Journal of Electronics and Electrical Engineering
https://ojs.wiserpub.com/index.php/JEEE

Research Article

A Straightforward Method to Estimate Battery's Condition Based on Its Internal Resistance Value

Juha Kallunki

School of Smart and Clean Solutions, Metropolia University of Applied Sciences, Helsinki, Finland
E-mail: juha.kallunki@metropolia.fi

Received: 21 July 2024; **Revised:** 12 September 2024; **Accepted:** 19 September 2024

Abstract: A battery condition monitor can be realized using several methods. Some of these methods have been proven to be more reliable than others. In this study, we focus on assessing a battery's condition based on its internal resistance value using a direct current method (DCM). We developed a simple, fast, and straightforward method, including the necessary equipment for this purpose. Only measurements of the battery's terminal (open-circuit) voltage and battery voltage under a certain load are required. We measured around 100 non-rechargeable AA batteries (double-A batteries) and estimated their internal resistances. Both alkaline and lithium-based batteries were tested. Our measurements show that measuring the terminal voltage (open-circuit voltage) alone does not provide an accurate enough status of a battery's condition or state-of-health, SoH. Especially when the battery condition is declining, the internal resistance value gives a better estimation of the battery's condition and usability.

***Keywords*:** battery, battery condition, internal resistance, condition monitoring

1. Introduction

A battery condition monitor is critical in almost all applications, especially industrial applications where batteries are used. With proper battery condition monitoring, it is possible to prevent unexpected maintenance breaks and reduce unexpected extra maintenance and downtime costs. The importance of battery condition monitoring has been increasing as many new battery-based applications have entered the market. Electrical transportation, especially electric cars, and renewables are a few examples of these applications. Battery characteristics change with age due to operating environment, temperature, loading, charging cycles, storage conditions, and battery construction, all of which contribute to the reduction of their state-of-health, SoH and available storage capacity. Several methods have been proposed to estimate battery condition or state-of-health, e.g., [1, 2, 3, 4, 5, 6, 7]. The state-of-health (SoH) can be defined as a percentage representing the current capacity (Q) of a battery compared to its original capacity (Q_n).

$$SoH\ (\%) = 100 \times \frac{Q}{Q_n} \tag{1}$$

where Q is battery's available capacity (charge) and Q_n is battery's nominal capacity (charge). A dead battery status is relatively easy to check by measuring the battery's open-circuit voltage. The more challenging task is evaluating a battery

DOI: https://doi.org/10.37256/jeee.3220245338

whose performance is approximately between 20 and 100 percent. In general, accurately and reliably monitoring the condition of batteries is rather challenging and complex. One challenge is that batteries cannot be reliably or easily tested on the fly. Some tests are more reliable but also more time-consuming. However, the most popular estimation methods are impedance measurement and pulse-based tests, as mentioned in [2]. In a pulse-based test, the battery is periodically discharged for short periods (two to three cycles), and the voltage is constantly measured. The battery condition can be estimated in this test by how closely the battery's open-circuit voltage returns to its level before discharge. In the second method mentioned, the battery's internal impedance (resistance) is measured. The internal resistance describes the battery's capability to carry current [8, 9, 10]. A battery with high resistance has a low capability to carry current, which significantly impacts its performance. This relationship comes directly from Ohm's law: higher resistance results in lower current flow.

Additionally, smart battery management systems are becoming more popular. In these systems, the battery's voltage and output current are continuously monitored, and the battery's remaining capacity can be estimated mathematically based on this data. One of the most straightforward battery tests is impedance measurement, usually referred to as internal resistance measurement. This study focuses on discussing battery state-of-health estimation based on internal resistance measurement.

The internal resistance value also depends on the battery's size, type, and quality. High-capacity batteries usually have lower internal resistance than small-capacity batteries, and in general, their resistance values vary from milliohms to several ohms. The internal resistance increases during the discharge process. For rechargeable batteries, it is important to recharge the battery before measuring the internal resistance. The internal resistance can be measured with a specific battery tester. However, high-quality battery testers suitable for all kinds of batteries can be very expensive, with prices ranging from a few hundred to thousands of euros. The internal resistance can also be measured accurately enough with a traditional multimeter and an extra load resistor. If the resistor is adjustable (a potentiometer), it enables measurements of batteries with varying capacities. In this work, we present a simple solution for measuring a battery's internal resistance using only a multimeter and an adjustable resistor. A specific measurement box or unit was built for this purpose. Our proposed system and method are repeatable, reliable, and cost-effective. This practical and straightforward solution can be implemented without any specific, expensive measurement equipment, such as a dedicated battery internal resistance tester.

In Section 2, we describe the battery model used, the Thevenin battery model. The internal battery resistance measurements and the developed measurement system are presented in Section 3. In the final Section 4, we provide detailed conclusions and discuss future investigations and possibilities.

2. Thevenin battery model

The simplified equivalent circuit of the battery is consisting of voltage source (V_0) and internal resistance (R_s). This model is called Thevenin battery model with a one RC parallel branch, e.g., [11]. The equivalent circuit of Thevenin battery model is also shown in Figure 1. The model does not take into account for instance the temperature dependency of battery resistance. However, with the simplified Thevenin battery model it is possible to estimate condition of the battery accurately enough. If we add one external resistance series with the battery. Together with external resistance (load resistance, R_l), we can define battery's internal resistance. In Figure 1, the measurement circuit is also presented. The value of this resistance has to be small enough that it does not loading battery too much, and thus circuits current is at a reasonable level. Necessary, required measurements for defining the external resistance are listed below.

1. An external load resistance (R_l) value must be measured including wiring etc.
2. The terminal voltage of the battery (V_t) must be measured
3. The voltage over load resistance (V_l) must be measured

All the listed measurement could be done using traditional multimeter. We can assume that terminal voltage (V_t) is equal with an open-source voltage (V_0). After completing above listed measurement, we can write a voltage formula for voltage over load resistance as

$$V_L = V_t \times \frac{R_l}{R_l + R_s} \tag{2}$$

And further, we can solve unknown battery's internal resistance value (R_s) from the previous equation. Thus, the internal resistance value (R_s) will get a form as

$$R_s = \frac{V_t R_l}{V_L} - R_l \tag{3}$$

We assume that the total internal resistance, R_s consists of the resistances R_s' and R_1 ($R_s = R_s' + R_1$).

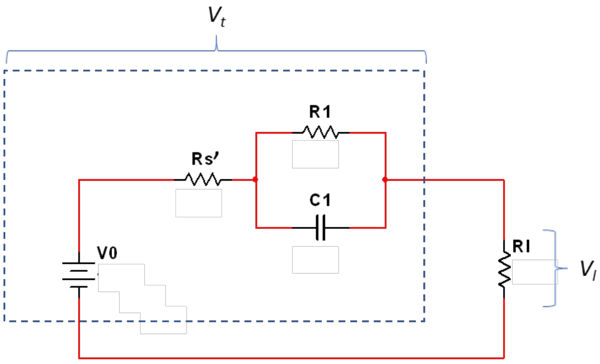

Figure 1. A simplified battery's equivalent circuit (marked as a dashed black line) and the measurement circuit for battery's internal resistance measurement. Resistance (R_s') is representing the battery's internal resistance together with R_1, which have a major impact to battery's total performance. Necessary voltage measurements (V_t ja V_l) are also presented

A battery model also includes a term for capacitance (C_1), which models the transient conditions and properties of the battery [11]. In this study, those features are not under investigation, and their effect on the battery's general condition or state-of-health (SoH) monitoring is rather small.

3. Measurements and measurement system-direct current method (DCM)

For measurement purposes, a specific measurement box (unit) was built. The box consists of an adjustable resistor (ranging from 0.3 to 200 ohms), a potentiometer, and necessary measurement connections for the multimeter and the battery under test. In Figure 2, the specific measurement box built for this purpose is shown. The total component cost of the measurement box was approximately 50 euros. With the proposed method and system, all kinds of batteries (with different capacities and sizes) can be tested without any modifications. The only required modification is the adjustment of the load resistor value, which must be matched with the battery capacity.

Figure 2. The battery's resistance measuring system. The lower red circle indicates an adjustable resistor (potentiometer). For the measurements, only specific boxes, certain measurement wires (red and black wires), and a reliable multimeter are required. The upper red circle marks the AA battery under test

During the measurement, we adjusted the load resistance so that the discharge current equals the rated capacity. For example, if the battery's rated capacity is 1000 mAh, the discharge current is 1000 mA/10 = 100 mA (C-rate of 0.1). Continuous allowed C-rates of AA batteries (double-A batteries) vary between 0.25 C and 0.5 C, depending on the battery type and quality. With higher C-rates, batteries start to heat up noticeably if the loading continues. In our test, we used a C-rate of 1. Such a high rate could be used since the test duration is short, up to a few seconds. Additionally, too small a discharge current could distort the results and provide unreliable outcomes.

Every test reduces some amount of the battery's capacity; thus, it is important that the test can be conducted rapidly without needlessly consuming the battery's capacity. For example, if the terminal voltage of an AA battery is 1.5 V and the external resistance value is 6 ohms, the load current is 250 mA. Assuming the battery's internal resistance value is 0.5 ohms, the voltage across the load resistance must be 1.38 V according to the earlier presented equation. The typical parameters of an alkaline AA battery are as follows: nominal voltage 1.5 V, capacity range between 1800 and 2850 mAh, and internal resistance value between 0.1 and 0.9 ohms depending on the battery's features (e.g., quality). This internal resistance value is valid when the battery is new. The proposed method could also be called the direct current resistance method. It has been reported earlier that the battery's resistance can be estimated with an error of less than 5% using a direct current method [11].

We tested our method with non-rechargeable AA (double-A) batteries, including both alkaline and lithium-based batteries. However, the majority of the tested batteries were alkaline. We managed to measure batteries from different manufacturers, including twelve (12) different brands in our tests. Additionally, we tested brand-new (unused), partially used, and almost empty batteries. In total, 102 batteries were measured and tested. For each battery, the measurement was repeated three times. A single battery measurement takes less than 10 s, making the testing fast and straightforward. The measurements were repeatable.

In Figure 3, the open-circuit voltage (V_0) measurements and calculated internal resistance values are shown. The plot illustrates the dependency between the battery's open-circuit voltage and internal resistance. Figure 3 shows that two different batteries may have a similar open-circuit voltage, but the difference in their internal resistance could be nearly one ohm. This also emphasizes that open-circuit voltage cannot reliably indicate the battery's state-of-health (SoH). Most of our tested batteries were typical alkaline batteries, with a minor portion being lithium-based. These battery types are also marked in Figures 3 and 4. All batteries were tested at room temperatures (from 20 to 22 °C), so the effect of temperature on the battery's internal resistance is negligibly small. Typically, higher ambient temperatures also mean higher battery internal resistance.

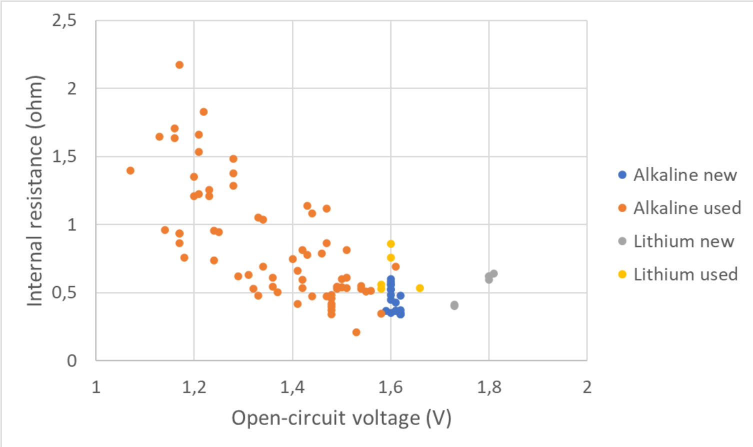

Figure 3. Measured batteries open-circuit voltages and their internal resistances. A dot represents a single measurement. Different colors indicate battery status (type and usage status), as presented in the figure's legend

In Figure 4, the measured voltage over the load resistance in relation to the battery's internal resistance is shown. Their relationship is almost linear, except for a few anomalies. We can also conclude that the voltage over the load provides a better and more reliable indication of the battery's condition than the open-circuit voltage.

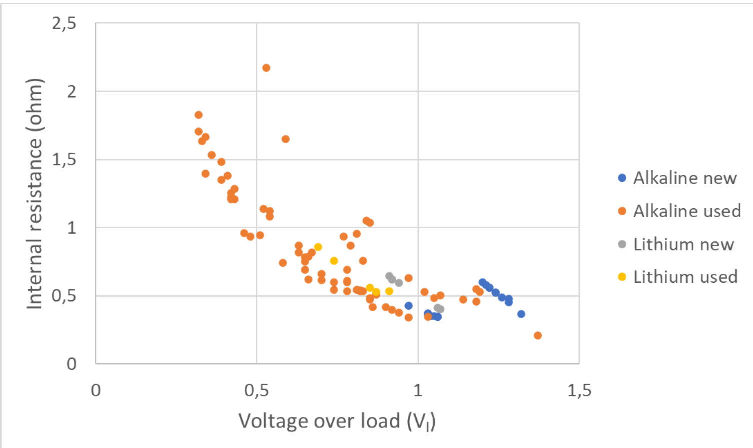

Figure 4. Measured voltage over the load (battery test circuit) and batteries' internal resistances. Each dot represents a single measurement. Different colors indicate the battery status (type and usage status), as presented in the figure legend

In Figure 5, all alkaline battery internal resistance measurements, as well as the exponential fit ($y = ae^{-bx}$) to the measurements, are shown. The y represents the battery's internal resistance, while the x represents the open-circuit voltage. The values for factors a and b are 22.68 and 2.49, respectively. The model and measurement results exhibit a decent relationship (correlation coefficient, $R^2 = 0.61$). This behavior underscores the importance of the internal resistance value as a battery condition indicator. The open-circuit voltage (V_0) value alone cannot reliably indicate the condition of the battery, especially as the battery ages with use. If the voltage over load (V_t) could be continuously monitored, a better estimation of the battery's condition could be provided. This behavior is illustrated in Figure 4.

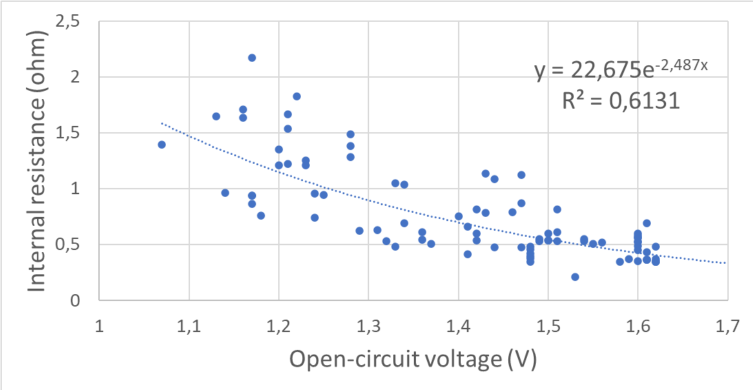

Figure 5. Alkaline batteries' (both new and used ones) open-circuit voltages and their internal resistances. A dot represents a single measurement. The blue dashed line is a fit line (exponential fit, $y = ae^{-b}$), which is done on the basis of measurements. The correlation coefficient (R^2) between measurements and a fit model is 0.61

4. Conclusions

Our measurement showed that the dependency between the battery's open-circuit voltage (V_0) and internal resistance is not linear; rather, it follows a logarithmic pattern. When the open-circuit (terminal) voltage is around 1.4 V or higher, the battery's internal resistance value remains relatively stable. The resistance changes by only about 0.3 ohms. However, when the voltage falls below that threshold value (1.4 V), the resistance increases rapidly, almost exponentially.

Pulse-based battery tests are also reliable but require more sophisticated technical solutions and special measurement tools. Test repeatability is important in every method, but it stands out more in this specific method. These tests also require a similar measurement principle and approach: the test should be conducted before the battery is put into use. Considering these limitations, the direct current method used in this study has many advantages compared to pulse-based battery test, such as its simplicity and shorter test duration.

Even a simplified battery model can accurately reveal the battery's state and conditions. An open-circuit voltage alone cannot accurately indicate the status of the battery, especially as the battery ages. Both open-circuit voltage and internal resistance measurements should be conducted. The open-circuit voltage measurement is quick and can easily determine if the battery is unusable. The battery's internal resistance measurement provides more detailed information about the battery's condition. To have a proper battery condition monitor, the battery's internal resistance should be measured before it is put into use. This value could serve as a reference for later comparisons. Even if, for instance, traditional AA battery internal resistance values are rather similar (usually between 0.3 and 0.45 ohms), the measurements also verify that the battery is intact before actual use.

Our results also illustrate the performance of more expensive lithium-based batteries. AA-size lithium-based batteries are still three to four times more expensive than alkaline batteries. This price difference will likely increase in the following years. Lithium batteries have a higher open-circuit voltage, closer to 1.8 V. Their internal resistance remains lower (<1 ohm) for longer periods, even though their initial internal resistance values are similar to those of alkaline batteries when new. In general, lithium-based batteries offer better performance than alkaline batteries [12]. Their energy capacity and density are higher than traditional alkaline batteries. However, as mentioned earlier, their prices are higher than alkaline batteries, at least for now. It is justified to use more expensive lithium-based batteries in applications where battery operation and performance are critical. We can also conclude that a developed, simple measurement unit is feasible for battery condition monitoring.

The measurement system could also be automated. For instance, an Arduino-based microcontroller system could be one possible solution. Arduino could control, for example, a relay, which could alternately connect the battery under test to the load or disconnect it. Such a solution and system are relatively straightforward to implement. This type of system is also capable of realizing a pulse-based battery test, allowing easy comparison of different battery condition monitor tests.

This project would be ideal for a bachelor student project requiring knowledge of electronics and programming. Several interesting technical proposals for automated battery testing have already been presented, e.g., [13].

Conflict of interest

There is no conflict of interest for this study.

References

[1] S. Brečko, A. Chowdhury, and M. Rodič, "Proposed method for battery state estimation," in *Conference Proceedings: 7th International Symposium on Applied Electromagnetics SAEM 18: Vol. SAEM 2018*. Maribor, Slovenia: University of Maribor Press, 2018.

[2] C. Zuluaga, C. A. Zuluaga, and J. V. Restrepo, "Estimation of Battery State of Health Using the Two-Pulse Method for $LiFePO_4$ Batteries," *Energies*, vol. 16, p. 7734, 2023. https://doi.org/10.3390/en16237734

[3] J. J. Saucedo-Dorantes, D. A. Elvira-Ortiz, C. G. Manriquez-Padilla, A. Y. Jaen-Cuellar, and A. Perez-Cruz, "New Trends and Challenges in Condition Monitoring Strategies for Assessing the State-of-charge in Batteries," in *Artificial Intelligence*, Rijeka, Croatia: IntechOpen, Feb. 15, 2023. https://doi.org/10.5772/intechopen.109062

[4] T. Kim, D. Makwana, A. Adhikaree, J. S. Vagdoda, and Y. Lee, "Cloud-Based Battery Condition Monitoring and Fault Diagnosis Platform for Large-Scale Lithium-Ion Battery Energy Storage Systems," *Energies*, vol. 11, p. 125, 2018. https://doi.org/10.3390/en11010125

[5] D. Selvabharathi and N. Muruganantham, "Real-Time Monitoring System for Lead Acid Battery Health and Performance using Fuzzy Logic and HIL Simulator," *Int. J. Eng. Trends Technol.*, vol. 71, no. 7, pp. 209–215, 2023. https://doi.org/10.14445/22315381/IJETT-V71I7P220

[6] D. Selvabharathi and N. Muruganantham, "Experimental analysis on battery based health monitoring system for electric vehicle," *Mater. Today: Proc.*, vol. 45, Part 2, pp. 1552–1558, 2021. https://doi.org/10.1016/j.matpr.2020.08.303

[7] T. Okoshi, K. Yamada, T. Hirasawa, and A. Emori, "Battery condition monitoring (BCM) technologies about lead-acid batteries," *J. Power Sources*, vol. 158, no. 2, pp. 874–878, 2006. https://doi.org/10.1016/j.jpowsour.2005.11.008

[8] A. Tenno, R. Tenno, and T. Suntio, "Battery impedance and its relationship to battery characteristics," in *Proc. 24th Annu. Int. Telecommun. Energy Conf.*, Montreal, QC, Canada, Sept. 29–Oct. 3, 2002, pp. 176–183. https://doi.org/10.1109/INTLEC.2002.1048653

[9] P. K. Jones, U. Stimming, and A. A. Lee, "Impedance-based forecasting of lithium-ion battery performance amid uneven usage," *Nat Commun.*, vol. 13, p. 4806, Aug. 2022. https://doi.org/10.1038/s41467-022-32422-w

[10] D. L. Stroe, M. J. Swierczynski, A.-I. Stroe, V. Knap, R. Teodorescu, and S. J. Andreasen, "Evaluation of different methods for measuring the impedance of Lithium-ion batteries during ageing," in *Proc. 2015 Tenth Int. Conf. Ecol. Vehicles Renew. Energies (EVER)*, Monte Carlo, Monaco, Mar. 31–Apr. 2, 2015, https://doi.org/10.1109/EVER.2015.7113024

[11] R. Thakkar, "Electrical Equivalent Circuit Models of Lithium-ion Battery," in *Management and Applications of Energy Storage Devices*. Rijeka, Croatia: IntechOpen, 2022. http://dx.doi.org/10.5772/intechopen.99851

[12] E. S. Mananga, "Lithium-ion Battery and the Future," *Recent Prog. Mater.*, vol. 3, p. 012, 2021. https://doi.org/10.21926/rpm.2102012

[13] S. Colnago, M. Faifer, E. Petkovski, and L. Piegari, "Automated test equipment for battery characterization: a proposal," in *Proc. 2022 IEEE Int. Conf. Metrol. Ext. Reality Artif. Intell. Neural Eng. (MetroXRAINE)*, Rome, Italy, Oct. 26–28, 2022, pp. 28–33. https://doi.org/10.1109/MetroXRAINE54828.2022.996761