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Extraction of thevenin-based equivalent circuit of multi-cell lead acid battery pack and SoC estimation

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ABSTRACT

Lead acid batteries are widely used in UPS due to their cheapness. In case of mains power failure, the length of the operating period powered by the battery depends on the energy capacity of the battery. In this case, predicting the remaining time depending on usage is important for the healthy operation of the system. Determining the remaining time can be done by monitoring the SoC of the batteries. SoC monitoring can be done using equivalent circuit models of the battery. In systems where a single battery cell is used, the equivalent circuit is generally considered for a single cell. Nowadays many serially connected batteries are used in UPS. In this case, it becomes difficult to make calculations in the equivalent circuit created by connecting the single cell equivalent circuit in series. In this study, the approach of using a single equivalent circuit model to be created for the entire system is proposed. In the study, the Thevenin equivalent circuit model of an uninterruptible power supply battery group, in which 8 batteries (12V) are connected in series, was created with only three parameters. The accuracy of the created equivalent circuit was ensured by comparing it with the values calculated using the current counting method. First, the discharge curve of the battery was obtained. SoC-Open Circuit Voltage graph was created from these curves. Equivalent circuit parameters were calculated from the dynamic behavior of the battery. During the process of fully discharging the battery, the values of SoC corresponding to the battery voltage were determined by counting the current. The values of SoC obtained because of the current counting process were compared with the values calculated through the equivalent circuit. As a result of the comparisons, an average accuracy rate of 99.85% was achieved in estimating the SoC. These results show that the proposed method can be used to estimate the SoC in systems using serially connected batteries.

Çok hücreli kurşun asit pil paketinin thevenin tabanlı eşdeğer devresinin çıkarılması ve şarj durumu tahmini

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ÖZET

Kurşun asitli aküler, ucuz olmaları nedeniyle UPS'lerde yaygın olarak kullanılmaktadır. Şebeke elektriğinin kesilmesi durumunda aküden beslenerek sağlanan çalışma süresinin uzunluğu, akünün enerji kapasitesine bağlıdır. Bu durumda kalan sürenin tahmin edilmesi sistemin sağlıklı çalışması açısından önemlidir. Kalan sürenin belirlenmesi pillerin SoC'ı izlenerek yapılabilir. Pilin eşdeğer devre modelleri kullanılarak SoC izlenebilir. Tek akü hücresinin kullanıldığı sistemlerde genellikle tek hücre için eşdeğer devre dikkate alınır. Günümüzde UPS'lerde seri bağlı birçok akü kullanılmaktadır. Bu durumda tek hücreli eşdeğer devrenin seri bağlanmasıyla oluşturulan eşdeğer devrede hesaplama yapmak zorlaşır. Bu çalışmada sistemin tamamı için oluşturulacak tek bir eşdeğer devre modelinin kullanılması yaklaşımı önerilmektedir. Çalışmada 8 adet 12 Voltluk pilin seri bağlı olduğu bir kesintisiz güç kaynağı pil grubunun Thevenin eşdeğer devre modeli sadece üç parametre ile oluşturulmuştur. Oluşturulan eşdeğer devrenin doğruluğu, akım sayma yöntemiyle hesaplanan değerlerle karşılaştırılarak sağlanmıştır. İlk olarak bataryanın deşarj eğrisi elde edilmiştir. Bu eğrilerden SoC-Açık Devre Gerilim grafiği oluşturulmuştur. Eşdeğer devre parametreleri pilin dinamik davranışından hesaplanmıştır. Akünün tamamen boşalması işlemi sırasında akım sayılarak akü voltajına karşılık gelen SoC değerleri belirlenmiştir. Akım sayma işlemi sonucunda elde edilen SoC değerleri, eşdeğer devre üzerinden hesaplanan değerlerle karşılaştırılmıştır. Karşılaştırmalar sonucunda SoC tahmininde ortalama %99,85 doğruluk oranına ulaşılmıştır. Bu sonuçlar, önerilen yöntemin seri bağlı pillerin kullanıldığı sistemlerde SoC'ı tahmin etmek için kullanılabileceğini göstermektedir.

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1. INTRODUCTION

Today, electrical energy is used in every field. Interruption of mains electricity causes disruption in services and therefore financial losses. To prevent losses caused by power outages, many users have turned to systems that store energy and provide uninterrupted power flow. Batteries are used to store energy in uninterruptible power supplies (UPS). The most preferred batteries here are lead acid batteries, which do not require maintenance and are low cost. The cell voltage of lead acid batteries is 2 volts. In applications, batteries made into packaged products in 6V, 12V and 24V serial cell structures are generally used. They are widely used especially in UPS because they are cheap and resistant to overcharging and deep discharges. Due to their resistance to overcharging, they are generally kept constantly charged with simple charging circuits. During the discharge process, the discharge is usually stopped by taking a determined voltage level as a reference. This reference level is notified to the user by the battery manufacturer through documentation. When discharged below this level, the charging capacity of the battery is permanently reduced. If the voltage drops to very low levels, the battery becomes unusable. Cutting off the discharge in UPS is often done by checking the value of the terminal voltage. Due to the electrochemical structure of the battery, reading the terminal voltage while current flowing from the battery will not give the actual open circuit voltage [1]. In order to read the open circuit voltage correctly, the terminal voltage must be read after waiting for a while while the battery is unloaded [2]. In practice, since standby cannot be performed when the UPS is under load, the voltage value is read while current is being drawn from the battery. Here, discharge is cut off at higher levels with tolerance due to the danger of falling below the reference voltage level. In this case, the capacity of the battery is used inefficiently. An approach must be developed to properly read the open circuit voltage when the battery is under load. For this, the equivalent circuit model of the battery is used [3, 4]. If the battery model is known, the battery open circuit voltage can be calculated through the model parameters when the battery terminal voltage is read. There are many models for the equivalent circuit in the literature [5]. The most important of these are Physical (Electrochemical) Battery Models. Physical battery models are based on the chemical structure of the battery. Due to its electrochemical structure, the physical model contains complex and nonlinear differential equations [6]. The accuracy of this model is high, but the need to know many parameters and the fact that it takes a long time to solve many differential equations make it difficult to use this method in practice.

Mathematical models are based on predicting the behavior of the battery. They are statistical models consisting of empirical equations or based on mathematics. They are generally used for state of charge (SoC) estimation. The number of equations has been reduced and simplified compared to the physical model. However, error rates are higher than physical models [7].

Data-based (Analytical) battery models are created by combining physical, statistical, and artificial intelligence approaches. The model is greatly simplified so that fewer parameters are needed in the model. These parameters are found using data obtained from experiments. Artificial intelligence techniques such as fuzzy logic, artificial neural networks, support vector machines etc. can be used in parameter determination processes [8-10]. This approach requires experimental data and requires high-capacity processors. Electrical equivalent circuit models are circuit models consisting entirely of electrical parameters. In this way, mathematical calculations can be made directly on the circuit model. The electrical equivalent circuit model is widely used in determining current and state of charge. As an electrical circuit model; Rint, Thevenin, Partnership for a New Generation of Vehicles (PNGV) and Double Pole (DP) models are used [11]. These circuit models are shown in Figure 1.

Equivalent circuits of batteries are usually created using voltage sources, resistors, and capacitors. The simplest battery model is the Rint model. It is the model that requires the least number of circuit parameters. It is widely used in steady-state analysis of batteries. To provide the dynamic behavior of the battery, a capacitor, and a resistor, parallel to each other but in series with the internal resistance of the battery, were added to the Rint model. This model created is called Thevenin model. The capacitor here is used to represent transient behavior during charging and discharging processes. In the PNGV model, a capacitor is added to the main branch in the Thevenin equivalent circuit. Thanks to this capacitor, the effect of load current accumulation on the open circuit voltage can be represented. It is called a body capacitor. To represent the polarization feature of batteries, a new equivalent circuit is created by adding a resistor and a capacitor in series to the main branch but parallel to each other on the Thevenin model. In this way, concentration polarization and electrochemical polarization can be represented separately. This created equivalent circuit is called DP equivalent circuit model. PNGV and DP models better represent the electrochemical properties of batteries. However, it requires higher order equation solutions in the solution process.

Studies show that models requiring high-order solutions do not significantly change their accuracy rates, and therefore models requiring first- and second-order solutions are preferred [12, 13].

For this reason, the Thevenin equivalent circuit model, one of the electrical equivalent circuit models, was used in this study because it requires less processing.

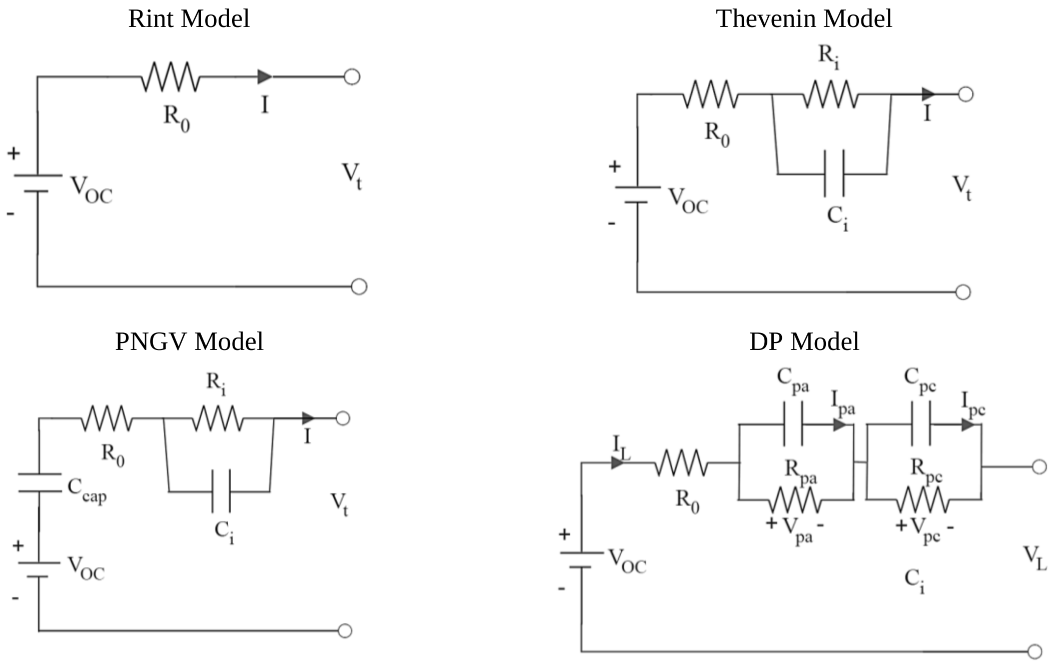

Figure 1. Some electrical equivalent circuit models for batteries.

The equivalent circuit models mentioned above are generally used for single-cell batteries. In this study, it is aimed to use a single Thevenin circuit as the equivalent circuit of the UPS battery group, in which eight 12V batteries are connected in series. An average accuracy value of 99.85% was reached with the model created because of the experimental studies. The results showed that the proposed model can be used as a single Thevenin equivalent circuit model in a system using multiple series connected batteries.

2. MATERIAL AND METHODS

2.1. Obtaining Experimental Setup and Battery Parameters

The battery group of a 10kVA UPS was used in the experiments. The battery group has 8 lead acid batteries connected in series. Each battery has a terminal voltage of 12V (containing six 2V lead-acid cells). Information about this battery is given in Table 1. The charging of the batteries was carried out through the UPS's own charging system. The discharge process was done through resistors by taking it from the terminal output of the battery group instead of the UPS inverter output. A contactor was used to separate the terminal from the inverter and connect it to the resistor group. The block diagram of the experimental setup is given in Figure 2, and photographs of the experimental setup and the components used are given in Figure 3. The voltage value was read from the battery group terminals during both charging and discharging processes. The current value flowing from the battery group was read from the output of the terminal. The terminal voltage was read directly and without isolation using a voltage reducer circuit. The battery current was read in isolation with a current sensor based on the Hall Effect. Digitalization of current and voltage was done with a data acquisition card (DAQ) and recorded on the hard disk via the computer. Experiments have been conducted using the Matlab/Simulink program for data collection and system control. The equivalent circuit parameters are calculated from the dynamic behavior curve of the battery voltage. Therefore, a high sampling frequency has been maintained to ensure accurate value calculation. In this way, the C_t value, which represents temporary situations, can be calculated properly. In the tests carried out for verification, the sampling frequency was kept low enough to not affect accuracy. Thus, repeated operations with the same valuable data, which occur due to the fast-sampling frequency, are avoided.

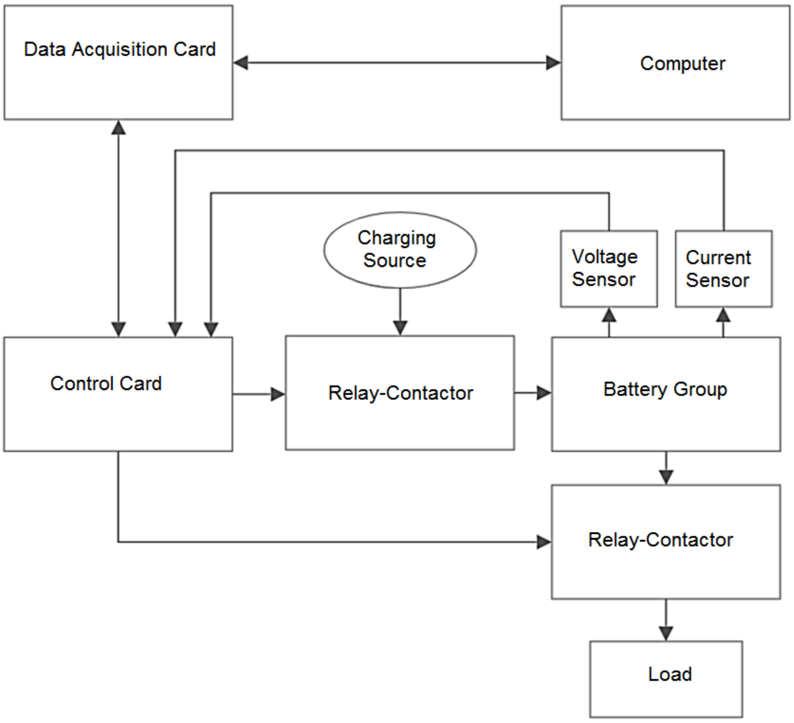

Figure 2. Experimental setup block diagram.

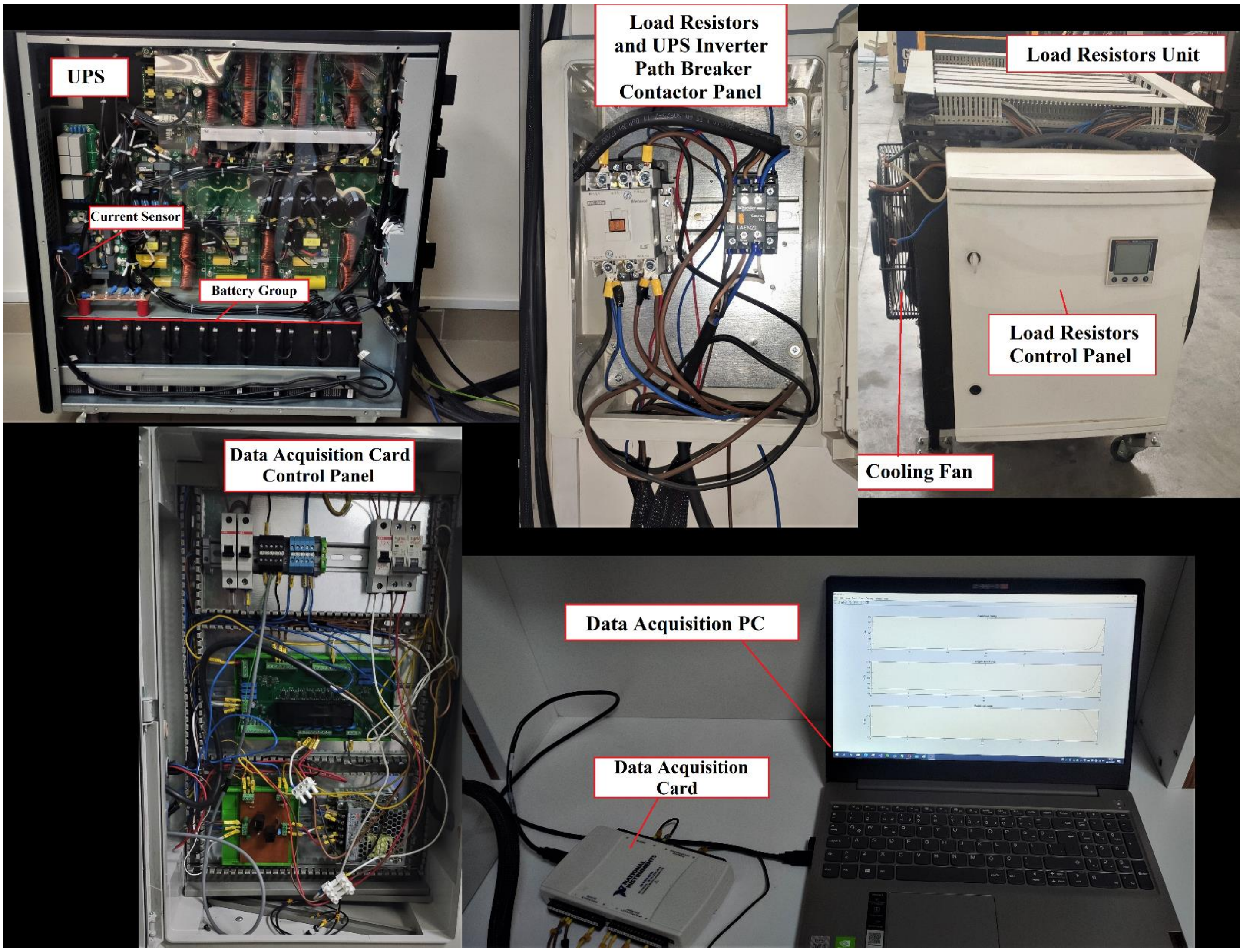

Figure 3. Photographs of the experimental setup and components.

Table 1. Information about one battery in the used battery pag

Parameter	Value
Rated Capacity	9Ah
Rated Voltage	12V
Charging Upper Limit Voltage	14.9V
Discharging Lower Limit Voltage	9.5V
Highest Continuous Charging Current	3.6A
Highest Continuous Discharge Current	135A
Life	%60 Capacity in 1200 Loops or 5 Years

In this study, the Thevenin circuit model, which has 3 parameters, was used for the battery equivalent circuit model of the system (Figure 1). These parameters are R_i representing the battery internal resistance, R_t representing the Thevenin resistance and C_t representing the Thevenin capacitor. These parameters are calculated from the voltage graph taken from the battery group-terminal voltage in the experiments [14]. Figure 4 shows the transient state graph of the battery at the time of loading and the marking of the lengths to be used. At the beginning, the current is 3.98 A. In the 1.08x107th sample, the current has been reduced to zero.

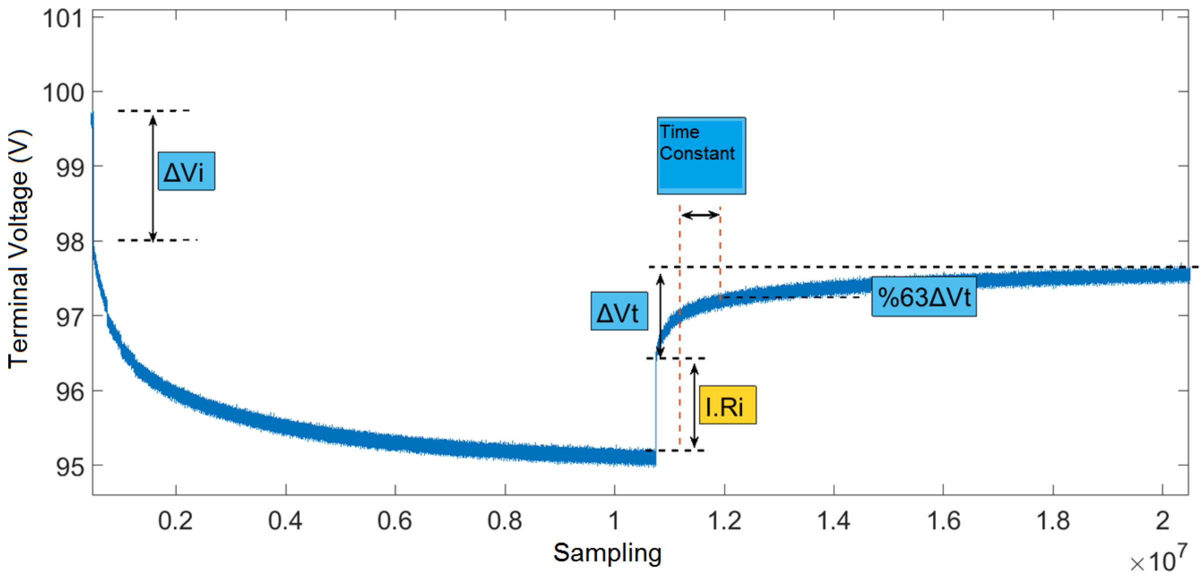

Figure 4. Transient graph at the time of battery loading.

First, the R_i value is found. When the battery is unloaded, the battery voltage will be read directly from the terminal. When a current starts to flow, a voltage drop will occur on R_i and this difference will be reflected in the terminal voltage. By determining the magnitude of this voltage drop (ΔV_i) from the graph, the R_i value can be calculated via Equation (1).

$$R_i = \frac{\Delta V_i}{I} \tag{1}$$

To calculate R_t and C_t , the voltage changes from the moment the current is cut to the settling period of the open circuit voltage is used. After the time constant "τ" is determined from the graph, R_t and C_t are calculated using Equation (2) and Equation (3).

$$\tau = R_t \, . C_t \tag{2}$$

$$R_t = \frac{\Delta V_t}{I} \tag{3}$$

As a result of the calculations, it was found that R_i = 0.4648 Ω, R_t = 0.2194 Ω and C_t = 24.078 F. The resulting equivalent circuit was used for charge state estimation.

3. RESULTS AND DISCUSSION

The accuracy of the parameters in the Thevenin equivalent circuit was made through the estimation of the SoC of the battery. For the verification process, the batteries were first fully charged via the UPS charging unit. This ensures that the batteries are fully charged. Afterwards, the battery group was fully discharged through fixed resistors so that the nominal current passed. In this way, the battery charging capacity was determined. The batteries have been fully charged again. The battery group was discharged via fixed resistors for 79 seconds off and 30 seconds on. During the discharge process, current and voltage values were sampled and recorded on the computer. In this way, the SoC curve corresponding to the open circuit voltage was obtained. The current-voltage graph obtained during the discharge process is given in Figure 5. The SoC curve corresponding to the resulting open circuit voltage is shown in Figure 6.

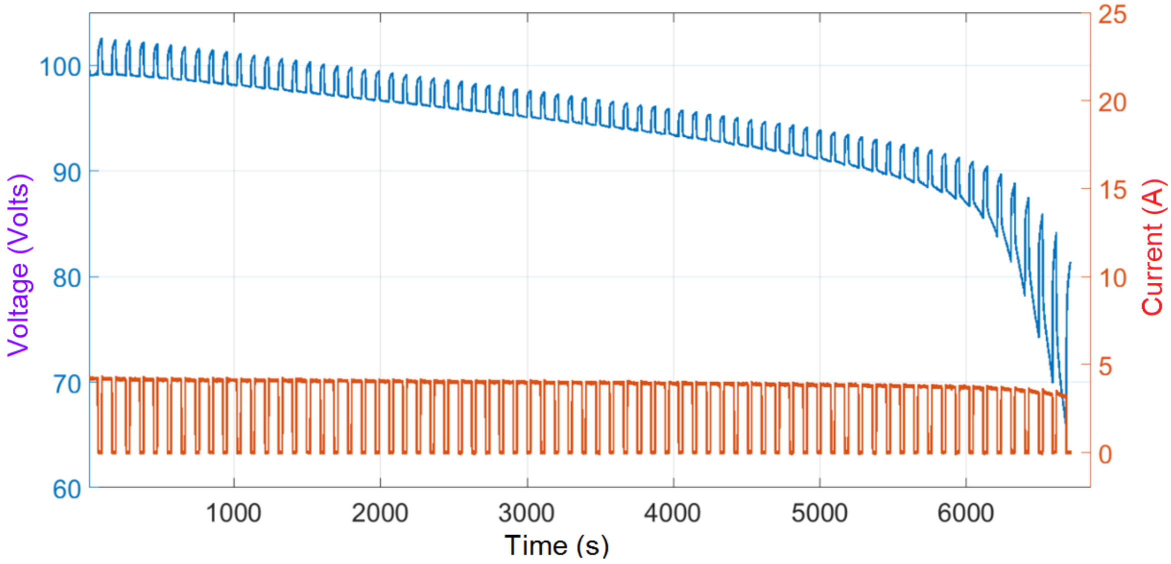

Figure 5. Current-voltage graph obtained during the discharge process.

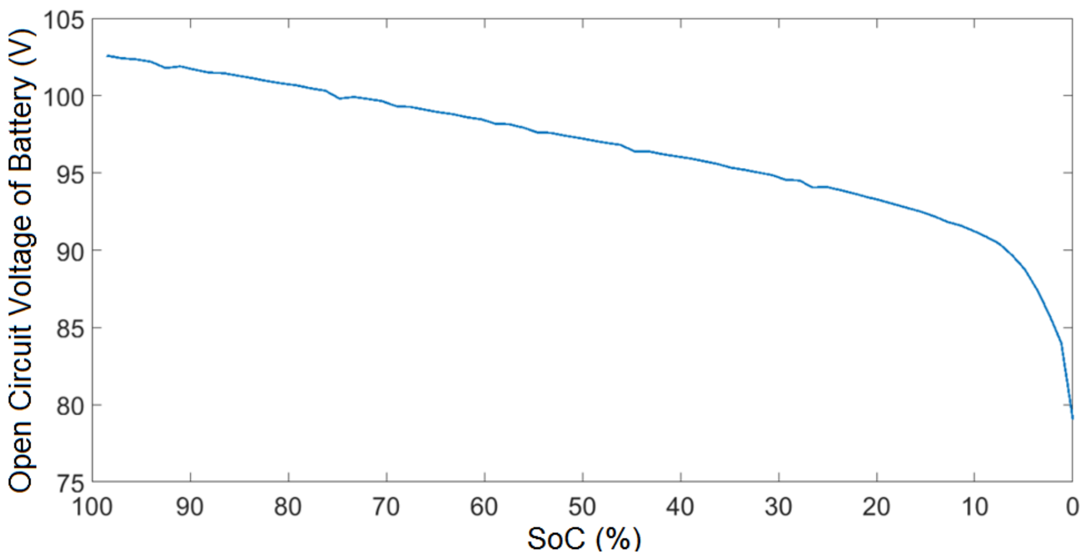

Figure 6. SoC curve corresponding to open circuit voltage.

The SoC was calculated during the discharge process with the current integration method and was taken as the verification value. Using the graph in Figure 5, the SoC level corresponding to each open circuit voltage was obtained. The graph in Figure 6 was created with these values. The comparison of the SoC values found through the current integration method and the SoC values calculated using the Thevenin equivalent circuit is given in Figure 7. The graph of the errors made depending on the voltage level is given in Figure 8.

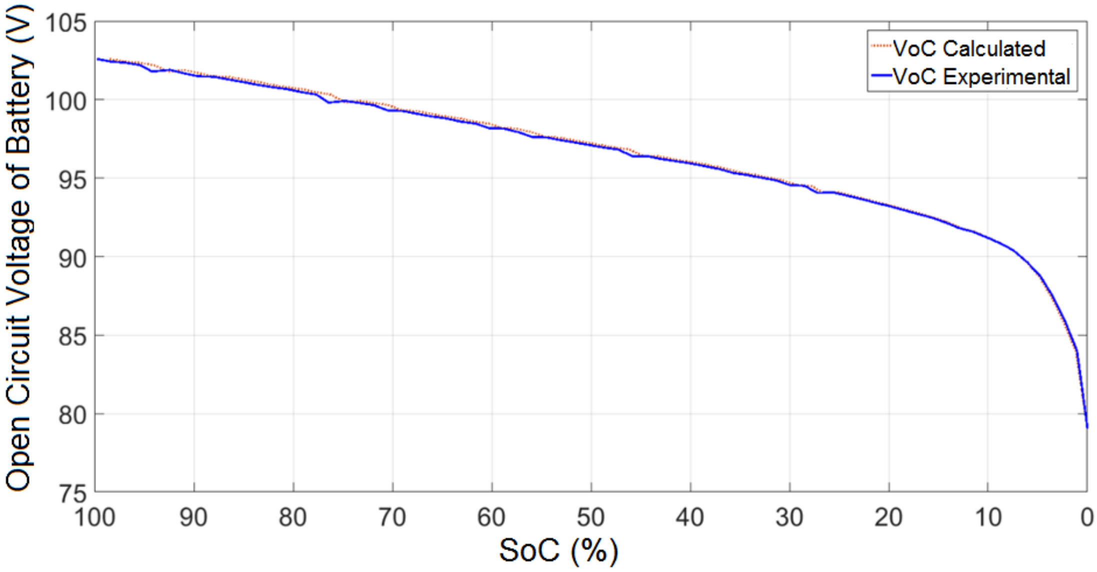

Figure 7. Comparison of SoC found through current integration and equivalent circuit.

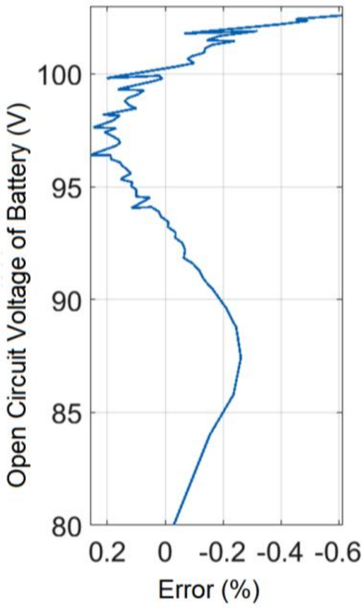

Figure 8. Error graph between experimentally found and calculated SoC values.

Between these two values, the maximum error value was calculated as 0.61% and the average absolute error value was calculated as 0.148%. These results show us that the battery groups in a UPS can be considered as a single battery and the Thevenin equivalent circuit obtained in this direction can be used in operations.

4. CONCLUSIONS

In the study, the SoC of UPSs was estimated directly from the terminal voltage. For this purpose, parameter calculations were made by considering the battery groups used in UPSs as a single battery. To demonstrate the accuracy of the obtained Thevenin equivalent circuit, the battery group was subjected to full charge and full discharge processes. The dynamic behavior of the battery under load was examined with data taken at high sampling frequency and the parameters were calculated using these values. The SoC was estimated with the resulting equivalent circuit and compared with the values calculated by current integration. The average absolute error is 0.96%. Considering that in practice, in UPSs, the SoC is calculated directly by considering the terminal voltage as the open circuit voltage, this error value can be at an acceptable value.

Since there is no constant current load unit that can meet the power of the UPSs used in this study, they were discharged with fixed value resistors. This situation made the calculations difficult and since there was no constant current load unit, it could not be determined whether it had any effect on the total error. However, it should be taken into consideration that the current will change as much as the decrease in voltage due to the use of a fixed value resistor and that this decrease remains at certain rates. Conducting experiments with constant current will make the verification process more accurate and reduce the error.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author contribution rates are equal in this study.

DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest.

DECLARATION OF ETHICAL STANDARDS

As the authors of this study, we declare that all ethical standards have been complied with.

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