Development of the Intelligent Charger with Battery State-Of-Health Estimation Using Online Impedance Spectroscopy

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Abstract — In this research, a novel intelligent charger with battery diagnosis function is proposed. The diagnosis function is implemented by way of impedance spectroscopy achieved by controlling the charger to create a frequency swept excitation voltage at the battery terminals with no additional hardware. The impedance variation of battery according to the degradation over the life is measured and used for evaluating the State-of-Health (SOH) of the battery. The voltage perturbation and the current response of the battery are measured by the digital lock-in amplifier embedded in the digital signal processor (DSP) in order to calculate the impedance of the battery. The parameters of the equivalent circuit model for the lead-acid battery are extracted by using the complex non-linear least square method and compared to the reference values to estimate the SOH of the battery. The design procedure of the proposed charger is detailed and the feasibility of the system is verified by the experiments.

Keywords—Intelligent charger; State-Of-Health; Battery Diagnosis; Electrochemical Impedance Spectroscopy; EIS

I. INTRODUCTION

Lead-acid batteries are often used as an energy storage element in the electric vehicle applications, back-up power supply systems and renewable energy systems due to their reliability and affordability.

Since the battery performance is in line with the end product reliability and lifetime expectations, it is important to know the State-of-Health (SOH) of the battery to avoid the possible replacement cost due to the sudden failure of the system associated with it. It is also important to know the SOH of the battery, while it is being used, for the scheduled maintenance and the replacement. However, since the battery is gradually aged as the operating hour accumulates and eventually it reaches its End-of-Life (EOL), it is difficult to decide the suitable time for the replacement of the battery. Thus, it is necessary to investigate the SOH of the battery in order to improve the reliability of the system.

The SOH of a battery is defined as the relative ratio of the battery capacity at its current state over the nominal capacity when it was new. As discovered in the previous research results, the SOH of the battery is affected by many factors such as the Depth-Of-Discharge (DOD), variation of the temperature, rate of the charge current, and etc., [1, 2]. Therefore, the SOH estimation of the battery is quite complex due to the nonlinear relationship between SOH and those factors. Various kinds of method to estimate the SOH have been proposed in [3, 4]. One method is to estimate the SOH of the battery by calculating the maximum available capacity of the battery by using coulomb counting [3]. However, since the battery has to be fully charged and discharged in order to perform the current integration, this method cannot be applied while it is being used. The other method is based on the Extended Kalman Filter (EKF) to perform online estimation of the State-Of-Charge (SOC) and SOH for the battery [4]. This method makes it possible to estimate the SOH of the battery with a good accuracy. However, the model of the battery should be accurate enough to provide the good estimation results and the algorithm is quite complex. Also the accuracy of the estimation would be getting worse as the battery degrades because the parameters of the battery vary.

Recent research results have found that the battery aging can be estimated by monitoring the variation of the internal impedance of the battery over its aging process [4, 5]. The SOH of the battery can be estimated through the periodical monitoring for the variation of the internal impedance. If this diagnosis function can be embedded in the charge controller, the reliability of the battery based system can be significantly improved since the SOH can be monitored after every charge process. Also, the cost and the time for system maintenance can be significantly reduced by monitoring the state of battery automatically and periodically.

In this research, a novel intelligent charger with SOH estimation function for the lead-acid battery is proposed. The proposed charger can charge the lead-acid battery by CC/CV method and perform the impedance spectroscopy by adding a swept sinusoidal voltage perturbation over the frequency of interests to the voltage controller of the charger. The digital lock-in amplifier is then used to calculate the impedance spectrum with the measured voltage and current data. The parameters for the equivalent circuit of the lead-acid battery
are extracted by using complex nonlinear least-squares fitting method and the parameters are compared to those of the fresh lead-acid batteries to estimate the SOH of the battery. It is advantageous that the proposed method is applicable to any type of the charge converter and can be implemented with no additional hardware.

II. STATE-OF-HEALTH ESTIMATION OF THE LEAD-ACID BATTERY BY USING ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY AND ITS EQUIVALENT CIRCUIT MODEL

Electrochemical impedance of the battery is a complex quantity, $Z(f)$, which represents the current state of the battery as it is [6] and it can be used as a powerful tool for modeling and diagnosing the electrochemical power sources such as battery, fuel cell and supercapacitor. Various methods can be used to measured the electrochemical impedance of the battery are also listed in [6]. However, most of the commercially available EIS instruments are developed suitable for measuring the impedance of the single cell or small module and very high in cost. Hence they are typically used for the research and development purposes.

The impedance spectroscopy technique can be generally performed using an impedance spectroscopy instruments which generate a small voltage or current excitation signal at the frequency of interest ($f$) to the battery. Then, with the measured current and voltage data the impedance of the battery can be calculated as follows.

$$Z(f) = \frac{V(f)}{I(f)}$$

Where:
- $Z(f)$: The electrochemical impedance of the battery at the frequency of $f$.
- $V(f)$: Voltage perturbation (or response) at the frequency of $f$.
- $I(f)$: Current response (or perturbation) with respect to the voltage perturbation at the frequency of $f$.

Since the response of the battery with respect to the excitation signal is different according to the different value of the battery impedance which represents the state of the battery, the electrochemical impedance determined by the equation (1) can be used to investigate the state of the battery.

The aging processes of the lead-acid battery consist of anodic corrosion, positive active mass degradation and loss of adherence to the grid, irreversible formation of lead sulfate in the active mass, short circuit and loss of water [7]. Among the processes, anodic corrosion is considered to be the major effect since it leads to the decrease in the cross section of the grid hence reducing the conductivity and mechanical stability accordingly. This results in decreasing the power performance due to the increase in internal resistance and the capacity loss, because parts of the active mass lose contact with the grid [8].

Generally, the increase of the ohmic resistance and the deterioration of the capacity are the main consideration for the aging of battery. Therefore, if the parameters of the battery equivalent circuit model shown in Fig. 1 can be extracted by the proposed charger, it is possible to estimate the SOH of the battery by monitoring the variation of the parameter values in the battery equivalent circuit over the degradation process. In [4], a method to estimated the arbitrary state of a battery using its equivalent circuit parameters is suggested. This method requires the equivalent circuit parameters of the battery in the fresh and aged conditions to estimate its SOH.

The SOH of an arbitrary battery can be estimated by using its internal resistance as (2) [4]:

$$SOH = \frac{R_{\text{electro}} - R_{\text{aged}}}{R_{\text{fresh}} - R_{\text{aged}}}$$

where:
- $R_{\text{electro}}$: The ohmic resistance of the battery at the test ($\Omega$).
- $R_{\text{fresh}}$: The ohmic resistance of the fresh battery ($\Omega$).
- $R_{\text{aged}}$: The ohmic resistance of the aged battery ($\Omega$).

III. PROPOSED INTELLIGENT CHARGER WITH EMBEDDED BATTERY DIAGNOSIS FUNCTION

Fig. 1 shows the block diagram of the proposed intelligent charger with embedded diagnosis function by using online impedance spectroscopy technique. The charger consists of a bidirectional DC/DC converter and a Digital-Signal-Processor (DSP) that performs the digital control of the charge converter and the diagnosis function for the battery by EIS.

The operation of the charger can be divided into two main operations, the charge and the EIS operation. In the charge operation, the charger charges the battery by CC/CV method until it is fully charged and then the impedance spectroscopy is performed to get the impedance spectrum of the battery. At the beginning, the battery is charged by the CC mode with the rated charge current, C/10 rate in this case, in order not to exceed the maximum charge current recommended by the battery manufacturer. Then the battery is charged by the constant voltage of 14.4 (V) until the charge current is decreased to 0.02C, which indicates that the battery is fully charged. In order to calculate the impedance of the battery at the frequency of interest, a small sinusoidal voltage
perturbation is applied to the battery terminal by way of the voltage controller of the charge converter and the current response with respect to the voltage perturbation is then measured over the measurement frequency range. In this study, the perturbation frequency is swept from 0.1 (Hz) to 1.0 (kHz) to get the useful impedance spectrum. The Digital Lock-In Amplifier (DLIA) implemented in the DSP is used to calculate the ac impedance of the battery at the frequency of interest. Since the charge converter is bidirectional, the battery can be charged and discharged within a cycle of perturbation. Hence the charge of the battery is the same before and after the test and the linearity of the test can also be ensured. The Complex Non-linear Least Square (CNLS) method is used to extract the parameters of the equivalent circuit for the lead-acid battery, which will be used to estimate the SOH of the battery by comparing the parameter values of the aged lead-acid battery to those of the fresh one.

Since the SOH of the battery can be monitored automatically and periodically by the proposed charger, sudden failure of the battery can be avoided. It also helps increase the reliability of the system and thus reduces the cost for the possible replacement and maintenance.

IV. DESIGN OF THE CONTROLLERS FOR THE PROPOSED INTELLIGENT CHARGER

The converter employed in the proposed charger is required to be bidirectional in order to generate the perturbation for the EIS of the lead-acid battery. It should be noticed that the battery need to be neither charged nor discharged during the impedance spectroscopy test since the battery parameters will vary consequently. Thus the EIS has to be performed after the battery is fully charged. The step-down converter topology is selected for the charger so that it can charge the lead-acid battery with the power from the utility. By replacing the diode in the conventional buck converter with an N-channel MOSFET, the bidirectional converter can be implemented as shown in Fig. 1.

By applying the small-signal modeling technique to the charge converter including simplified R-C model of the lead-acid battery, the control to output voltage ($G_{vd}$) and the control to inductor current ($G_{id}$) transfer functions can be obtained as follows:

$$G_{id} = \frac{V_{dss} \times (R_{g} C_{d} + 1)}{s^2 L_{R} R_{p} C_{out} + s^2 L_{C} C_{out} + s R_{p} C_{o} + 1}$$  \hspace{1cm} (3)

$$G_{vd} = \frac{V_{dss} \times [C_{out} R_{p} + (C_{o} + C_{out}) s]}{s^2 L_{R} R_{p} C_{out} + s^2 L_{C} C_{out} + s R_{p} C_{o} + 1}$$  \hspace{1cm} (4)

In the design of the voltage controller, the selection of the crossover frequency is important because the perturbation should not be distorted for the accurate impedance measurements. Since the impedance measurements need to be performed from 0.1 [Hz] to 1 [kHz] to get the useful impedance spectrum, the bandwidth of the closed-loop system should be selected ten times higher than the highest frequency of measurements in order to avoid the distortion. Thus, the bandwidth of the voltage loop is selected at 10.0 [kHz] in this case. There is no difficulty in designing the current controller since the charge process does not require high dynamic of the current control loop. In this case, the bandwidth of the closed-current loop system is chosen at 3.0 [kHz], 1/20 of the switching frequency, to reduce the effects of high frequency noise to the closed-loop system.

V. DIGITAL LOCK-IN AMPLIFIER EMBEDDED IN THE DIGITAL SIGNAL PROCESSOR

DLIA technique is used to calculate the impedance spectrum with the measured voltage and current. It is a popular signal extracting technique due to its precise measurement performance even in the presence of the high noise levels. The small ac signal superimposed by a dc component and noise detected by the DLIA can be expressed in discrete form as

$$X[n] = DC + A \sin \left(2 \pi \frac{f}{f_r} n + \theta\right) + u(n) ; n = 0,1,2,... \hspace{1cm} (5)$$

In the digital lock-in amplifier, the sine and cosine reference signals at the same frequency of interest are numerically generated by the microcontroller as shown in (6). The advantage of the numerically generated reference signal is that it can be immunized from noise [9].

$$S[n] = \sin \left(2 \pi \frac{f}{f_r} n\right), \quad n = 0,1,2,... \hspace{1cm} (6)$$

$$C[n] = \cos \left(2 \pi \frac{f}{f_r} n\right), \quad n = 0,1,2,...$$

The detected signal is then multiplied by the sine and cosine reference signal respectively in order to get the in-phase and quadrature-phase signal as follows.

$$I[n] = X[n] \times S[n] = \frac{A}{2} \cos(\theta) + AC \hspace{1cm} (7)$$

$$Q[n] = X[n] \times C[n] = \frac{A}{2} \sin(\theta) + AC \hspace{1cm} (8)$$

By filtering the ac component in (7) and (8) by using Moving Average Filter (MAF), the magnitude and phase of the input signal can be computed as in (9) and (10).

$$x = 2 \times I[n] = A \cos(\theta)$$

$$y = 2 \times Q[n] = A \sin(\theta)$$

$$M = \sqrt{x^2 + y^2} = A; \quad \theta = \tan^{-1} \left(\frac{y}{x}\right)$$  \hspace{1cm} (10)

The complex impedance of the battery can be formed by the equation (11).

$$Z(a_j) = R(a_j) + jX(a_j)$$  \hspace{1cm} (11)

Where,
VI. PARAMETER EXTRACTION OF THE EQUIVALENT CIRCUIT MODEL FOR LEAD-ACID BATTERY

The lead-acid battery can be modeled by the equivalent circuit model as shown in Fig. 2. This equivalent circuit consists of elements that reflect the electrochemical reaction occurring inside the lead-acid battery. \( L \) is the inductance caused by metallic connection between the poles and electrodes of the battery. \( R_s \) is the ohmic resistance determined by the conductivity of the electrolyte and the electrical pathway. \( R_p \) and \( C_p \) describe the transient behavior caused by the charge transfer reaction. \( W \) is the Warburg impedance that describes the diffusion phenomenon of the battery.

![Fig. 2. Equivalent circuit model of the lead-acid battery](image)

In order to estimate the SOH of the lead-acid battery, it is required to obtain the parameters of the equivalent circuit of the battery which can be extracted by using the least-square fitting algorithm.

In this work, the complex nonlinear least-squares (CNLS) fitting method is used to estimate the value of the battery parameters. The CNLS method is a kind of the Levenberg–Marquardt least-square method which can be applied for complex number. The method requires the measured impedance data of the battery and the equivalent circuit model as shown in Fig. 2 [10]. Then it tries to minimize the error between the measured impedance data and the calculated impedance data with a certain set of model parameters by the iterative calculation in order to get the best fitted parameters. The complex impedance at the frequency of interest of the battery which can be extracted by using the least-square fitting algorithm.

The charge profile of the lead-acid battery obtained by the proposed intelligent charger is shown in Fig. 4. At the beginning of the operation, the lead-acid battery is charged by CC mode with the rated charge current (4.0A, 0.1C), in this its previous value and the variation of the approximated parameters. If the approximated parameters have a variation, \( \Delta \), the following expression can be obtained by using Taylor series expansion as (15).

\[
Z(\omega)_{\text{new}} = Z(\omega)_{\text{old}} + \frac{\partial Z(\omega)}{\partial \theta_i} \Delta \theta_i, \quad i = 1, 2, \ldots, 5
\]

The value of \( \Delta L, \Delta R_s, \Delta R_p, \Delta C_p, \) and \( \Delta A_W \) are then calculated by using (16).

\[
\Delta \theta = A^T.G
\]

Where,

\[
A = \left[ \begin{array}{c} (Z_R)^\top - Z_R + (Z_i)^\top - Z_i \\ (Z_R)^\top - Z_R + (Z_i)^\top - Z_i \end{array} \right]
\]

\[
G = \left[ \begin{array}{c} -\Delta y_R + (Z_i)^\top \cdot \Delta y_i \\ -\Delta y_R + (Z_i)^\top \cdot \Delta y_i \end{array} \right]
\]

\[
[Z_R]_i = \text{Re} \left( \frac{\partial Z}{\partial \theta_i} \right); \quad [Z_i]_i = \text{Im} \left( \frac{\partial Z}{\partial \theta_i} \right)
\]

\[
[\Delta y_R]_i = \text{Re} (Y - Z_i); \quad [\Delta y_i]_i = \text{Im} (Y - Z_i)
\]

The above process can be performed by using an iterative method implemented in a digital-signal-processor. In the first iteration loop, the value of \( \Phi \) is calculated with the initial value of the approximated parameters. Then the variation of the parameters is calculated and \( L, R_s, R_p, C_p, \) and \( A_W \) are updated for the next iteration. The calculation is repeated until the value \( \Phi \) converges to a certain limit in order to obtain the best fitted value for the battery model parameters.

VII. EXPERIMENTAL RESULT

Fig. 3 shows the experimental set-up of the proposed system which consists of a DC power supply, a 12V 40 Ah lead-acid battery and the proposed charger. The charge controller and the EIS function are implemented in a DSP TMS320F28335 from Texas Instrument.

![Fig. 3. Experimental setup for the proposed intelligent charger](image)
case. After the battery voltage reaches 14.4V recommended by the battery manufacturer, the charge operation is switched to CV mode to charge the battery at the rated voltage of 14.4V until the charge current reduced to 0.8A (0.02C) indicating the fully charged state of the battery. The EIS is invoked to calculate the impedance spectrum of the battery after the charge operation. A small perturbation voltage is generated and applied to the battery by adding a small sinusoidal signal to the reference value of the voltage controller. The voltage perturbation sweeps from 0.1 (Hz) to 1.0 (kHz) to get the useful impedance spectrum.

In order to verify the accuracy of the impedance measured by the proposed charger, the results obtained by the proposed charger are compared to those by the commercial EIS instrument (BPS instrument, Kumho). As shown in Fig. 5 two results are well-matched and the Chi-square calculated is 0.91% which represents the strong correlation between two results.

VIII. CONCLUSION

A novel lead-acid battery charger with embedded diagnosis function using online impedance spectroscopy was proposed. The impedance spectrum of the battery was successfully measured by the proposed charger. Also, the battery parameters were consequently extracted by the CNLS method implemented in the DSP of the proposed charger. With the proposed method the SOH of the battery can be monitored automatically and periodically, sudden failure of the battery can be avoided. It will also contribute to increase the reliability of the system thereby reducing the cost for the possible replacement and maintenance.

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