온라인 임피던스 분광법을 이용한 배터리 진단 기능을 가진 3kW 충전기

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A 3kW Battery Charger with Battery Diagnosis Function Using Online Impedance Spectroscopy

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ABSTRACT

In the battery based applications such as electric vehicle and energy storage system, the performance of the system highly depends on the reliability of the battery. However, it is difficult to obtain the accurate information about the state-of-health (SOH) of battery during its operation. In this paper a 3kw battery charger with battery diagnosis function which can estimate the SOH of the battery by using online impedance spectroscopy technique is introduced. For the charger phase shift full bridge converter with synchronous rectification has been adopted to implement the charge and diagnosis functions. The impedance spectroscopy is performed after the charge to obtain the information about the internal impedance of the battery module, hence the SOH can be estimated online by observing the impedance variation of the battery over time. All the design procedure of the proposed charger is detailed and the feasibility of the system is verified by the experimental results.

Index Terms – Charger, Battery Diagnosis, SOH, Phase Shift Full Bridge Converter, Impedance Spectroscopy

1. Introduction

In the battery based applications such as electric vehicle and energy storage system, the performance of the system highly depends on the reliability of the battery. Knowing the state-of-heath (SOH) of battery, it can not only prevent system from sudden failure but also prolong the service time of the battery. Since the battery lifetime is unpredictable and its aging is affected by many factors such as Depth-Of-Discharge (DOD), value of the charge/discharge current, temperature variation, corrosion, and etc.,[1,2,3]. Hence, it is difficult to obtain the accurate information about the SOH of the battery during its operation. Various battery SOH estimation methods have been proposed such as coulomb counting, model identification algorithms and electrochemical impedance spectroscopy (EIS)[1,3]. The EIS method can estimate SOH of battery with a good accuracy and easiness of hardware implementation[3]. However, most of the commercial EIS instruments are very high in cost and require additional hardware set-up for the SOH estimation.

In this research, a 3kw battery charger with battery diagnostic function for the lead-acid battery is presented. The proposed charger can provide conventional charge function for the lead-acid battery by constant current/constant voltage (CC/CV) charge method and perform the battery diagnosis function through electrochemical impedance spectroscopy. By adding a swept sinusoidal excitation signal to the voltage controller of the charger, the impedance spectrum of battery can be calculated based on the measured voltage and current data. Then the parameters for the equivalent circuit of the lead-acid battery are extracted for the online estimation of the SOH of the battery.

2. Design of the 3kW battery charger

The Phase-Shifted Full Bridge (PSFB) topology is employed to implement the 3kW charger as shown in Fig. 1. This topology guarantees the high efficiency during the charge process and bidirectional power flow for EIS operation. All the primary side switches (S_1, S_2, S_3 and S_4) are controlled by the phase shifted PWM scheme. With the help of resonance tank composed of leakage inductance of transformer and output parasitic capacitor of MOSFETs, the zero-voltage-switching (ZVS) can be achieved and it reduces the dominant loss at the primary side. Meanwhile, at the secondary side, the MOSFET switches are used for the synchronous rectification in order to reduce the conduction losses which would be significant with diodes and to provide bidirectional power flow for the EIS operation.

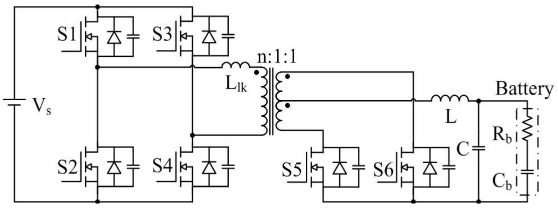

Fig. 1 Proposed battery charger with diagnostic function using online EIS.

Since the operation principle of the proposed converter is the same as conventional PSFB converter, hence it is omitted here. However the design of the controller is important to guarantee the successful EIS operation. The transfer function of control-to-inductor current, and control-to-output voltage, are expressed in equation (1), (2), respectively.

$$G_{id}=\frac{nV_S}{\frac{Z_bLCs^2+Ls+Z_b}{1+sZ_bC}+R_d} \tag{1}$$

$$G_{vd}=\frac{nV_S}{s^2LC+s\left(\frac{L}{Z_b}+R_dC\right)+\frac{R_d}{Z_b}+1} \tag{2}$$

Where $R_d=4n^2L_{lk}f_s$; $Z_b=R_b+\frac{1}{(sC_b)}$; n is the turns ratio of the transformer, L_{lk} is the leakage inductance of the transformer, and f_s is the switching frequency of the converter.

The dual loop control is used for the CC/CV charge method. It consists of an outer control loop, regulating the converter output voltage (CV mode) and an inner control loop, serving for output current control (CC mode). The battery current in CC mode is limited by the appropriate charge current value (0.12C, 45[A]).

The specification of the charger and the battery module can be found in Table 1.

Table 1 Specification of 3kW battery charger.

Input voltage	V_s	400 V
Output voltage	V_o	56.4 V
Rated power	P_o	3000 W
Switching frequency	f_s	60 kHz
Output capacitor	C	3000 µF
Output inductor	L	100 µH
Transformer ratio	N_p:N_s	25:5
Leakage inductance	L_{lk}	25 µH
Battery Capacity	Q	365Ah
Nominal voltage of the battery	V_{nom}	48.0 V
Maximum voltage of the battery	V_{max}	42.0 V
Minimum voltage of the battery	V_{min}	56.4 V
Equivalent capacitance of the battery	C_b	91250 F
Equivalent series resistance of the battery	R_b	118 mΩ

3. Battery diagnosis using impedance spectroscopy

After fully charge the battery, it is rested for an hour. Once the equilibrium is reestablished with open circuit voltage V_{oc}, the EIS method is performed by adding the small excitation voltage at the frequency of interest to the voltage controller.

$$V = V_{oc} + \Delta V = V_{oc} + V_m sin\omega t \tag{3}$$

This perturbation yields sinusoidal current response.

$$\Delta I = I_m sin(\omega t - \varphi) \tag{4}$$

If the voltage perturbation is small enough, the linearity of the test can be guaranteed. Also, if the charge/discharge operation within one cycle of excitation is balanced, the SOC would not be changed before and after the test thereby ensuring the reliability of the test. The voltage and the current responses are measured and the impedance of the battery at each frequency is calculated by the digital lock-in amplifier implemented in the digital signal processor.

The impedance of the battery can be calculated as (5)

$$Z(\omega) = \frac{\Delta V}{\Delta I} = \frac{V_m}{I_m} e^{j\varphi} \tag{5}$$

As shown in (5), the electrochemical impedance of the battery module is a frequency-dependent parameter. It can be characterized either by its real and imaginary parts, or its modulus and phase angle. By sweeping the excitation signal from 0.1Hz to 1kHz, the impedance spectrum of the battery in complex form can be investigated to investigate the state of the battery. In order to guarantee the EIS operation, the bandwidth of the voltage controller should be much higher than maximum frequency of sweeping signal. in order to get the 1kHz excitation signal, the voltage controller has to be designed to have 5 kHz bandwidth.

The Digital Lock-In Amplifier (DLIA) is used to calculate the complex form of impedance as (6)

$$Z(\omega) = R(\omega) + jX(\omega) = \frac{V_x I_x + V_y I_y}{I_x^2 + I_y^2} + j\frac{V_y I_x - V_x I_y}{I_x^2 + I_y^2} \tag{6}$$

Where: V_x and V_y are the in-phase and quadrature phase components of the excitation voltage and I_x and I_y are the in-phase and quadrature phase components of the measured current response.

A popular model of lead-acid battery used in this research is shown in Fig. 2. Where R_{HF} is ohmic resistance which represents the connection, the electrolyte resistivity and the surface coverage of the electrodes by crystallized lead sulphate; C_{dl} is capacitance due to space charge distribution in the electrochemical double layers, R_t is resistance of charge transfer at the electrodes and Z_W is Warbug impedance due to ion diffusion in the electrolyte and in the pores of the electrodes.

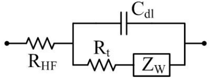

Fig. 2 Equivalent circuit model of a lead-acid battery

From the spectrum of impedance of battery and an equivalent circuit model of battery, the parameters of equivalent circuit can be extracted by using complex nonlinear least-squares (CNLQ) fitting method.

The complex impedance at the frequency of interest of the equivalent circuit model can be expressed as (7)

$$Z(\omega) = f(\omega, \theta_i);\ \theta_i = R_{HT}, R_{ct}, C_{dl}, W \tag{7}$$

Using CNLQ method, the parameters of the circuit for the lead-acid battery would be estimated by minimizing the error function (8)

$$\Phi = \sum_{i=1}^{n} [Re(y_i - Z_i)^2 + Im(y_i - Z_i)^2] \tag{8}$$

Once these parameters of equivalent circuit are extracted, by comparing with those data of fresh battery, the SOH of battery can be estimated as (9)

$$SOH = \frac{SOH_m - SOH_{aged}}{SOH_{fresh} - SOH_{aged}} \tag{9}$$

Where SOH_m, SOH_{fresh} and SOH_{aged} are the values of SOH of battery under the test, fresh battery, and aged battery, respectively.

4. Experimental results

A 3kW charger with the specification in Table 1 was implemented. CC/CV charge and EIS function are implemented together in a DSP TMS320F28335. The CC/CV charge profile of electric forklift's battery obtained through the experiment is shown in Fig 3. The battery is charged with CC mode (45A) at the beginning (OCV 47V). When the battery voltage reaches the nominal value (56.4 V), the battery is charged with CV mode. The charge process is terminated when the battery current falls down ti its cut-off value. After the CC/CV charge is completed, the EIS is performed with excitation signal ranging from 0.1 Hz to 1kHz. Based on the measured voltage and current waveforms, the impedance spectrum can be obtained as show in Fig. 4. Using the CNLQ fitting algorithm embedded in DSP, the parameters of equivalent circuit of aged battery are extracted with R_{HT} = 67.58mΩ, R_t = 5.57mΩ, C_{dl} = 4.02F. These parameters can be compared with those data of fresh battery to estimate the SOH of the battery.

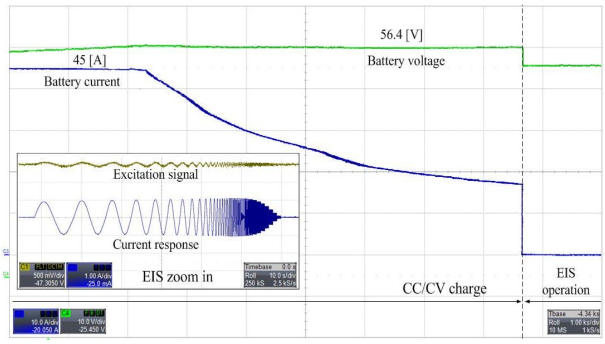

Fig. 3: CC/CV charge profile with EIS operation.

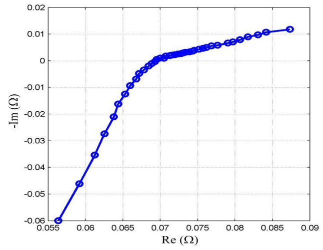

Fig. 4: Impedance spectrum of lead-acid battery of electric forklift.

5. Conclusion

A 3kW charger with battery diagnosis function using online impedance spectroscopy is proposed. The CC/CV charge function and impedance spectrum of the battery has successfully implemented by the DSP in the proposed charger. The integrated battery diagnosis feature provides low-cost, simple, and fast solution to estimate SOH of battery. It can help to enhance the reliability of system by preventing the sudden failure and longer the service time of the battery module.

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