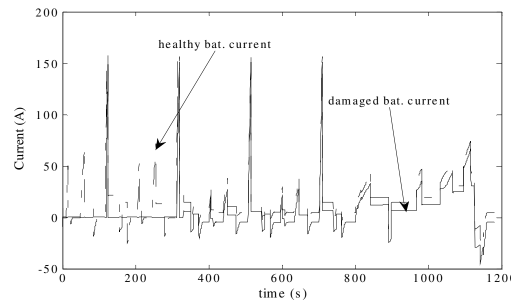


(d) State of charges of both batteries

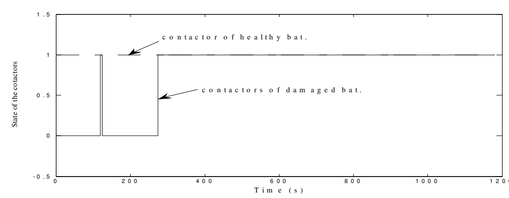
Fig. 6. Case of 2 cell failure in battery 2



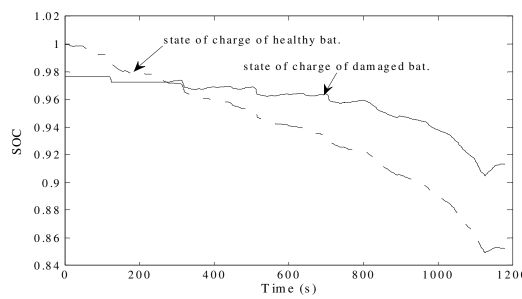
(a) Terminal voltages of two batteries



(b) Currents of two batteries



(c) States of the battery contactors



(d) State of charges of both batteries

Fig. 7. Case of 5 cell failure in battery 2

5 CONCLUSIONS

In this paper, the ZEBRA battery model has been developed and integrated in vehicle model implemented in Simulink/ Matlab software. The vehicle energy storage system in the model is 2x ZEBRA battery connected in parallel and controlled via a multi-battery service MBS.

Although the ZEBRA battery can tolerate up to 10% series cell failures, none of the available software packages could simulate this feature in a specific battery in the case of damage occurring in a variety of failed cell combinations.

In this paper, a simulation model for this feature has been discussed and results for two examples presented. The results show the effect of the cell failure on the vehicle performance.

An BMS algorithm has been implemented to maintain the vehicle functionality and manage the unbalanced battery system. The strategy of MBS is to disconnect the faulty battery or the lower state of charge battery in order to discharge other batteries to a same level.

Acknowledgments

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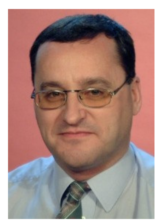

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