Monitoring battery charging and discharging conditions with the LMG600

Introduction

Batteries as electrical storage have entered the electrical industry since many years and their development in terms of size, capacity and efficiency has taken many leaps since then. Careful design as well as accurate monitoring of the electrical properties of a battery is crucial during their development phase. Moreover, their late integration in renewable energy production, electrical vehicles and increasingly small mobile devices has raised the bar significantly.

For more than 30 years, ZES ZIMMER Electronic Systems has provided solutions to precision power measurement in all sectors of the electrical and electronic industry. Our latest series of power analyzers, the LMG600, achieves top accuracy and versatility in the market. It is therefore intriguing to present and investigate the LMG600 power analyzer as a smart battery testing system.

When it comes to battery testing measurements, the LMG600 brings the following features on the table:

- Continuous measurement of voltage, current, power, energy, charge etc.
- Maximal overall accuracy: 0.025 %
- Separation of AC and DC measurements
- User configurable Custom Menus
- Integrated Script Editor
- Script configurable sync interface with digital inputs and outputs (GPIO)
- Optional process signal interface with analog and digital inputs and outputs (PSI), for temperature measurements or tracking of individual cells

The LMG600 therefore allows the implementation of customized, versatile and powerful battery tester. With easy to use and customize GUI and an intelligent Script Editor, important measurements of the battery characteristics such voltage, current, energy and charge as well as DC internal resistance and Joule energy dissipation can be displayed in a single screen. In short, the LMG600 provides everything necessary for detailed and accurate energy balance measurements, from charge to discharge.

Application and definitions

The purpose of this application is to measure the basic electrical characteristics of a battery during charging and discharging conditions. The important quantities to be measured consist of:

- the DC voltage on the battery U_{dc} as well as its minimum and maximum values U_{min} and U_{max}
- the DC current I_{dc}
- the power, energy and charge of the battery P_1, E_1 and q_1
- the internal resistance of the battery R_b

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- the power and energy dissipation P_j and E_j in the battery due to the Joule effect

The values of U_{dc}, I_{dc}, P_1, E_1 and q_1 are directly measured by the power analyzer. The rest are defined as:

- $U_{min} = \min(U_{dc})$ total minimum value of the DC voltage during the duration of the test
- $U_{max} = \max(U_{dc})$ total maximum value of the DC voltage during the duration of the test
- $R_b \approx Z_b = \frac{U_{ac}}{I_{ac}}$ where U_{ac} and I_{ac} the AC components of the battery voltage and current, provided that U_{ac} and I_{ac} are in phase
- $P_j = R_b * I_{trms}^2$ where I_{trms} the total current in the battery
- $E_j = E_{j0} + (P_j \cdot \frac{\Delta t_{en}}{3600})$ where E_{j0} the initial energy stored in the battery and Δt_{en} the duration of the current cycle

Precise measurement of the above mentioned quantities allows a detailed study of the battery's capacity and efficiency as well as continuous monitoring of the internal resistance and the dissipated energy via resistive heating. The use of a multi-channel LMG600 for the simultaneous measurement of the charger efficiency can provide a better overview of the system. Moreover a multi-channel power analyzer can track the voltage of multiple cells in series. The results can be displayed in numerical and graphical form and be stored and extracted to PC for further processing in Excel or Matlab.

The battery can be tested under different conditions, under stable DC input, modulated DC for internal resistance measurements, stress tests with pulsed input or random charging and discharging to simulate real-life conditions.

Measurement setup and wiring

The proposed test setup as shown in Figure 1 incorporates the following components:

- ZES ZIMMER LMG610 power analyzer
- 2400 mAh Nickel-Cadmium 6-cell battery
- DC current source as battery charger
- Signal generator in combination with 900 µH inductor & 100 µF capacitor for the measurement of the internal resistance
- 12 Ω power resistor as load
- Relay circuit for switching between charge/discharge/standby modes

The battery is connected in parallel to the charger during charging and the load during discharging. A circuit composed of 2 relays is used to switch between the two operating modes, which will be controlled by the GPIO interface of the LMG600. When both the relays are open, then the battery is open circuited (standby mode). The relays must be controlled in such a way, that they are never closed at the same time. The basic measurement circuits during charge and discharge are shown in Figure 2 and Figure 3.

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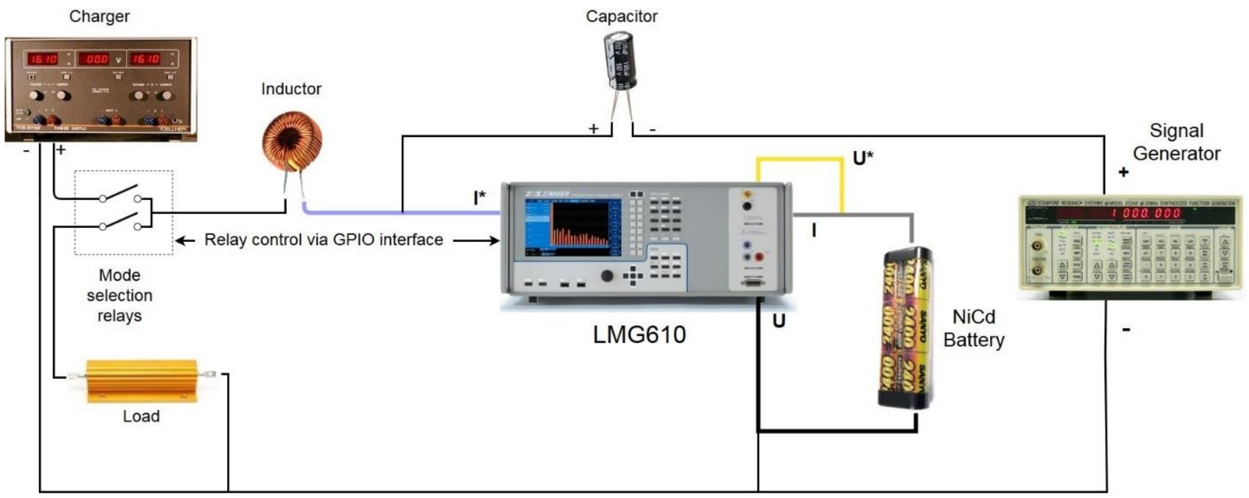

Figure 1: Measurement setup

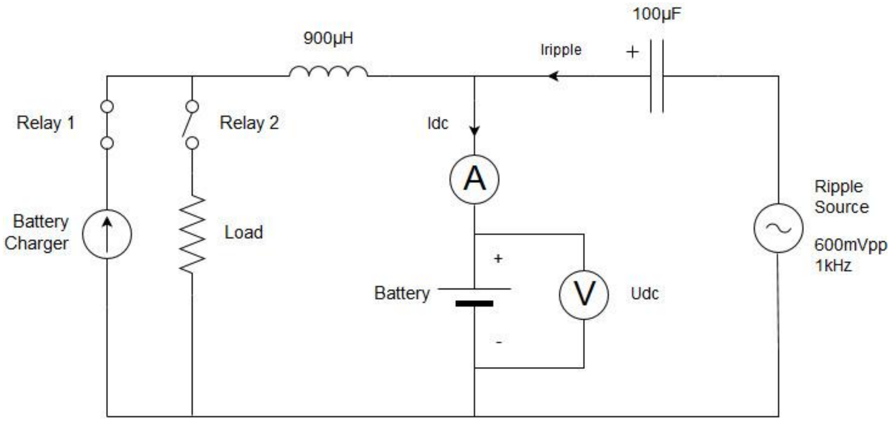

Figure 2: Measurement circuit during charging

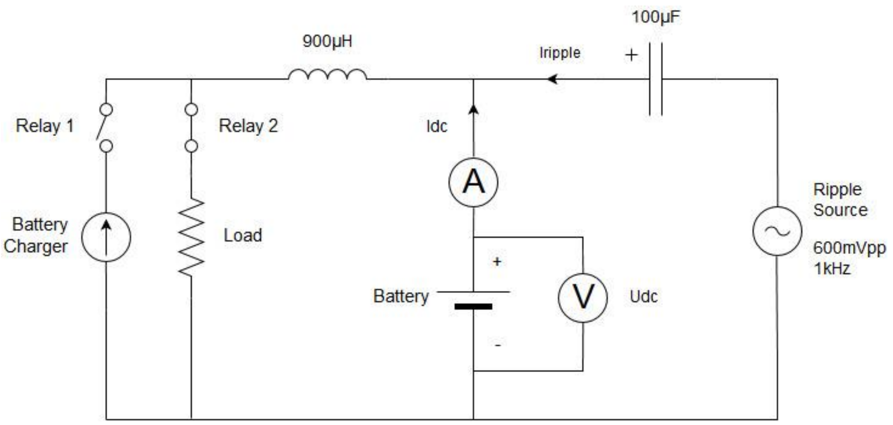

Figure 3: Measurement circuit during discharging

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Testing the battery

Charging the battery can happen in either fast or slow rates. A NiCd battery with capacity of 2400 mAh theoretically needs 1 hour to be fully charged under 2.4 A of current. Slow charging usually happens with 10% of this current and lasts 14-16 hours – instead of 10 – due to increased thermal losses during the end of the charging period.

It is however more interesting to monitor the battery during fast charging. Usually in this case the battery is charged with its nominal current. While fast charging, the battery will experience a rise on its temperature as it approaches its full charge which is more significant than in the case of slow charging. This temperature rise will cause a voltage drop which indicates that the battery is fully loaded. Monitoring this voltage drop with the LMG600 allows the user to detect this event by setting the proper voltage threshold. Once the voltage drop exceeds this threshold, the user is warned to stop the charging by using the GPIO interface and the appropriate relay circuitry to effectively disconnect the battery from the current source.

While discharging, it is also important to know when the battery is reaching its empty state. Following the Cell Voltage– to–Discharge Capacity characteristics, provided by the manufacturer the user can set a lower voltage limit. The power analyzer will detect when the battery voltage drops lower than this limit and warn the user that the battery is almost empty. The battery will be at the same time automatically disconnected from the load.

Although it is easy to detect when the battery is discharged, properly detecting its charged state can be complicated. The typical voltage drop at the end of the charging is easily recognized by the user but programming an advanced algorithm to distinguish this state among various other types of voltage drops that may occur, is in practice quite tricky. For this reason, a warning only is produced when this voltage drop is detected but the charging will not immediately stop. This will happen after a few cycles, if the user fails to notice and manually switch to discharge or standby in time.

In this experiment we set the charger to provide with a maximum of 800 mA to the battery during charging. The voltage drop limit is set to 60mV according to the manufacturer specifications. Discharging happens by connecting a 12Ω resistor as load to the battery which depending on the voltage results to 400-700 mA discharge current. In this case the lower voltage limit of the battery is set to 6.2 V, or 1.05 V per cell.

Measuring the internal thermal losses requires knowledge of the battery's internal resistance over time. The formula $R_b = \frac{U_{ac}}{I_{ac}}$ requires a modulated current. Obviously with no ripple on the battery current, this value would take random or infinite values and would not make any sense. To generate this current ripple we use a signal generator. The 100 μF capacitor prevents the DC current from flowing towards the signal generator, leading it all through the battery. Similarly, the 900 μH coil is used to prevent the AC current from flowing towards the charger or the load.

A signal of frequency of 1 kHz is often used in battery impedance measurements. The amplitude is selected after measuring the ripple voltage and current through the battery and adjusting the value until a power factor of almost 1 is achieved. This way the measured impedance corresponds to the internal resistance and further calculations of the joule losses are possible.

Presenting the measurements and scripting the calculations

The LMG600 allows the user to build custom menus in order to display their measurements, settings and graphs in a summarized, comprehensive and application oriented way. As seen in Figure 4 the custom screen for this application includes all the important battery stats, a graph to display any desired value over time as well as controls and settings. A script that works in cooperation with the custom menu will apply the measurement settings and calculate the not directly measured values such as the internal resistance and the Joule losses of the battery. This script specifically allows:

- to calculate quantities and define their units of measurement: e.g. Umax, Umin, Rb, Ej
- to reset values, start and stop integration
- to compare measurements to previously defined thresholds and trigger actions
- to control digital outputs to synchronize with external devices or trigger relays
- to log the values at the end of every cycle

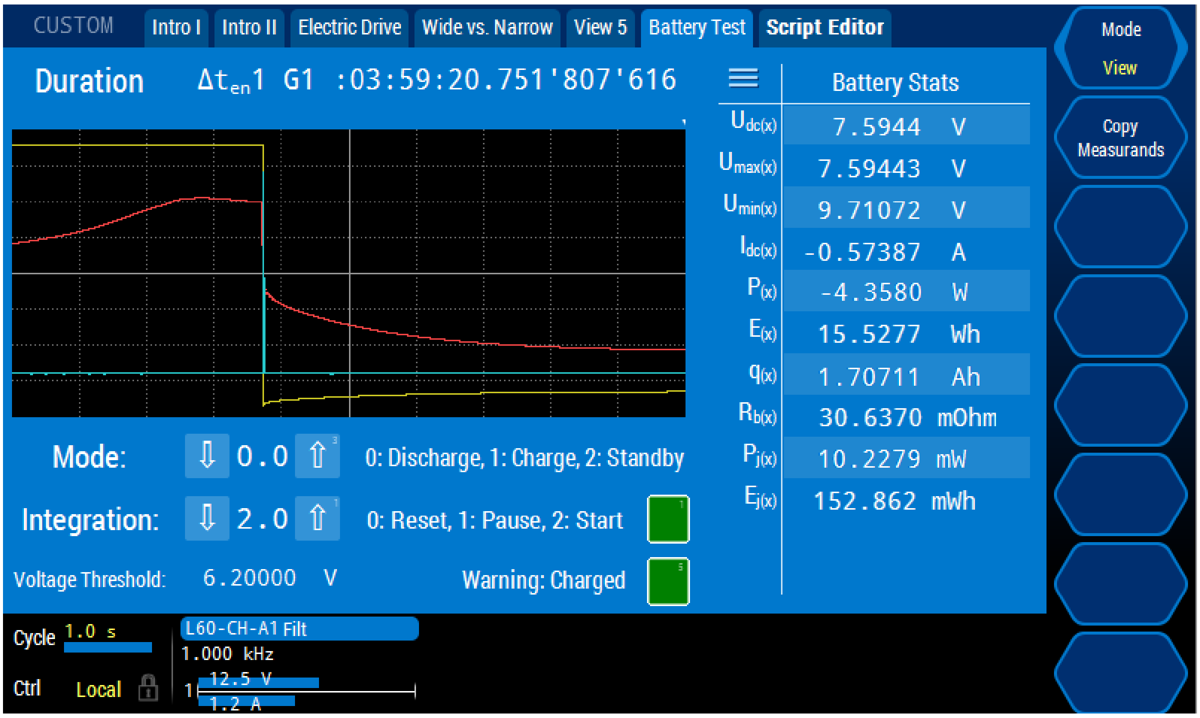

Figure 4: Custom menu for battery testing application

The user can select the type of the test (charging, discharging or standby) by changing the Mode setting. Integration is started by the script when the mode is Discharge or Charge and is paused during Standby. Pressing the down arrow once while on Standby will set the Integration to 0 and reset the time and the energy/charge values. The total elapsed time is shown on the top of the screen. The Voltage Threshold is set by the script and also displayed but cannot be changed during the measurement.

The following script can be considered as example for the above custom menu.

Example script "Battery_Test_NiCd"

```
//definition of calculated values
def{
R_b="Ohm";
U_dc="V";
I_dc="A";
P="W";
E="Wh";
```


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```
q="Ah";
U_max=0.0"V";
U_min=0.0"V";
U_th=0.0"V";
P_j="W";
E_j=0.0"Wh";

//auxiliary variables
$zero=time(0.0);
$count=0.0;
$ctrlPath1 = -1;
$ctrlPath3 = -1;

//calculation of basic properties
U_dc=[udc1111?]                              //DC voltage
I_dc=[idc1111?]                              //DC current
P=[p1111?]                                   //power
E=[ep1111?]                                  //energy
q=[ei1111?]                                  //charge
R_b = ([uac1111?]/[iac1111?])                //internal resistance
P_j = R_b*[itrms1111?]* [itrms1111?]         //Joule power
if ([duren1111?]==$zero) {
        U_max=0.;
        U_min=20.;
}
U_max = max([udc1111?], U_max);              //maximum DC voltage
U_min = min([udc1111?], U_min);              //minimum DC voltage

//start-stop-reset the integration
if (env(1) == 2) {
   E_j=E_j+(P_j*float([durnorm1111?])/3600); //Joule energy
   if($ctrlPath1 != 2) {
     $ctrlPath1 = 2
     StartEnergy();
   }
} else if (env(1) == 1 && $ctrlPath1 != 1) {
        $ctrlPath1 = 1
        StopEnergy();
} else if (env(1)==0 && $ctrlPath1 != 0) {
        $ctrlPath1 = 0
        ResetEnergy();
        E_j=0.0;
        U_min=-20.0;
        U_max=0.0;
}
//detect from current if battery is charging or discharging
if (I_dc > 0.002) {
        $mode=1.0;            //it is charging
} else if(I_dc < -0.002) {
        $mode=0.0;            //it is discharging
} else {
        $mode=2.0;            //it is floating
}
```


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```
//control the relay according to Mode Setting
if (env(3) == 1) { //if Mode is Charging
        if (U_max-U_dc > U_th && $mode==1.0) {
                Beep();                         //Beep as warning
                $count=$count+1;                //count cycles
                $charged=1.0;
                setEnv(5,$charged);
                if($count>5){setEnv(3,2);}      //count up to 5 cycles and disconnect the battery
                                                // if not done manually by the user
        } else {
                $charged=0.0;
                setEnv(5,$charged);
        }
   if($ctrlPath3 != 1) {
        $ctrlPath3 = 1
        U_th=0.06;              //set the voltage threshold
        SetGPIOOut(4,0);        //open the discharging relay
        SetGPIOOut(3,1);        //close the charging relay
        Setenv(1,2);            //start/resume integration
   }
} else if (env(3)==0) {         //if Mode is Discharging

        if(U_dc<U_th && $mode==0.0){ //check voltage limit
                Beep();
                SetEnv(3,2);    //set the Mode to Standby
        }
        if($ctrlPath3 != 0) {
                $ctrlPath3 = 0;
                U_th=6.2;               //set the voltage threshold
                $charged=0.0;
                Setenv(5,$charged);
                SetGPIOOut(3,0);        //open the charging relay
                SetGPIOOut(4,1);        //close the discharging relay
                Setenv(1,2);            //start/resume integration
        }
} else if (env(3)==2 && $ctrlPath3 != 2) { //if Mode is Standby
   $ctrlPath3 = 2;
        SetGPIOOut(3,0);        //open the charging relay
        SetGPIOOut(4,0);        //open the discharging relay
        if(env(1)==2){
                Setenv(1,1);    //pause integration
        }
        U_th=0.0;               //set voltage threshold to 0V
        U_max=0.0;              //reset voltage min and max
        U_min=20.0;
}
Operation=$mode
// end of cycle, log all values
logOnce()
```

To record the measurements the user must define a log file in the STORAGE - Log menu and select the values to be exported with every recording. Enabling the Script logOnce setting, will allow the script to record the values whenever the logOnce() command is called at the end of every cycle.

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Moreover, on the INSTR. – GPIO & Sync screen, the Direction of the GPIO slots 1 to 4 is set as “Output”. As soon as the Script is installed, the State of the slots 3 and 4 changes to “Script Ctrl”.

Results

The results of a full charging-discharging test are presented below. The battery is empty at the beginning of the test as well as in the end. Before beginning the test it is convenient that the battery is not connected neither to the charger nor the load (standby mode, both relays open).

The results are as mentioned logged after every measurement cycle and can be exported in excel format. It is easy then to process the results and present them in graphs.

In Figure 5 one can see the DC voltage and current during a full charge – discharge cycle. Charging with 800mA or at C/3 rate lasts as expected almost 3 hours. Towards the end of this period, voltage takes its maximum value before beginning to drop. At this point we consider the battery as fully charged and the analyzer shows a warning indication.

The discharging of the battery starts immediately afterwards and is carried out through a 12 Ω resistor. The current during this period is of course negative as it flows towards the opposite direction. As the voltage of the battery decreases, so does almost proportionally the current. When the DC voltage reaches a level below 6.2 V the power analyzer signals the end of the charging and automatically sets the mode again to Standby.

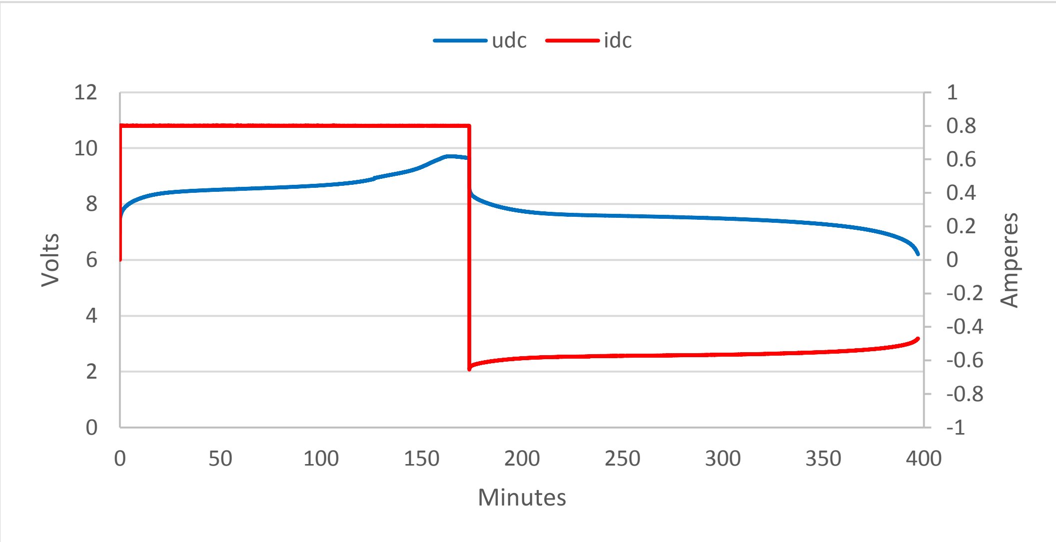

Figure 5: DC voltage and current during a charging cycle

Figure 6 shows the power, energy and charge the battery draws and releases during a full cycle. Initially the battery is considered as fully discharged which means that according to our definition, when connected to the 12 Ω resistive load it’s voltage will be 6.2 V. At this point the stored energy and charge are not known but are considered as zero (Integration is set to 0:Reset), for reference before starting the measurement. Even though the stored energy and charge in the battery are not directly measured it is safe to assume that by the end of the discharging their value is more or less the same as it was at the beginning of the test. That is because the conditions according to which we define the point of zero energy and charge (Vdc = 6.2 V) are the same before and after the test. So better control of these conditions with the LMG600 means better accuracy on this assumption.

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The battery draws in total, 2.32 Ah of charge, which is quite close to its nominal capacity. The total energy that the battery has drawn during charging is 20.3 Wh and includes all losses in thermal, chemical or other form. The level of the energy at the end of the test is not zero and can be therefore considered as the total energy loss during a charge-discharge cycle, which in this case is 4.65 Wh.

The power follows an entirely predictable curve.

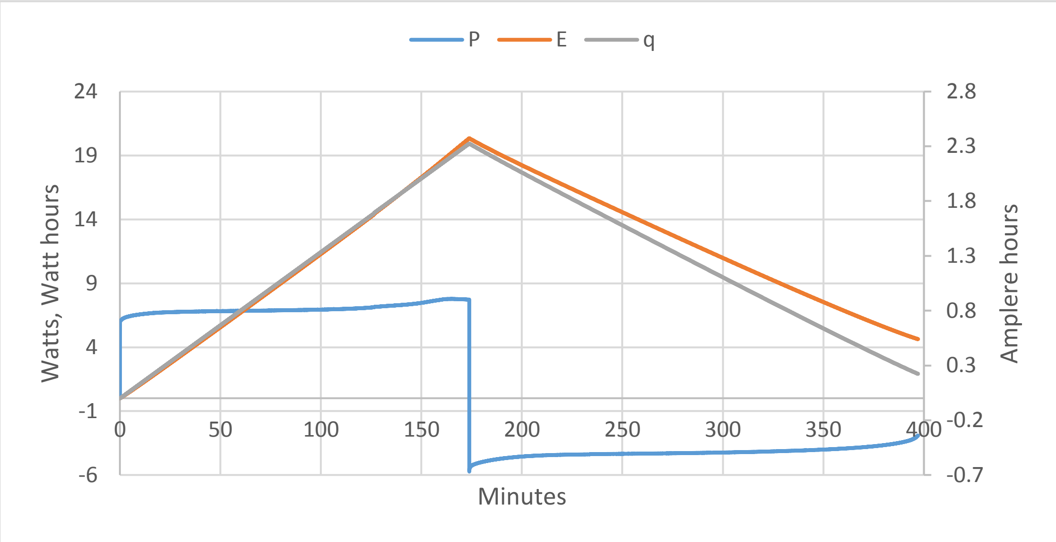

Figure 6: Power, energy, charge

An overview of the Joule losses can be achieved by monitoring the battery's internal resistance, which is seen in Figure 7. It is generally decreasing during charging and increasing during discharging, but a "bump" can be observed towards the end of the charging. Based on the measured internal resistance, the joule energy and power are calculated by the script and presented in Figure 8. According to this, the battery dissipates 104 mWh as heat due to its internal resistance, during a full cycle.

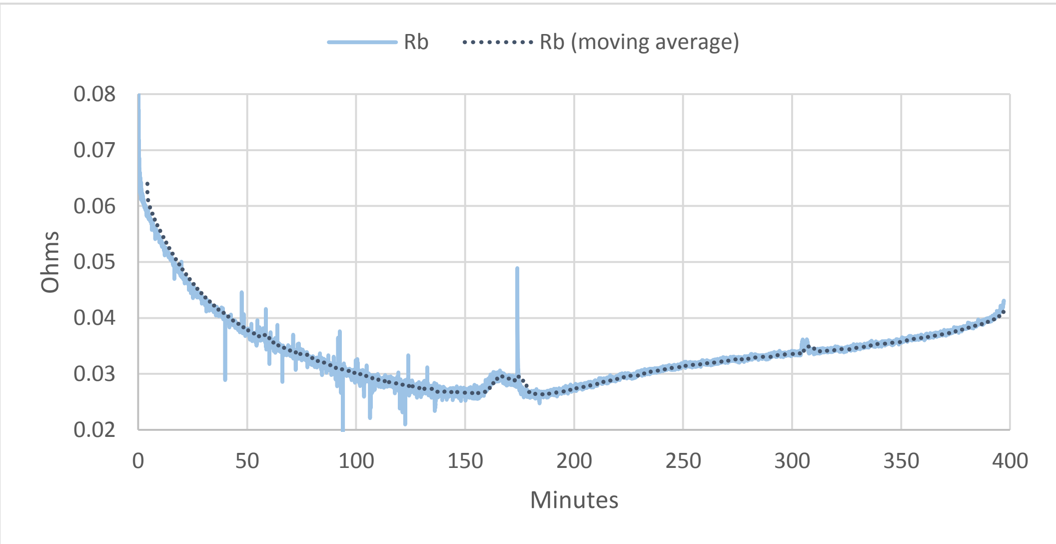

Figure 7: Internal resistance

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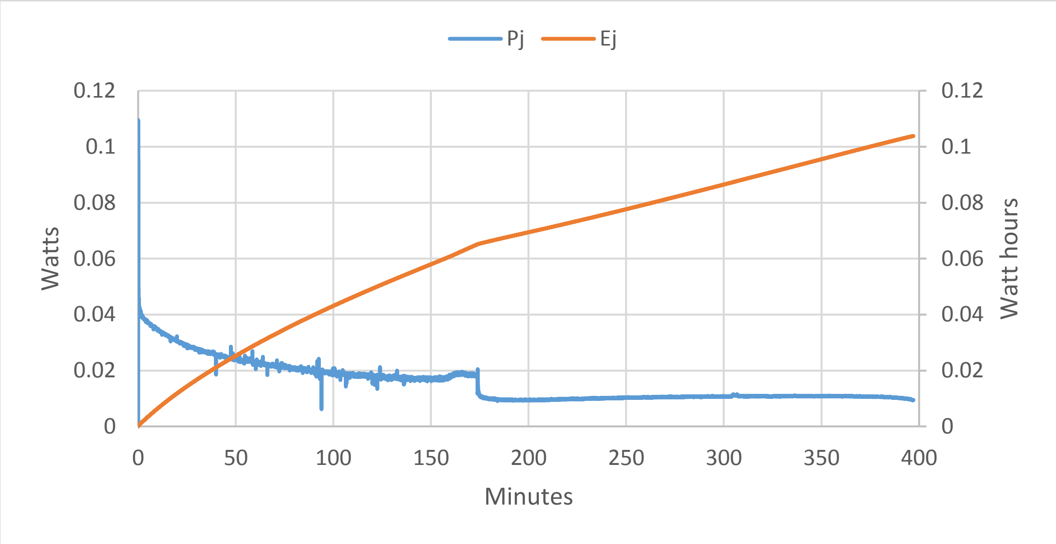

Figure 8: Joule power and energy

Conclusions

- LMG600 covers the first and most basic principle of a testing system: Accurate measurement of the fundamental properties.
- At the same time offers continuous data recording and exporting as well as built in programming capabilities.
- Charging routines or specific tests (e.g. an AC or DC sweep) can be scripted and automated with the use of programmable equipment and the LMG600s I/O interfaces (GPIO, CAN, PSI).
- Granted these features, our simple script for NiCd batteries can be expanded to an advanced algorithm in an R&D lab for any type of batteries and test scenarios.

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