

Estimation Algorithm of Equivalent Series Resistance of DC Input Capacitor in Single-Phase DC-AC Converter Based on Least Mean Square Approach

LMS 기반 단상 DC-AC 컨버터의 DC 입력 커패시터의 ESR 추정 알고리즘

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Abstract

In this research, the internal resistance of the input capacitor in the DC/AC single-phase converter, equivalent series resistance (ESR), is estimated by the least mean square method. This paper firstly applied the LMS algorithm to identify the amplitude of the equivalent series resistance of the dc-link capacitor of the dc-ac converters, by using signals of capacitor voltage and current. In addition, conditions for optimal performance were confirmed by adjusting the sampling time of the data. The error was analyzed by comparing the estimated and measured using the algorithm. As a result, it was confirmed that the estimation accuracy was relatively high at 98 % at a capacitor capacity. Furthermore, the algorithm of this paper compared the accuracy according to sampling time and data section. Accordingly, it was confirmed which of the two factors had a greater effect on accuracy. This result is a contribution to this paper. It was confirmed that the sampling time had a greater effect than the section of the data.

Key Words

Capacitor Monitoring, Electrolytic Capacitors, Least Mean Square (LMS)

1. Introduction

An electrolytic capacitor is an essential element of a power electronic system and is a device having many advantages. Due to its structural characteristics, it can have a large capacitance compared to a small volume and can be manufactured at a relatively low price. For this reason, electrolytic capacitor is often used in power conversion systems. Electrolytic capacitors inside the system are subject to voltage and current ripple during system operation, increasing the internal temperature. When temperature rises, the electrolyte inside the capacitor evaporates and leaks. This is one of the main aging mechanisms of capacitors [1]. As capacitors are continuously maintained in these environments, current ripple and power dissipation lead to changes in capacitance and equivalent series resistance (ESR) increase. This degrades the performance of the

system, causes failure, and it lowers the trust of the whole system. To increase the system reliability, it should monitor the capacitor's state. Capacitor monitoring can diagnose through internal capacitance and internal resistance ESR. As aging progresses, capacitance decreases and ESR increases, and the time of failure can be determined through the ratio. When the capacitance decreases by more than 20% and the ESR increases by 2 to 3 times, it can be said to be a failure [2, 3]. Among them, the change in ESR has a more prominent feature than the change in capacitance. In addition, the volume of the electrolyte changes with aging, and the rate of change is directly related to the rate of change in ESR. Therefore, ESR is considered more reliable than capacitance as an indicator for monitoring the condition of electrolytic capacitors [4, 5].

According to the aforementioned results, many techniques for monitoring the state of DC Link electrolytic capacitors through

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ESR estimation have been proposed [22-24]. Methods for estimating parameters can be roughly divided into three types [6]. These are a small-signal ripple-based scheme with a period, a large-signal-based scheme without a period, and a data-based scheme, as shown in Fig. 1. First, the small-signal ripple-based technique with a period uses the capacitor data ripple component. There are several methodologies for this technique. An example of this is to measure the ripple signal using a voltage sensor and a current sensor, and to estimate the ESR in an intermediate frequency band or a frequency domain such as a switching frequency [7-12]. There is discrete Fourier transform (DFT) and least mean square (LMS) technique for estimating using current and voltage [13]. ESR is derived from relationship between average power loss and capacitor current [14-16]. ESR can also be derived through internal ripple change by injecting an external signal [17]. Second, the large-signal-based technique that does not have a period utilizes the voltage charged and discharged in the capacitor. The capacitor is discharged in the circuit through the operation of the switch, and its characteristics are substituted into the discharge equation to calculate [18, 19]. The two techniques mentioned above estimate ESR using the equivalent circuit of a capacitor. However, the data-based method is sometimes called a black box model because it does not utilize capacitor equivalent circuits and circuit models. The state of the capacitor is modeled through a large amount of data training and testing. ESR is estimated using signal data such as input/output voltage and current during operation [20, 21]. This technique has the advantage of being simple because it does not require a modeling process but has the disadvantage that it requires a large amount of data.

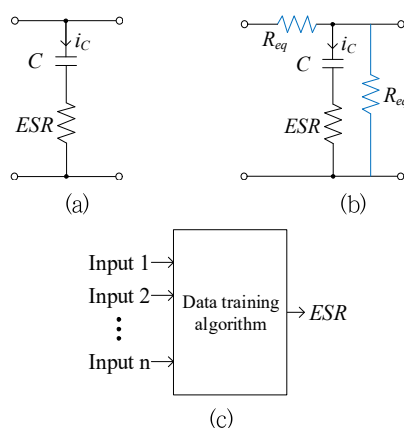


Fig. 1 Model based method (a) Small signal ripple-based method (b) Large signal based method (c) Data based method

In this paper, ESR is estimated using a small-signal

ripple-based technique with a period. The formula expressing the capacitor equivalent circuit model through capacitor voltage and current is applied to the least mean square technique. ESR can be derived by calculating an unknown parameter matrix. This algorithm was implemented in MATLAB, and data were collected through experiments. This technique does not require a large amount of data, and complex processes such as signal injection do not exist. In addition, unlike many results of frequency analysis, since data in the time domain is directly used, a conversion process into the frequency domain is not required. As shown in other studies through formula derivation, it has the advantage of being applicable to all types of topologies, unlike techniques limited to a specific topology. First, capacitor data are collected through DC/AC single-phase converter experiment to collect data to be applied to least mean square technique. Data is collected under the conditions of three capacitor capacities, and ESR is estimated. In addition, in order to consider the effect of noise and shape of the data, the condition with the highest estimation accuracy was found using data with sampling times of 12 μs , and 40 μs . Afterwards, the estimation error according to the length and the section of the data was compared.

The following is a brief outline of this paper. First, Chapter 1 is an introduction. Chapter 2 describes a method for estimating the ESR of a capacitor based on the least mean square technique. Chapter 3 shows the data collection process through experiments. Chapter 4 describes the results of ESR estimation using LMS. Finally, Chapter 5 summarizes the conclusions of the study.

2. Estimation of capacitor internal resistance based on least mean square (LMS) technique

In this study, ESR, the internal resistance of a capacitor, is estimated by the LMS method. This technique is a parameter identification technique, which estimates parameters in an unknown parameter using known signal. That is, the ESR of the capacitor, which is an unknown internal parameter, is estimated through measurable capacitor voltage and current data. The internal resistance value at which the error is minimized is estimated through the error function consisting of the measured value and the calculated value. First, it is assumed that there is a model expressed in the form of Equation (1).

$$Y = \Phi \bar{\theta} \quad (1)$$

In Equation (1), Y and Φ are already known measured data, and θ is an unknown parameter. The loss function for this

expression can be expressed as Equation (3).

$$J(\theta) = \frac{1}{2} \bar{\epsilon}^T \bar{\epsilon}, \bar{\epsilon} = Y - \Phi\theta \quad (2)$$

$$J(\theta) = \frac{1}{2} (Y - \Phi\theta)^T (Y - \Phi\theta) \quad (3)$$

Using the principle that the point where the slope of the loss function is 0 as shown in Equation (4) is the minimum value of the loss function, θ can be calculated when $\Phi^T \Phi$ is nonsingular.

$$\frac{dJ(\theta)}{d\theta} = -Y^T \Phi + \theta^T \Phi^T \Phi = 0 \quad (4)$$

$$\theta = (\Phi^T \Phi)^{-1} \Phi^T Y \quad (5)$$

Based on this technique, the ESR inside of the model is estimated by measuring voltage and current applied to the DC-Link stage. A capacitor's equivalent model is expressed as an internal resistor and an internal capacitor in series like Fig. 2. Therefore, as expressed in Equation (6), the voltage across the capacitor terminal is expressed as the sum of V_{Cap} , which is the voltage across the internal capacitor, and V_{ESR} , which is the voltage across the internal resistor. Using this model structure, an estimation algorithm based on least mean square was derived.

$$V_C = V_{Cap} + V_{ESR} = \frac{1}{C} \int i_C dt + ESR \times i_C \quad (6)$$

$$V_C - ESR i_C = \frac{1}{C} \int i_C dt \quad (7)$$

$$\frac{d}{dt} (V_C - ESR i_C) = \frac{i_C}{C} \quad (8)$$

$$\Delta (V_C - ESR i_C) = \frac{i_C}{C} \Delta t \quad (9)$$

If the voltage across the capacitor is expressed using current, it can be expressed as Equation (6). By arranging the equation, it can be arranged in a discrete form with a sampling step as shown in Equation (9).

$$\{v_C(n+1) - ESR i_C(n+1)\} - \{v_C(n) - ESR i_C(n)\} = \frac{1}{C} i_C(n) T_s \quad (10)$$

$$v_C(n+1) - v_C(n) = ESR \{i_C(n+1) - i_C(n)\} + \frac{1}{C} i_C(n) T_s \quad (11)$$

$$\theta_1 = ESR, \theta_2 = \frac{1}{C}, \theta_3 = \text{Constant variable}$$

$$v_C(n+1) - v_C(n) = \theta_1 \{i_C(n+1) - i_C(n)\} + \theta_2 i_C(n) T_s + \theta_3 \quad (12)$$

where θ_3 is added to consider a possible constant component in the measured data.

It is expressed the difference between previous and current according to the sampling step, and this measurement is performed at every sampling step. These measured data for nth sampling time are accumulated, which can be expressed as a form of a matrix equation in (13).

$$\begin{bmatrix} v_C(2) - v_C(1) \\ v_C(3) - v_C(2) \\ \vdots \\ v_C(N) - v_C(N-1) \end{bmatrix} = \begin{bmatrix} \{i_C(2) - i_C(1)\} & T_s i_C(1) & 1 \\ \{i_C(3) - i_C(2)\} & T_s i_C(2) & 1 \\ \vdots & \vdots & \vdots \\ \{i_C(N) - i_C(N-1)\} & T_s i_C(N-1) & 1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} \quad (13)$$

The matrix of Equation (13) can be expressed according to the structure of Equation (1). The sizes of the Y , Φ , $\bar{\theta}$ matrices are $(N-1) \times 1$, $(N-1) \times 3$, 3×1 , respectively.

$$Y = \begin{bmatrix} v_C(2) - v_C(1) \\ v_C(3) - v_C(2) \\ \vdots \\ v_C(N) - v_C(N-1) \end{bmatrix} \quad (14)$$

$$\Phi = \begin{bmatrix} \{i_C(2) - i_C(1)\} & T_s i_C(1) & 1 \\ \{i_C(3) - i_C(2)\} & T_s i_C(2) & 1 \\ \vdots & \vdots & \vdots \\ \{i_C(N) - i_C(N-1)\} & T_s i_C(N-1) & 1 \end{bmatrix} \quad (15)$$

$$\bar{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} \quad \text{where ESR gives (17)} \quad (16)$$

$$R = \theta_1 \quad (17)$$

According to Equation (5), the parameters of the $\bar{\theta}$ matrix can be calculated through Y and Φ , which are information that can be known through measurement. In conclusion, ESR can be estimated as Equation (17).

3. Data collection through experiments

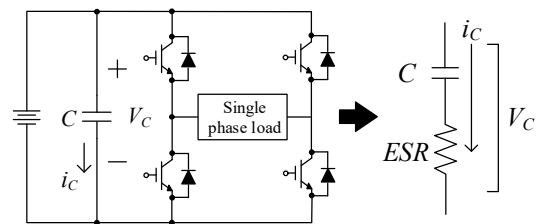


Fig. 2 DC/AC converter and input capacitor equivalent circuit

Table 1 Measured values of capacitors used in the experiment

Rated C	Measured C	Measured ESR
122 μF (Sample 1)	106 μF	490 $m\Omega$
386 μF (Sample 2)	330 μF	155 $m\Omega$
650 μF (Sample 3)	553 μF	103 $m\Omega$

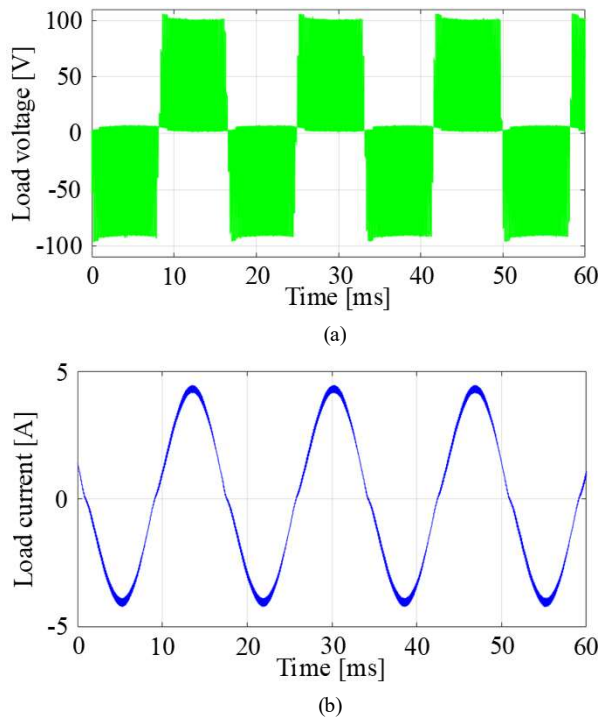
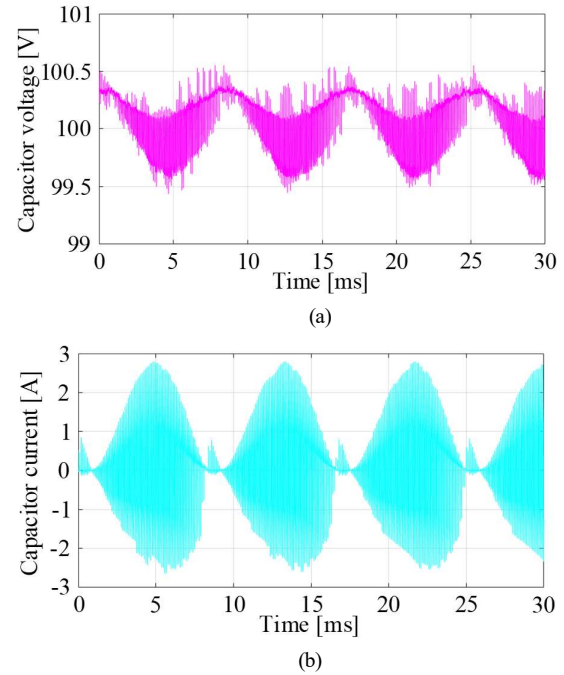


Fig. 3 DC/AC single-phase converter waveform (a) load voltage (b) load current

Experiments were conducted in DC/AC single-phase converter topology estimating a capacitor's internal resistance using a parameter identification algorithm. As shown in Fig. 2, the equivalent circuit of a capacitor can be expressed by internal capacitance (C) and internal resistance (ESR). Therefore, capacitor data were collected to estimate ESR. Converter's DC voltage is 100 V, it is configured to have a resistance of 10 Ω and an inductor of 10 mH as a single-phase load. In addition, it was controlled by a Sinusoidal PWM (SPWM) method with 5 kHz switching frequency by DSP (TMS320F28335). Input capacitor C was set to have three capacitances by connecting one 100 μF and several 22 μF in parallel. Table 1 shows measured capacitance and ESR values of the three capacitors used for estimation. Data varying according to the three capacitances were collected and used for ESR estimation. Fig. 3 and 4 are the waveforms of the converter and voltage, current collected when the internal capacitance and ESR is 330 μF and 155 $m\Omega$.

Fig. 4 (a) Capacitor voltage (b) Capacitor current of ESR 155 $m\Omega$

4. ESR estimation result

ESR was estimated based on capacitor data, and the error was confirmed. There are three types of capacitors used for estimation: 122 μF , 386 μF and 650 μF . Each capacitor is named samples 1, 2 and 3. And each ESR was measured using an LCR meter (E4980A) in the 5 kHz frequency, which is the characteristic area of ESR.

First, there is a difference between the current and voltage ripple magnitude according to ESR, the shape of the waveform changes accordingly. The error trend was analyzed by substituting known measured capacitance and ESR values and collected data into Equation (11). Fig. 5 is a waveform showing the difference between the values of the left and right terms of Equation (11). And here, the difference between the two sides of Equation (11) is called the model error. Looking at the results of Fig. 5, the model error magnitudes of 103 $m\Omega$ and 155 $m\Omega$ seem to be between +0.2 V and -0.2 V. In the case of 490 $m\Omega$, it shows between +0.5 V and -0.5 V. Therefore, in all cases, it is judged that there is a relatively small error, and it is predicted that estimation through capacitor voltage and current data is possible. Afterwards, it was checked whether the same results as predicted were obtained through ESR estimation. In addition, in order to consider the effect of noise included in the data, the sampling time was adjusted to determine the estimation possibility. The total data was collected for 4 seconds, and the sampling times were 12 μs , and 40 μs , comparing the three conditions.

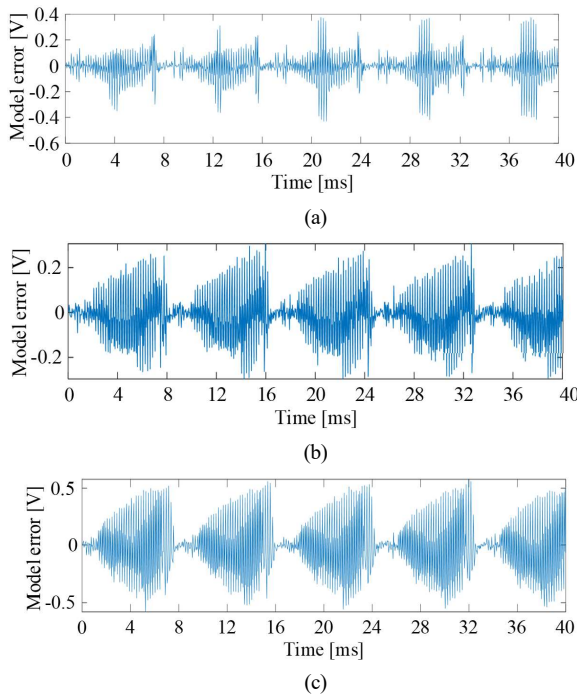


Fig. 5 Model error analysis according to ESR (a) 103 $m\Omega$ (b) 155 $m\Omega$ (c) 490 $m\Omega$

Table 2 ESR Estimation with Sampling Time

Sampling Time	Measured ESR by LCR meter		
	103 $m\Omega$ (Sample3)	155 $m\Omega$ (Sample2)	490 $m\Omega$ (Sample1)
12 μs	94.43 $m\Omega$	155.43 $m\Omega$	493.56 $m\Omega$
40 μs	97.69 $m\Omega$	176.80 $m\Omega$	536.07 $m\Omega$

Table 3 Average error according to sampling time

Sampling Time	Average error
12 μs	3.11 %
40 μs	9.54 %

In Table 2, the average of the estimation errors in 3 types of samples is calculated. Therefore, Table 3 shows the estimated average errors at 12 μs , and 40 μs , respectively. As a result, the lowest error was shown at 12 μs . On the other hand, in the case of 40 μs , it was confirmed that the data required for estimation was lost because the data collection interval was too wide. Therefore, it was confirmed that 12 μs is an appropriate value for obtaining noise and information. Therefore, it was confirmed that the highest estimation accuracy was achieved when the data sampling time was 12 μs , so ESR was estimated using this data. Fig. 6 shows ESR estimation over time when the sampling time is 12 μs . After about ms, convergence to the estimated value was confirmed. Due to the characteristics of the data, the effect of noise may be different depending on the section. Here, "section" is data of a specific length randomly extracted from the entire 4 seconds. For example, A in Fig. 7 consists of data from 1 to 1000. At this

time, the number means that the beginning of the data of 4 seconds is 1, and the names are named in order. Therefore, an optimal section with less noise was found, and ESR estimation was performed. In a total of 4 seconds, the length or section of the data was randomly selected, and the error was compared. Comparing the previous cases, it was confirmed that the data estimation result of 155 $m\Omega$ was relatively accurate. Therefore, in the case of 155 $m\Omega$, the estimation results according to the data section and length were examined. The result is shown in Fig. 7. The x-axis represents the data length and section of five types, and the y-axis represents ESR. Since we used data of 155 $m\Omega$, the closer to 155 $m\Omega$ indicated by the blue line, the more accurate the estimate. In this case, the data number means the order when all data are arranged in a line.

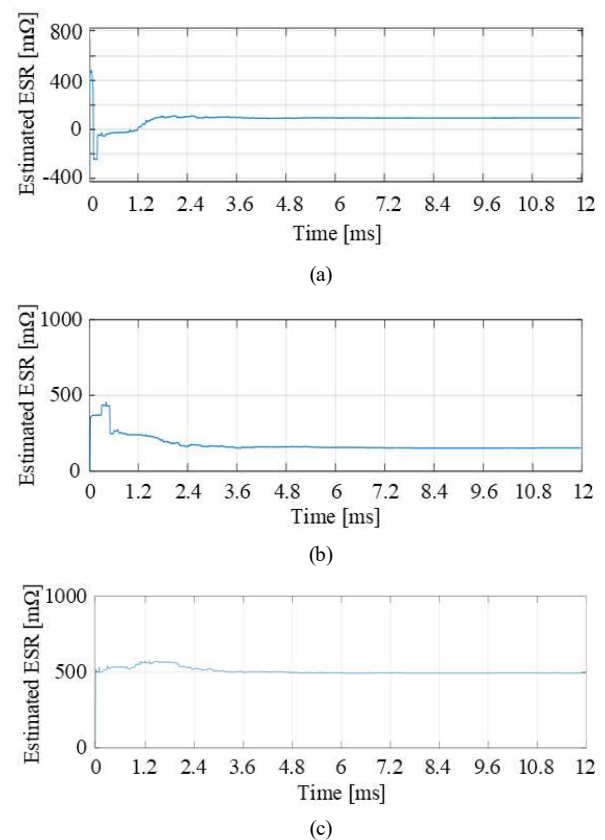
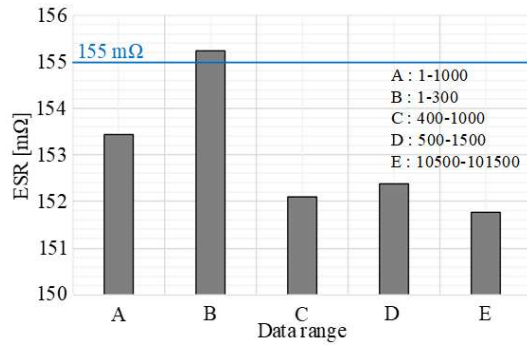


Fig. 6 ESR estimation at 12 μs sampling time (a) 103 $m\Omega$ (b) 155 $m\Omega$ (c) 490 $m\Omega$

As a result, it was confirmed that the estimation results according to the data section were similar at a minimum of 0.07 % and a maximum of 2.31 %. Because the data is repeated at regular intervals, the length does not increase the amount of information. Also, when Tables 3 and 4 are compared, the error in Table 3 is relatively large. It can be seen that the effect of the data sampling time is greater than the effect of the length and section of data on performance. Therefore, if the capacitor data having 12 μs sampling time are applied to the least mean square, the ESR estimated with about 98 % accuracy.

Fig. 7 Estimate 155 $m\Omega$ according to data interval and lengthTable 4 155 $m\Omega$ estimation error according to data interval and length

	A	B	C	D	E
Error	1.23 %	0.07 %	2.09 %	1.92 %	2.31 %

5. Conclusion

In this paper, the input capacitor ESR of converter is estimated by the least mean square method. The structure of the capacitor was modeled by utilizing the characteristic that it can be expressed as a series circuit of an internal capacitor and ESR. In addition, unknown parameter values can be calculated through derivation of the loss function that becomes the minimum. It is calculated for each sampling step and proceeds in the direction of reducing the error. The voltage, current across the capacitor were to be used in the least mean square technique collected through experiments. First, the applicability of the least mean square method was identified using the collected data. As a result, it was confirmed that it was relatively accurate at a sampling time of 12 μs . After that, the accuracy according to the section and length of the data was compared. As a result, it was confirmed that the accuracy was similar regardless of the section and length. Therefore, when the Least Mean Square is applied to the capacitor estimation technique, the effect of the sampling time on the estimation performance is greater than that of the length/section. The algorithm studied in this paper has the advantage of being able to select a sampling time suitable for the data to be used. Section has less influence on estimation accuracy than sampling time. Therefore, it is possible to secure the most accurate accuracy by selecting an appropriate sampling time and section. In addition, there is an advantage in that only the capacitor voltage current can be measured and applied to the estimation while applying the Least Mean Square to the ESR estimation. However, it is necessary to check which sampling time and section have the highest accuracy considering the noise of the data. This is the difference from other research subjects.

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