Application Note

BATTERY SIMULATION WITH THE DC POWER SUPPLIES R&S®NGM200 AND R&S®NGU201

Products:

- R&S®NGM201
- R&S®NGM202
- R&S®NGU201
- R&S®NGM-K106
- R&S®NGU-K106

Marc Strohal, Thomas Lechner | 1GP136 | Version 3e | 12.2024

http://www.rohde-schwarz.com/appnote/1GP136

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Contents

1 Overview

This application note is about creating your own battery model for the R&S®NGM200 and R&S®NGU201, beyond the standard models provided within the battery simulation option NGM-K106 and NGU-K106. To get to a battery model, a few steps are required. To determine the parameters for the battery model, it is necessary to discharge a battery using a selected method, to record the data and to calculate the model on this basis. With this software, a connection can be established to the instrument, batteries can be measured using various measurement methods, and a model can then be created from these measurements. These models, which are determined from the measurements, can then be simulated with the power supply, thus creating a digital twin of the battery. Using these, test scenarios can be carried out in a safe and reproducible environment.

Batteries are quite dynamic energy sources and the voltage of a battery is not constant. It varies depending on the state of charge, load, temperature, the age of the battery and much more. Think of a car battery on a cold winter's day, which may have difficulty starting the car, while on a warm summer day this would normally not be a problem. The reason for this is that the battery itself performs through chemical reactions that are influenced by several factors. The geometry of the cell, the surface of the electrodes, the temperature of the reactants, the diffusion rate within the electrolyte and many more, all affect the reaction speed of the battery. Hardly any value remains constant in the battery while the battery is discharging or the outside temperature changes. Due to this dynamic behavior, the simulation of a battery requires a good model. With the R&S®NGM200/NGU201, developers can simulate the behavior of a battery under different conditions and requirements. As a result, a real battery can essentially be replaced at the beginning of the R&D cycle. The selection of batteries or rechargeable batteries during the development of various battery-powered products is often a challenge. However, with the essential requirements, the characteristics of available batteries can be compared or selected with the battery requirements. Only seldom does a battery system fulfill all requirements. Consequently, the selection process usually involves compromises between the different battery properties. The R&S®NGM200/NGU201 can make it easier for the developer of a battery-powered product to select the right battery. By replacing the battery with the simulation in the development of battery-powered systems, a safer environment can be ensured for the developer. In addition, any system state of the battery, can be achieved by simple actions.

2 Safety Instructions

⚠ WARNING

Risk of fire

Experimental charging of batteries poses the risk of fire.

- Do not leave the setup unattended.
- Place batteries to be charged in a fire-proof containment.
- Observe the rules and limits for charging, and the safety guidelines given for the respective battery types.
- Make sure that the work space is equipped with fire and smoke detectors and fire extinguishers.

3 Battery characterization

3.1 Battery Model

Electrical circuit models (ECMs) of batteries are widely used to represent the behavior of the battery's voltage and current. In these, the real system is usually replaced with a voltage source (in this case, the open-circuit voltage), resistances, capacitances, and inductances. These model the dynamic behavior of a battery. This modeling offers many advantages, since the model complexity is adjustable, the parameterization is easier and the computation times can be adjusted depending on which model is chosen. Figure 1 shows the different equivalent circuits. The simpler the equivalent circuit is, the faster the parameters of the model can be determined. As the complexity of the model decreases, the accuracy also decreases.

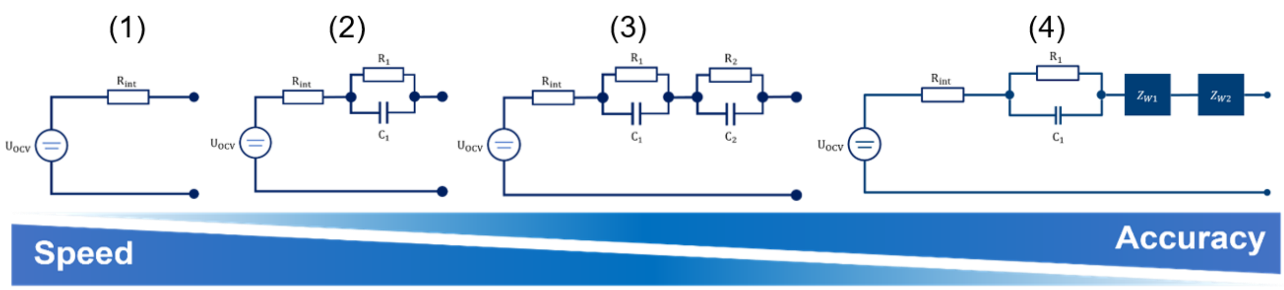

Figure 1: Equivalent circuit models according to accuracy and speed [1]

The choice of the model depends on the requirements and the application. Since in this application the modeling of the batteries for the simulation is worked out on the basis of DC power supplies, the equivalent circuits with RC- component or warburg- impedance (see Figure 1 (3) and (4)), are not applicable, since the RC components cannot be emulated by the device. The power supply can only switch a variable resistor serially to the voltage supply based on a characteristic curve. As the internal resistance of the battery is never constant, the equivalent circuit can thus be accomplished with this function.

The parameters required by the power supply unit, include the capacity, the OCV and the internal resistance. In addition, the battery model requires a progression of the respective parameters over the State of Charge.

3.2 Terminology

This chapter describes the respective parameters required for the final modeling of the battery.

3.2.1 Capacity

The capacity of a battery is the amount of charge that can be taken from the battery after a full charge by a full discharge and is indicated in Ah or mAh. Q is used as the formula character. The nominal capacity of a battery describes the amount of charge that can be delivered under standard conditions defined by the manufacturer. The values defined by the manufacturer must be verifiable under the specified rules. The standard conditions include the ambient temperature, the strength of the discharge current, the final charge and discharge voltage, and the choice of the discharge sequence. The nominal capacity is defined by the following formula:

$$Q_N[Ah] = \left(\int_0^{T_{discharge}} I_{discharge}\,dt\right) \cdot \frac{1}{3600} \quad (1)$$

$$Q_N = Nominal\ Capacity\ [Ah]$$

The actual capacity of a battery changes over the service life due to aging processes. For a fully charged cell, the capacity can be determined in exactly the same way as the nominal capacity. The integrated current over time provides the capacity of the cell.

3.2.2 Open Circuit Voltage

Open circuit voltage (OCV) is an important characteristic parameter of batteries, which is used to analyze the changes of electronic energy in electrode materials and to estimate the state of charge (SOC) of the battery. Therefore, accurate determination of the OCV is of great importance for battery modeling.

The open-circuit voltage describes the voltage of the cell when it is in the idle state. No load is applied to the battery or a sufficiently long time has passed without load after the last current flow. If the ideal quiescent condition (i = 0) is not completely reached, e.g. due to quiescent currents of the connected electronics, there is only an approximation of the OCV. The OCV (open circuit voltage) or VOC (voltage open circuit) depends mainly on the state of charge of the battery. As the battery is fuller, its open-circuit voltage is also higher. If the OCV values are measured at several states of charge, the open circuit voltage characteristic can be plotted against the state of charge. Later in this paper, methods are presented to determine the open circuit voltage.

3.2.3 State of charge

The state of charge of a cell describes what proportion of the battery capacity can still be removed until the final discharge voltage is reached. The SoC is given as percentage and can be defined by the following formula.

$$\boldsymbol{SoC}\,[\%] = \left(\boldsymbol{1} - \frac{\boldsymbol{Q}}{\boldsymbol{Q_{max}}}\right) \cdot \boldsymbol{100} \qquad 2$$

Q represents the capacity (integral of the discharge) that was reduced from the battery upon time x. Qmax represents the maximum battery capacity that can be reached.

3.2.4 Internal resistance

The internal resistance has high importance for the operation of the battery. This is made up of various contact resistances in the battery and the ionic resistance in the electrolyte. It should be considered that the presence of this series resistance in the model also implies that the internal resistance of the cell dissipates power in the form of heat and therefore the energy efficiency of the cell is not perfect [2]. The internal resistance can be calculated on one hand by switching a current pulse to a battery and waiting for its voltage response and on the other hand, from the hysteresis of a constant current measurement. For pulse measurement, the duration of the current pulse must be selected depending on the effects to be considered. With short durations, the effects described above are considered in the calculation. If one wants to consider the effects of double layers, charge passage or diffusion, a longer duration must be selected [3]. For constant current measurement, on the other hand, only the slowly proceeding effects are considered. The internal resistance is calculated for both methods using the following formula:

$$\boldsymbol{R_{int}}[\Omega] = \frac{\boldsymbol{\Delta U}}{\boldsymbol{\Delta I}} \qquad 3$$

When the OCV and the internal resistor are connected in series, a voltage drop occurs at the resistor. If no current flows in the battery, the voltage drop is zero due to the internal resistance. Thus, the voltage at the terminals is equal to the open circuit voltage. If a certain current is taken from or supplied to the battery (positive or negative for charge/discharge phases), the resistance of the external load is connected in series with the battery's internal resistance.

3.2.5 Parallel and Serial Cells

The single cell is the simplest battery pack. However, if higher voltages or capacities are desired, single cells must be interconnected to form modules. To achieve higher voltage, cells can be connected in series. The voltage is then added from the respective single cells. To achieve higher capacities, cells are connected in parallel. Each individual cell increases the total capacity by its own capacity.

Laptop batteries usually have four 3.6 V Li-ion cells in series to achieve a nominal voltage of 14.4 V and two in parallel to increase the capacity from 2,400 mAh to 4,800 mAh. Such a configuration is called 4s2p, which means four cells in series and two in parallel [4]. The following formulas represent the respective parameters of the battery with serial connection:

$$U_{Bat} = \sum_{0}^{n} U_{Cell,n} \qquad Q_{Bat} = Q_{Cell,n} \qquad R_{Bat} = \sum_{0}^{n} R_{Cell,n} \tag{4}$$

The parameters of the battery with parallel connection are calculated as follows:

$$U_{Bat} = U_{Cell,n} \qquad Q_{Bat} = \sum_{0}^{n} Q_{Cell,n} \qquad R_{Bat} = \frac{R_{Cell,n}}{n} \tag{5}$$

Most battery chemistries are suitable for series and parallel connection. It is important to use the same type of battery with the same voltage and capacity (Ah) and different makes and sizes should never be mixed. A weaker cell would cause an imbalance. This is especially critical in a series configuration because a battery is only as strong as the weakest link in the chain. In this case, the weaker cell does not fail immediately, but it is always more heavily loaded than other cells and is thus exhausted more quickly.

4 Methodology

This chapter describes the methods that are necessary for determining the required parameters for the battery model. The aim of the modeling is to achieve an accurate replica of the real battery, with the given boundary conditions.

4.1.1 OCV determination

The determination of this voltage is of great importance. In connection with the determination of the SoC from the estimation of the OCV, the exact determination of the different OCVs for different SoCs is essential in order to determine the SoC of the battery at a certain point in time. In order to determine these, two methods are presented in this application note, the relaxation measurement and the constant current measurement, which are also built into the Battery Modelling Tool.

4.1.1.1 Relaxation measurement

During the relaxation measurement, a fully charged battery is discharged in multiple cycles of two steps each. The first step of the cycle consists of the discharge. The load duration should be chosen depending on the user's application. Long phases would rather represent a constant discharge, whereas short discharge phases would rather reflect the behavior of, for example, IOT devices. The load phase is followed by a relaxation of the voltage or a pause in the discharge, which represents the second step. This involves waiting until all overpotentials have decayed and the cell voltage has decayed to equilibrium level. Repeating these cycles until the final discharge voltage is reached, the open-circuit voltage characteristic can be determined via the SoC for the discharge. Current and pulse duration define how finely the SoC area is scanned.

In general, the longer the relaxation time, the closer the measured battery voltage is to the actual OCV. However, this does not yet determine a time that can be used in a measurement. To determine this time, a measurement is recommended. The battery is discharged with a current pulse, with a height and duration selected to suit the application. Then the battery is rested until the maximum voltage is reached. This measurement can then be used to determine the duration until the open-circuit voltage is reached. Or, depending on the application and desired accuracy, a time can be selected. This measurement function is also implemented in the Battery Modeling Tool.

If a relaxation measurement is now performed for the entire state of charge range, with the relaxation time determined in the relaxation time measurement, the entire course of the OCV over the SoC is obtained. The following figure shows such a measurement.

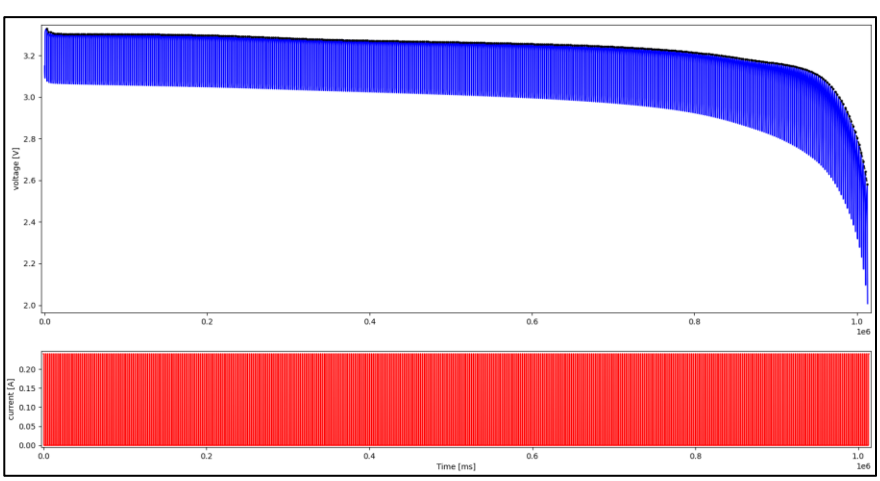

Figure 2: Relaxation measurement

The blue curve represents the measured voltage at the battery, whereas the red curve represents the current. The black curve indicates the maximum values that are reached after the relaxation measurement and thus represents the OCV of the battery.

4.1.1.2 Constant current measurement

Another method - constant current measurement - can be used to determine the open circuit voltage and the internal resistance. In constant current measurement, the cell is charged with the CC-CV method and discharged with a constant current. After reaching the charging or discharging end behavior, the direction of the current can be reversed, resulting in a cyclic behavior. The cutoff current at which the charging must be terminated is usually specified by the manufacturers. The cell is discharged up to the end-of-discharge voltage specified by the manufacturer. By integrating the current, the capacity and the state of charge can be determined. In this type of measurement, one chooses the same current for the charge as well as the discharge of the battery. If the charge and discharge voltages are now plotted across the SoC, a hysteresis is detected. This is due to the fact that a voltage drops across the internal resistance during charging and discharging. If the battery is charged, the measured voltage is ΔU above the open-circuit voltage. If the battery is discharged, the measured voltage is ΔU below the open-circuit voltage. The ohmic overvoltage is proportional to the current and can be derived from Ohm's law.

The OCV can be determined on the basis of this hysteresis voltage. It can be calculated as the average of these two voltage curves. If large currents are selected, the measured voltages are further away from the resulting open-circuit voltage. Thus, the charging or discharging currents should not be chosen too large [1].

The following figure shows the respective course of the measurements as well as the course of the OCV, which represents the average value from the charge and discharge curves.

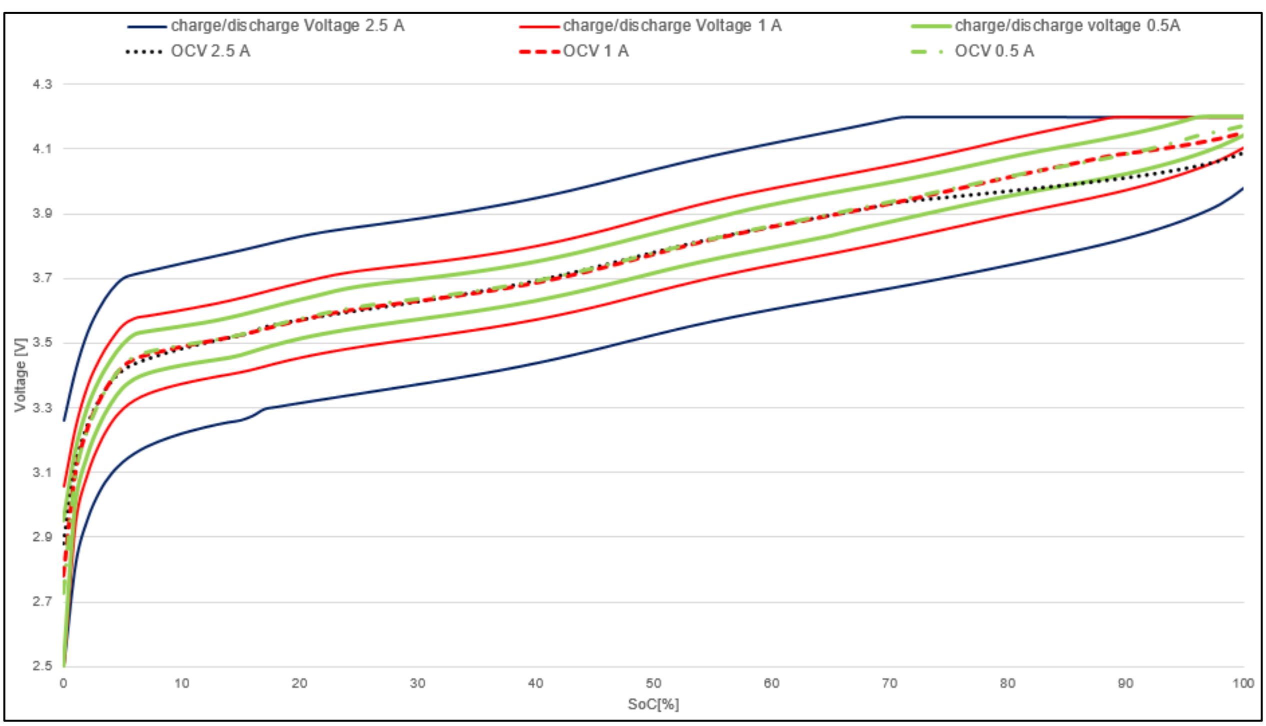

Figure 3: Constant current measurement

From this it can be determined that the open-circuit voltage for large discharge currents deviates from the real open-circuit voltage. This deviation is also interpreted as a disadvantage with this type of measurement. The advantage is the measuring time, which is much shorter compared to the relaxation measurement.

4.1.2 Internal resistance determination

In relaxation measurement, the voltage delta is formed from the OCV and the voltage under load. The current delta is formed from the current that is present during the discharge and the smallest possible current that can be managed by the measuring device during a measurement, in this case 1 mA. The following figure shows a section of the current and voltage curve from a schematic relaxation measurement and how the respective deltas are formed.

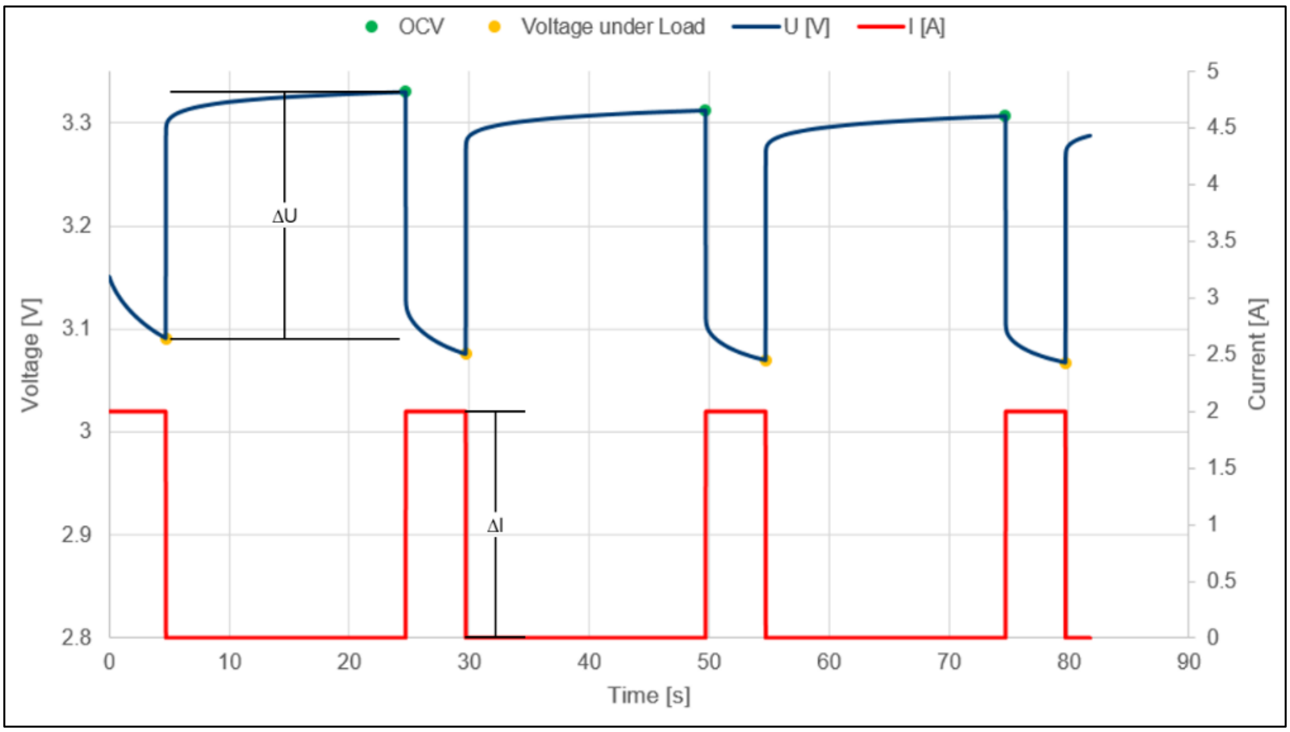

Figure 4: Schematic relaxation measurement and the determination of parameters

The green dots describe the set OCV at the end of the relaxation phase. The yellow dots describe the minimum voltage at the end of the discharge phase. The delta of these two voltages is represented by the ΔU in the figure. The ΔI can be calculated from the delta of the currents, as shown in the Figure 4 above. The internal resistance can then be determined using formula 3.

The internal resistance can also be determined from the data during constant current measurement. By dividing the voltage differences between the charge and discharge curves through the current difference (twice the current amount), the internal resistance can be obtained. This internal resistance represents the total resistance, which is formed from diffusion, the electrolyte, mass transfer, double layer and electrode resistances [1].

5 Battery Modeling Tool

This chapter is about creating your own battery model with the Battery Modelling Tool. Thereby it is described step by step how to proceed. Before you get started, you need to download the software from the Rohde und Schwarz website.

5.1 Prerequisites

The interfaces supported in the application are LAN and USB. If you want to use USB, TMC must be activated. Using LAN doesn't require any presetting. GPIB is not supported in this application.

The software runs on Windows 10 and Windows 11. Older operating systems have not been tested and are therefore not supported.

For the instrument remote control, the controlling PC must have a compatible VISA library installed. A free VISA library is available from the R&S® web site [5].

It might be that the Installer of the Battery Modeling Tool displays a warning message. This is due to the version of the Microsoft Edge WebView2 control, which is used as the rendering module for this software and displays the web content of the app. If the installer doesn't display the warning message, then WebView2 is already installed and there is no need to go through the following.

The latest version of WebView2 is available at the following location:

https://developer.microsoft.com/en-us/microsoft-edge/webview2/#download-section

► On this page, the version marked in red in the following figure can be downloaded and then installed. Afterwards, the Battery Modeling Tool should run without any problems.

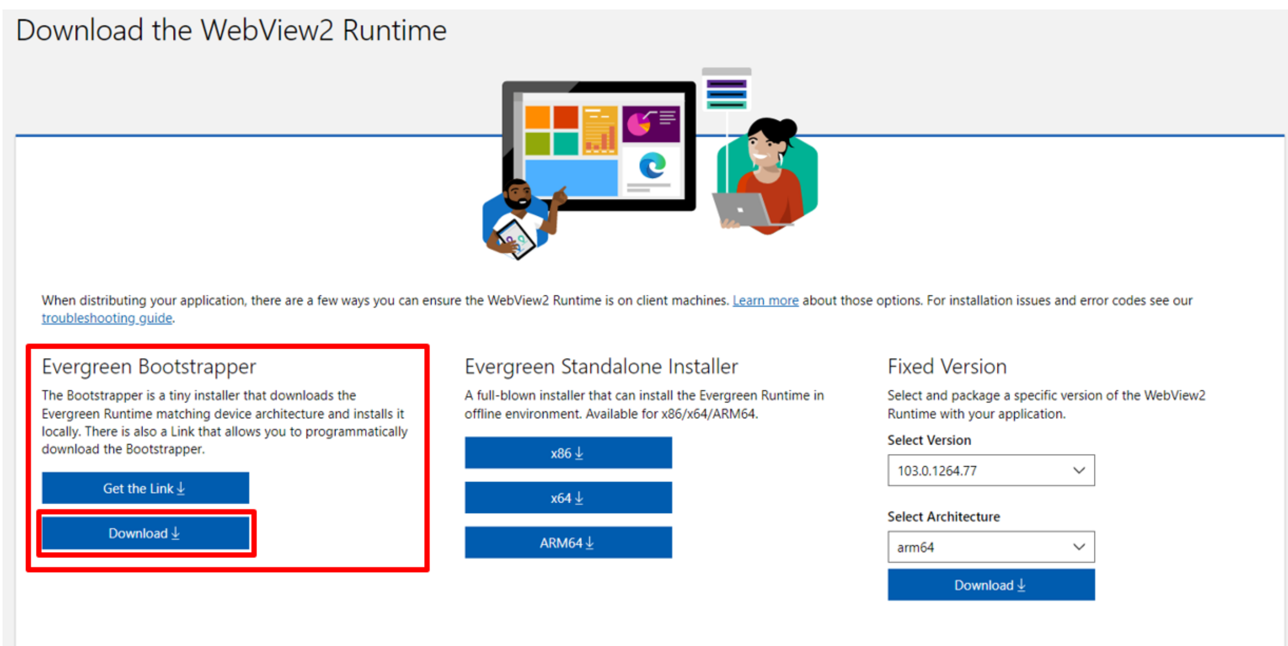

Figure 5: Download information WebView2

5.2 Measurement setup

Since the internal resistance of batteries can be very low, the measurements must be as accurate as possible in order to avoid large errors. When connecting the device under test to the power supply, unwanted resistance can arise from lines or contacts. The Four-wire measurement connection is the most accurate technique. It is used, if the resistance range of the measurement is below 10 Ω. This kind of measurement eliminates failures due to parasitic effects like lead and contact resistances. During the measurement with a four-wire connection, the DUT needs to be connected with the channel as well as the sense inputs of the power supply. This arrangement causes the cancelation of voltage drop across current cables, thus the measurement is very accurate [6].

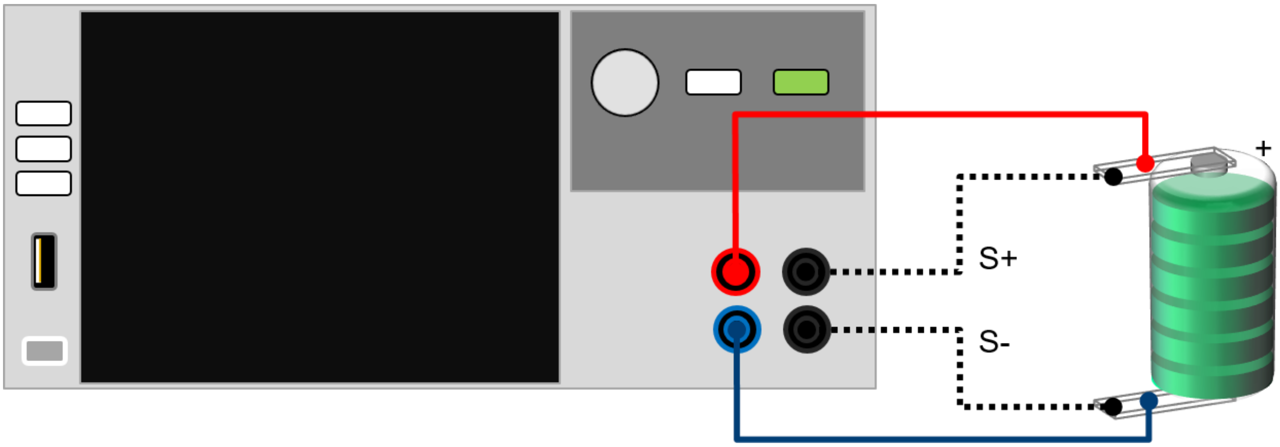

Figure 6: Measurement setup

For the connection between Battery Modeling Tool and power supply, a connection via LAN or USB to the computer must be established. How this can be done exactly is described in the manual of the respective power supplies [7] [8].

5.3 Recording the data

Before starting the measurement, a connection must be established. There are three alternative ways to establish the remote connection to an instrument:

1. If this program is started from the "power supplies and meters application dashboard" 1GP140 with an instrument selected, the ID string of the selected instrument appears in the instrument dropdown of this program when the initial warning message is closed. Click on ID string to select this instrument and to close the dropdown. Subsequently click the "Connect" button.
2. For a LAN connection with known IPv4 address, enter this address in the field on top right and click the "Verify and enter" button. If the device with the entered IP address is available on the ethernet and supported by this program, the ID string appears in the instrument dropdown. Click on ID string to select this instrument and to close the dropdown. Subsequently click the "Connect" button.
3. Click on the "Discover Rohde & Schwarz power supplies"- button. Then select the device from the drop-down menu and click "connect". After that, all the information about the device, as well as the options are displayed. Discovery works on the ethernet only in the same subnet where the controlling PS is connected. On USB, devices in "TMC" (Test and Measurement Class) mode are found.

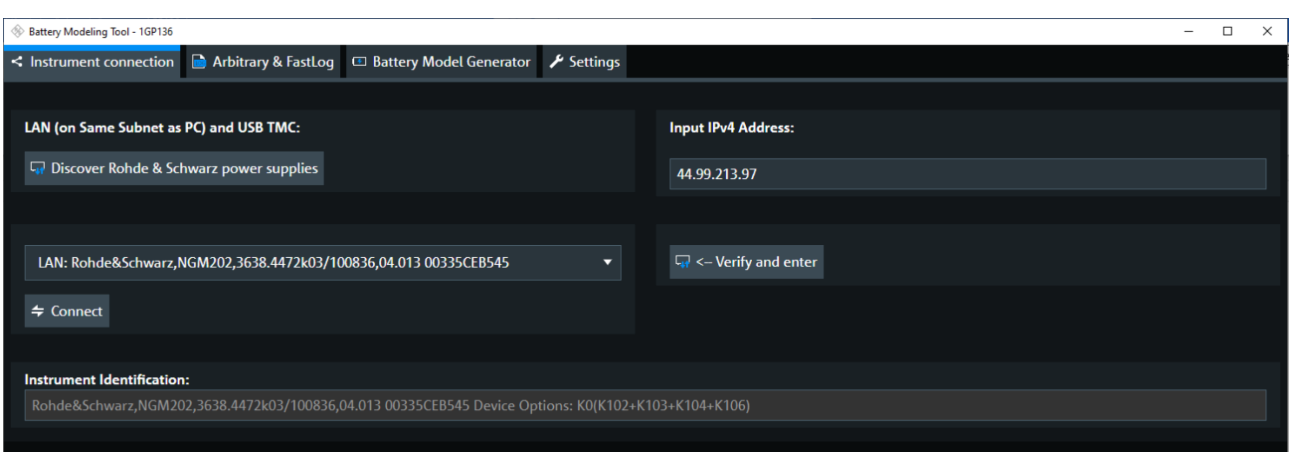

Figure 7: Connection page of the Battery Modeling Tool

Once the device has connected, you can proceed to the next page (Arbitrary & FastLog). On this page, you can select the channel from the drop-down-menu on which the measurement has to be made and then choose from three measurements. The first measurement is used, as already described in chapter 4.1.1.1, to determine the relaxation time for the entire relaxation measurement. For this, a maximum time can be specified after which the measurement is to be terminated. Since the battery is also loaded with 1 mA during the measurement, it does not take that long at all until the quiescent voltage is reached. Therefore, it would make sense not to choose too long times. Furthermore, the value and duration of the current pulse can be specified here. After the measurement is finished, three different times are suggested. Once the most accurate time needed to reach the OCV. Furthermore, times are suggested that are needed to achieve 1mV deviation and 0.1 mV. Depending on which time is chosen, the measurement time can be reduced. But therefore, also the accuracy decreases. If you have made such a measurement before, you can upload it here to calculate the time.

In the next step, the battery can then be discharged with the specified time over the entire SoC range. The charging and discharging voltages and currents can be taken from the database. The most common battery types are represented in this database. The following figure shows the database integrated in the Battery Modeling Tool.

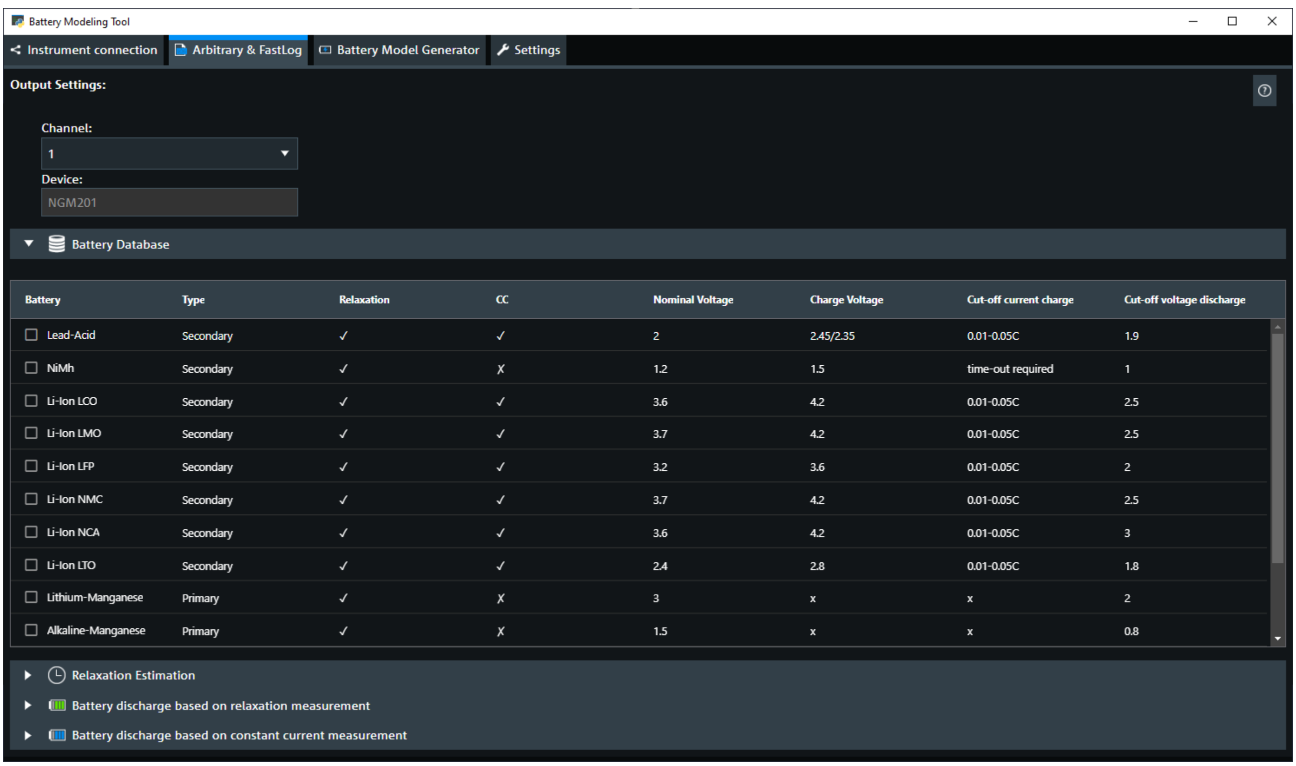

Figure 8: Database of the Battery Modeling Tool

The duration and the value of the current pulse are also specified for this measurement. If the measurement is started, a waiting indicator runs until the measurement is finished. The measurement is automatically saved at the position selected in the Battery Modeling Tool on the "Settings" page.

The next expander includes the constant current measurement. Here, the battery can be precharged, discharged and charged. If all three checkboxes are selected, the measurement runs exactly in this order. The cell can be either charged or discharged only, or cycled by applying both. The charge and discharge end conditions can be used here again from the database. After all parameters for the measurement have been entered, the measurement can be started. Again, a waiting indicator runs during the measurement until it is finished and the file is saved.

All measurements can be **aborted** with switching off the "output"- button on the power supply.

5.4 Battery Model Generator

On the "Battery Model Generator" page, a battery model can be calculated from the results of the previously created measurements. For the relaxation measurement, the measurement file is uploaded via the "Load File"- button. While the model is being calculated, a waiting indicator is displayed again. Afterwards, the measured voltage curve is displayed, as well as the data for the battery model.

Also, with the modeling from the results from the constant current measurement, the respective measurement files must be loaded. It must be ensured that the files are loaded via the button provided for this purpose (first discharge file, then charge file). The model is then calculated via the "Extract battery model"- button. Again, the original measurement data and the model data are output.

In the next type of modeling, an existing battery model that was created with the previously described procedures can be used to model a battery module. To do this, the model file is loaded into the tool and the number of cells to be connected in parallel and series is specified. The new model is then calculated on the basis of the input. To calculate this new model, formulas 5 & 6 are applied to the existing battery model. Make sure that the maximum ratings for voltage, current and power of the channels of the power supply are not exceeded.

If you have already determined the OCV, for example with the relaxation measurement, and you want to generate a new model with a different load (only the internal resistance curve changes), you can do this with the "Battery Model based on different loads" function. Here you load an already created model that contains the desired OCV into the tool. Then you select the new discharge measurement, which was created before, in the explorer. This measurement can be performed by means of discharge at constant current. For this, the same fully charged battery is discharged with the desired load. A new model, with a new internal resistance curve is then generated from these two files.

All generated model files are stored in the location specified by the user on the "Settings" page. By default, a folder is created here under "C:/Users/YourName/APPDATA/Roaming/Rohde-Schwarz/Battery Modeling Tool".

6 Testing the battery model

After you have generated your battery model, you can open it in the battery simulator of the R&S®NGM200/NGU201. With the integrated USB interface, the stored data can be easily loaded from an USB storage. This is done in the channel menu via the load from file button. Now you can select the battery model file from your USB storage. Another way to transfer the file to the instrument is described in [9]. The R&S®NGM200/NGU201 loads the selected file into the battery simulation. Now you can set the SoC with which you want to start the simulation of your battery. The loaded parameters from the file will be reproduced by the battery simulation depending on the change of the SoC caused by the current at the output.

Figure 9: Simulation Page of the power supply

7 Conclusion

Batteries are dynamic energy sources whose behavior in many cases deviates from an ideal voltage source. A model with an adjustable internal resistance, which changes depending on the state of charge, is used by R&S®NGM200/NGU201 to simulate batteries. The parameterization of this model requires, without the Battery Modeling Tool, on the one hand a long research to determine the correct measurement method and on the other hand a high computational effort. Here, the Battery Modeling Tool is a great support. The biggest advantage of this application software is that users of Rohde & Schwarz power supplies no longer need to write their own scripts to perform instrument control, measurement, data processing, data display and model calculation.

8 Ordering Information

Designation	Type	Order No.
Single-Channel Power Supply	R&S®NGM201	3638.4472.02
Dual-Channel Power Supply	R&S®NGM202	3638.4472.03
Battery simulation	R&S®NGM-K106	3636.6626.02
Two-Quadrant Source Measure Unit	R&S®NGU201	3639.3763.02
Battery simulation	R&S®NGU-K106	3663.0625.02

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