Adaptive State of Health Evaluation Method Study for High Power Aerial Lithium-ion Battery Packs

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Abstract. A novel and effective method is proposed to estimate the SOH (State of Health) value of the high power aerial LIB (Lithium-Ion Battery) packs. The comprehensive SOH evaluation is realized by using the improved CI-EKF (Credibility Inference - Extended Kalman Filter) algorithm together with the discharging and charging maintenance experimental process, implying the accurate and adaptive SOH effect. The proposed method is used in the SOH evaluation process of the aerial LIB pack, with minimal time demand of self-learning treatment. The results indicate that the SOH values can be estimated effectively at different working conditions, in which the evaluation accuracy rate is up to 95.00% for the experimental samples of the aerial LIB pack, providing the technical support for the reliable application of the high power LIB pack and playing a core role in its power supply promotion.

1. Introduction

The parameter of SOH (state of health) is one of the core factors for the battery-based energy storage and supply systems in various energy supply applications. With respect to the cell to cell variation in the lithium-ion battery (LIB) packs of the high power energy supply application, the SOH evaluation in the associated battery management system is becoming more and more challenging. This should be solved under the limited computational resource requirement conditions (Lim et al., 2016). The discharging and charging voltage-temperature pattern recognition of the improved SOH prediction at various temperatures based on the application of the Hamming network-dual EKF (Extended Kalman Filter) is investigated (Kim et al., 2015). This was implemented by the bilinear interpolation method. The advanced SOH evaluation methods are described (Dave et al., 2016) by the detailed deduction of an interaction of the standard KF(Kalman Filter) and the UKF (Unscented Kalman Filter) together with the SVM (Support Vector Machine) algorithm. However, the monitoring methods of the LIBs of the high power aerial LIB pack are still lack of systematic evaluation methods are critically reviewed. A novel comprehensive evaluation method that is based on the CI-EKF(Credibility Inference - Extended Kalman Filter) algorithm and the discharging and charging experimental process is presented in this manuscript.
2. Mathematical Model Analysis

The internal working state monitoring structure of the associated battery management system, including the SOH evaluation model, is built for the application feature description and the state evaluation process of the aerial LIB pack. Especially in the aircraft application environment, the actual SOH values of the power LIB pack should be the crucial factors to be monitored because of its high security requirement. Meanwhile, the CI (credibility inference) algorithm is also used in the real-time correction treatment and self-learning dynamic evaluation adaptation of the aerial LIB packs. The parameter SOH is an important aspect for the aerial LIB pack that should be estimated by the associated BMS equipment. This is usually described as the core battery parameter correlated with its aging performance of internal resistance and capacity, indicating the power and capacity states of the aerial LIB pack. A novel online calculation and correction method is proposed in this study to realize the SOH evaluation of the aerial LIB pack, which is conducted by the application of the AI technology. The SOH evaluation model is shown in Fig. 1, which is built for the health assessment of the aerial LIB pack.

![Figure 1. The construction of the SOH evaluation model.](image)

The proposed method performs high accuracy advantages in the SOH evaluation process of the aerial LIB pack, in which the pattern recognition and CI treatment are conducted at various temperatures and discharging/charging current rates. In the comprehensive SOH evaluation process of the aerial LIB pack, the uncertainty representation of the SOH value for the individual LIB cell is established firstly by using the EKF method and its error covariance evaluation treatment. Those are used in the comprehensive SOH evaluation and evaluation process afterwards. The parameters are defined as follows. The prerequisite is predicated by the parameter $E$ for the evidence and the reasoning conclusion is predicated by the parameter $C$. The function $CF(C, E)$ is the certainty factor of the reasoning credibility and the concepts for cell level and pack level characterization are definite, which clearly describe the relationship between the connected battery cells and the total LIB pack and the calculation process is introduced as shown in Eq. 1.

$$CF(C, E) = MB(C, E) - MD(C, E)$$

(1)

The SOH values of every time points are estimated at long time intervals of the SOH evaluation framework for the aerial LIB pack, while other parameters used here are estimated in real time. In the framework implementation calculation treatment, the nonlinear CI method is used in the accurate evaluation process. When using this equation, a few characteristic parameters should be understood. In the equation, the function $MB(*, *)$ represents the measuring belief and credibility values in the evaluation process of the aerial LIB pack, which also indicates the confidence degree of the
characterization growth. The precondition evidence parameter $E$ makes the confidence degree $C$ of the growing conclusion to be true. The calculation process of the function $MB(*, *)$ is shown in Eq. 2.

$$MB(C,E) = \begin{cases} \frac{1}{\max\{P(C/E), p(C)\}} \cdot P(C) & \text{if } \{P(C) = 1\} \\ 1 - P(C) & \text{if } \{P(C) \neq 1\} \end{cases} \quad (2)$$

A detailed methodology to assess the SOH value of the aerial LIB pack from the knowledge of individual cells, electrical topology and balance control approach that are conducted in our previous work is presented in this manuscript. The evaluated value of the aerial LIB pack is correlated with the remaining capacity of the individual battery cells. This is due to the aerial LIB pack being composed of battery cells in series and parallel connection with the real-time balance adjustment. The function $MD(*, *)$ represents the measuring disbelief degree and indicates the distrust characterization growth, in which the precondition evidence parameter $E$ does not match the trust growth conclusion of the parameter $C$. The calculation process of the function $MD(*, *)$ is shown in Eq. 3.

$$MD(C,E) = \begin{cases} \frac{1}{\max\{P(C/E), p(C)\}} \cdot P(C) & \text{if } \{P(C) = 1\} \\ 1 - P(C) & \text{if } \{P(C) \neq 1\} \end{cases} \quad (3)$$

Wherein, the prerequisite parameter $P(C)$ is the priori probability of the parameter $C$. When $MB(C,E)>0$ and $MB(C,E)>P(C)$, the evidence indicates that the corresponding parameter $E$ appears to increase the confidence degree of the parameter $C$. When $MB(C,E)>0$ and $MB(C,E)<P(C)$, the evidence indicates that the corresponding parameter $E$ appears to increase the distrust value of the parameter $C$. Both of the function $MB(C,E)$ and the function $MD(C,E)$ are mutually exclusive. Specially, the inaccurate online SOH evaluation is the main drawback in the commercialization process of the power LIB pack in different working conditions. The characteristic limits the endurance mileage of the power supply application. Moreover, the associated BMS equipment including the accurate SOH evaluation requires high cost in replacing the LIB cell to the aerial LIB pack. This prevents the manufacturers from binging LIB pack into the power supply application, even though this reduces their everyday cost considerably. The power capability of the aerial LIB pack is restricted by the lower voltage limit of the internal connected battery cells in the discharging process. This will also be restricted by the upper voltage limit in the charging process. The battery cell with the largest internal resistance will first reach the low voltage limit. The comprehensive value of the aerial LIB pack is highly determined by the battery cell with the largest internal resistance. According to the calculation process established above, the seeking method of the function $CF(C,E)$ is shown in Eq. 4.

$$CF(C,E) = \begin{cases} \frac{P(C/E) \cdot P(C)}{1 - P(C)} & \text{if } \{P(C/E) > P(C)\} \\ 0 & \text{if } \{P(C/E) = P(C)\} \\ \frac{P(C/E) \cdot P(C)}{P(C)} & \text{if } \{P(C/E) < P(C)\} \end{cases} \quad (4)$$

The comprehensive SOH evaluation problem of the aerial LIB pack is casted into the evaluation problem correlated with the parameters of capacity and internal resistance with these definitions in mind and for the simplicity of the discussion and treatment. The condition that the parameter $P(C/E)$ equals to the parameter $P(C)$ indicates that the corresponding characters of $E$ and $C$ are independent evidences and the factor $CF(C, E)$ is in the range of [-1, 1]. The structural analysis model is built for the
SOH evaluation of the aerial LIB pack with the characteristics of multi-input conditions. As a result, the CI reasoning model needs to be built for the combination of varying working conditions, in case of multiple characters. During the different step calculation and analysis process of the temperature, voltage, and other parameters, the analyzing and reasoning model is built for the comprehensive evaluation of the credit combination conditions and these input-parameters have conjunctive relations. These multiple input parameters constitute a combination of various conditions, some of which have conjunctive relationships as shown in the first part of the equation. As the AI and machine learning techniques grow rapidly in advance for the data-driven prognostics, it has become quite popular for the working state evaluation of the power LIB pack in the associated BMS equipment, especially in the online SOH evaluation. The credibility matrix of various input parameters \((E_1, E_2, E_3, \ldots, E_n)\) were established, which are shown as \(CF(E_1), CF(E_2), CF(E_3), \ldots, CF(E_n)\). Then, the total credibility calculation for these input parameters were shown in the second part of Eq. 5.

\[
\begin{align*}
E &= E_1 \wedge E_2 \wedge E_3 \wedge \cdots \wedge E_n \\
CF(E) &= \min\{CF(E_1), CF(E_2), CF(E_3), \ldots, CF(E_n)\}
\end{align*}
\]  

The electrolyte resistance and charge transfer resistance are adopted as the model inputs of the aerial LIB pack. The values are predicted to compute the corresponding battery capacity. As stated above, the comprehensive SOH evaluation has high energy and power specifications. Therefore, the evaluation model design for the aerial LIB pack should consider a number of working environment-related input parameters aiming to satisfy the energy and power requirements of the high power supply application simultaneously, some of which are in disjunctive conditions as shown in the first part of Eq.6. A multi-time-scale framework is built for estimating the SOH value in the associated BMS equipment with series and parallel topology in order to characterize the working performance of the aerial LIB pack. According to the definitions of the working state parameters for the aerial LIB pack, the level information of the battery cell in the aerial LIB pack need to be known. However, the separate evaluation step of every LIB cell at every time point will cause extremely high computational effort. As a result, this is not practical for the high power packing energy supply applications. In order to solve this problem, the comprehensive credibility of these various input parameters were established, which were described by using the above specificity values and the total confidence calculation process of these input parameters as shown in the second part of Eq. 6.

\[
\begin{align*}
E &= E_1 \vee E_2 \vee E_3 \vee \cdots \vee E_n \\
CF(E) &= \max\{CF(E_1), CF(E_2), CF(E_3), \ldots, CF(E_n)\}
\end{align*}
\]  

The ECM technique is used as the first principle characterization, which is expressed by using the partial differential equations in the SOH evaluation process of the aerial LIB pack. Due to their mathematical complexity, it is not suitable for solving the real-time working state evaluation problems directly in the associated BMS equipment. However, it can capture the dynamic performance of the input and output parameters of the battery power supply system by using the electrical circuit elements. The construction of the ECM proposed in this manuscript can be obtained by electro-chemical impedance spectroscopy or the time-domain parameter identification techniques. The proposed comprehensive evaluation method represents an excellent compromise between accuracy and calculation complexity, which makes it suitable for the real-time application in the associated BMS equipment of the aerial LIB pack. The individual condition credit of the parameter \(E\) can be characterized by the parameter \(CF(E)\) and the condition establishing rule of the inference credit.
reliability can be described by using the function $CF(C, E)$, in which the reliability calculation process of the parameter $C$ is shown in Eq. 7.

$$CF(C) = CF(C, E) \times \max\{0, CF(E)\}$$  \hspace{1cm} (7)

The CI-based comprehensive SOH evaluation of the aerial LIB pack is different to the traditional evaluation methods by using these multi-input parameters. Every calculation process has been treated to strike the comprehensive credibility by using the synthesis algorithm. Each independent multi-criterion in the comprehensive synthesis method is described and the comprehensive value for different input conditions can be realized under these two input parameter conditions. The reliability of the evaluation results can be calculated according to the above equation, which can be stricken to the calculation as shown in Eq. 8.

$$\begin{align*}
CF_1(C) &= CF(C, E_1) \times \max\{0, CF(E_1)\} \\
CF_2(C) &= CF(C, E_2) \times \max\{0, CF(E_2)\}
\end{align*}$$  \hspace{1cm} (8)

The comprehensive SOH value of the aerial LIB pack is not estimated directly. However, it can be calculated by estimating the actual capacity and the Ohmic resistance of each battery cell. Herein, the comprehensive evaluation value can be calculated, the calculation process of which is based on a single one battery cell evaluation value calculation condition in order to evaluate the credibility. This calculation process is to strike the combined evaluation effect of the parameter $E_1$ and the parameter $E_2$, in which the CI value of the parameter $CF(C)$ is used in the credibility formation treatment process and the calculation process of the parameter $CF_{1,2}(C)$ is shown in Eq. 9.

$$CF_{1,2}(C) = \begin{cases} 
\frac{CF_1(C) + CF_2(C) - CF_1(C) \times CF_2(C)}{1 - \min\{|CF_1(C)|, |CF_2(C)|\}} & \text{if } \{CF_1(C) > 0, CF_2(C) > 0\} \\
\frac{CF_1(C) + CF_2(C) + CF_1(C) \times CF_2(C)}{1 - \min\{|CF_1(C)|, |CF_2(C)|\}} & \text{if } \{CF_1(C) \times CF_2(C) < 0\} \\
\frac{CF_1(C) + CF_2(C) + CF_1(C) \times CF_2(C)}{1 - \min\{|CF_1(C)|, |CF_2(C)|\}} & \text{if } \{CF_1(C) < 0, CF_2(C) < 0\}
\end{cases}$$  \hspace{1cm} (9)

According to this pair-wise computational process, the proposed comprehensive evaluation method is realized for the aerial LIB pack in the associated BMS equipment by using the credibility based calculation process. The evaluation process can be done accordingly by the modeling establishment of the multiple-input parameter condition for the aerial LIB pack power supply system, such as temperature, voltage, current, time, and fault number among others. In order to form a comprehensive credibility evaluation system for the multi-input conditions, the associated BMS equipment was designed and promoted. This was used for the real-time working state monitoring and energy management, protecting the safety of the power supply system for the aerial LIB pack.

3. Experimental Analysis

The M-ICPXX series of the aerial LIB packs are chosen as experimental samples and then the comprehensive SOH evaluation experiments were carried out by the multi-input integrated inference credibility bases of the aerial LIB pack parameters, which include voltage, current, temperature, time, and internal resistances. The comprehensive credibility under various working conditions should be evaluated to determine the SOH value of the aerial LIB pack experimental samples. Extending the concept of the capacity definition for an individual cell into pack level definition, the pack capacity is given by the total ampere-hours drawn from the fully charged cell in the battery pack until one of the cells in the pack is fully discharged. The comprehensive SOH evaluation experiments are carried out
by the multi-input integrated inference credibility basis of the LIBs parameters. The comprehensive credibility under various conditions is evaluated to determine the health status of the LIBs. The accuracy of the prediction results is verified by comparing with the original health status values of the LIBs samples. The evaluation results are shown in Fig. 2.

![Graph showing SOH evaluation results](image)

Figure 2. The experimental results of the SOH evaluation.

The parameter Bat-Type represents Battery Type and Bat-Num represents Battery Number, which can be gained from the comparative analysis of the experimental SOH value and the original SOH value. The battery SOH evaluation model uses five alternative types of the experimental study. The original and experimental values are estimated by using the percentile (%) numerical representation, which characterizes the range of the interval evaluation appropriately. Experimental results show that the comprehensive SOH evaluation method based on the credibility inference obtains the values with high consistency. The judgment accuracy rate value is bigger than 90% by using the comprehensive SOH evaluation strategy, which indicates that this method can estimate the health status of the aerial LIB pack effectively.

4. Conclusion

In this study, a novel and powerful SOH evaluation method for the aerial LIB pack named as CI-EKF has been successfully reported in which the CI mathematical methodology can be combined for this purpose. This method is developed for the working state evaluation of the aerial LIB pack, the comprehensive evaluation model of which is realized by using the ideological credibility inference treatment, effectively guaranteeing the reliability of the emergency battery power supply application, which plays a positive useful role of the promotion of the high power LIB pack.

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