46740 Distributed Energy Technologies, Modelling and Control

Assignment 1: Battery modelling and control

Group 41

Frederik Skou Fertin, s203679

Simon Vincentz Hansen, s203678

Thomas Reenberg Trosborg, s203658

2024-03-14

Contents

1 Battery cell configuration **1**

2 Initial model **1**

2. a) The dynamic behaviour of the model 1

2. b) Process losses and cycling of the battery 2

2. c) Maximum temperature and internal resistance of the battery 3

3 Adding a cooling unit **3**

3. a) Dynamic behaviour of the temperature 3

3. b) Process losses improvement from battery cooling 4

3. c) Ambient temperature (and initial temperature of battery) of 25°C 4

3. d) Cooling unit power usage during battery discharge 4

4 Assessing the passive cooling characteristics of the battery **5**

4. a) Model simplification and findings 5

5 Simulating the dynamic behaviour of the EV battery using data sampled during a trip from Denmark to Italy **5**

5. a) Overview of battery usage during the trip 5

5. b) Average driving consumption during the trip 6

5. c) Comparison of power supply to rpm of the electric motor 6

A Appendix **7**

1 Battery cell configuration

The specifications for the battery in this report can be found in table 1 in the appendix.

In order to obtain the desired battery specifications the required number of cells in series n_{series} and parallel $n_{parallel}$ can be found in the following way:

$$n_{series} = \frac{V_{batt}}{V_{cell}} = 96 \tag{1}$$

$$n_{parallel} = \frac{E_{batt}}{V_{batt} \cdot I_{cell}} = 3 \tag{2}$$

where V_{batt} and V_{cell} denote the nominal battery and cell voltages, E_{batt} the nominal battery capacity, and I_{cell} the nominal cell current. Thus, the battery contains 288 cells. This also implies that the nominal battery current (C_{rate} = 1) is 176.4 A. The heat capacity of the battery can be determined by multiplying the specific heat capacity with the mass of the battery. The heat capacity is 318.27 kJ/K. The open circuit voltage and internal resistance of the battery is modelled through look-up tables, which base the values solely on the SOC of the battery.

2 Initial model

With the battery model initialized with the previously mentioned specifications and SOC-dependent voltage and resistance characteristics, a discharge and charge cycle is simulated. The battery is simulated with an initial SOC of 95%, the ambient temperature (and initial temperature of the battery) is 10°C. The battery is discharged with 20 kW for 180 minutes followed by a charging period of 60 minutes.

2. a) The dynamic behaviour of the model

Fig. 1 illustrates the power profiles (upper) and the SOC and voltage profiles (lower) during the simulation. As evident from the power profiles, the DC and AC power of the battery deviate from the power reference when the SOC reaches 5% as this is enforced as a hard lower limit (i.e., discharging is prevented when the SOC is 5% or lower). Additionally, there is a second deviation towards the end of the charging period when the reference voltage exceeds the maximum allowed battery voltage. As the battery voltage is capped below the necessary reference voltage during this period, the power setpoint is not met as evident from the upper figure. It is also worth mentioning that the DC power is higher than the AC power during discharging due to losses to the inverter and naturally, the absolute value of the AC power is higher than that of the DC power during charging. Somewhat correspondingly, the reference and battery voltages are lower than the open circuit voltage during discharging to draw a DC current out of the battery while the opposite is true during charging. To clarify, the current drawn from the battery is determined by the difference between the OC and battery voltages divided by the internal resistance.

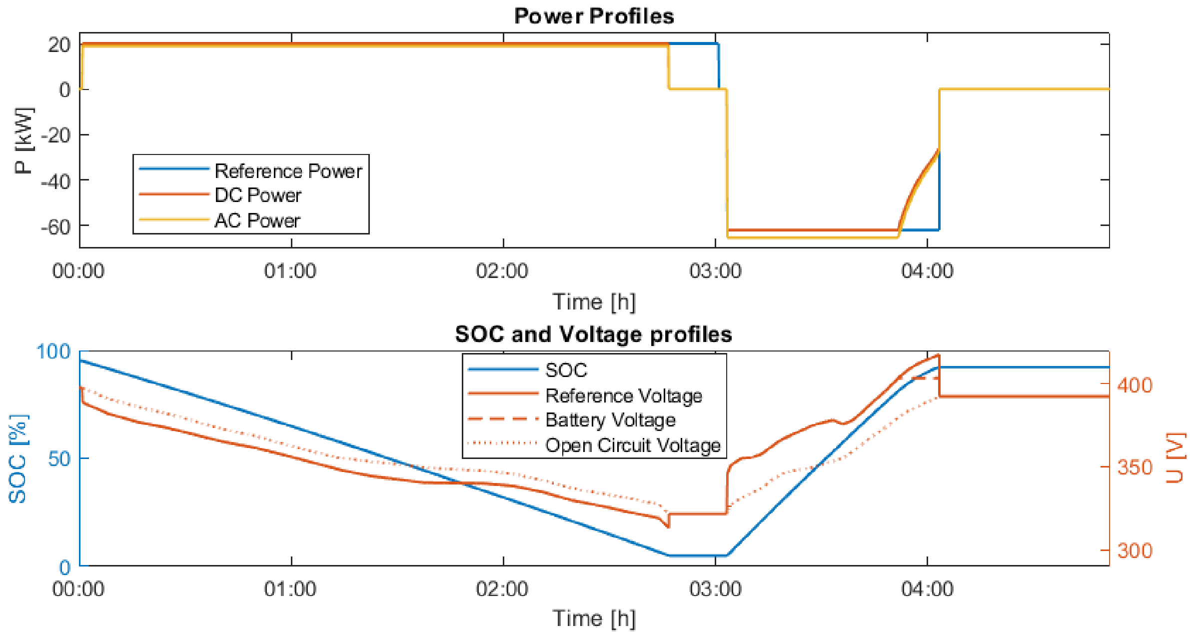

Figure 1: Power flow is observed as positive when the battery is discharging and negative during charging. Voltage profiles and SOC development during the discharging and charging periods. The battery voltage follows the reference power voltage except for the last part of the charging period, where the voltage protection kicks in.

2. b) Process losses and cycling of the battery

Fig. 2 illustrates the thermal losses (blue), Joule losses (broken blue), and battery temperature (red) during the previously described simulation. As the battery is initially in thermal equilibrium with the ambient (at 10°C) there are no thermal losses in the beginning. The joule losses, however, begin to heat up the battery when discharging is started. As the thermal losses are given by the temperature difference between the battery and the ambient, the heat losses increase as the battery temperature increases. As long as the joule losses exceed the thermal losses to the ambient, however, the battery temperature keeps increasing. Hence, during the short period between discharging and charging (while the joule losses are zero) the temperature drops slightly due to the thermal losses to the ambient. Then, the temperature increases rapidly when the battery is charging with 62 kW.

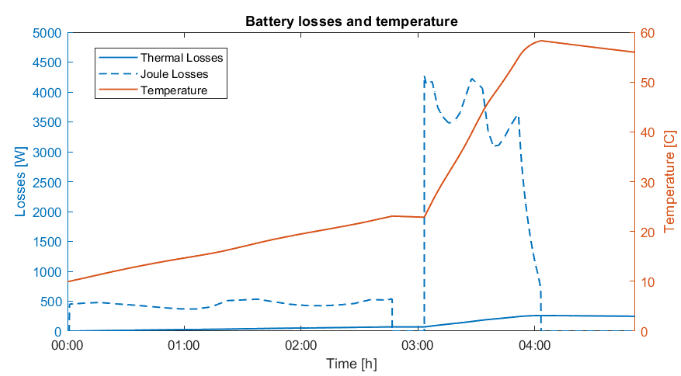

Figure 2: Temperature evolution plotted along with joule losses in the battery and heat dissipation to the ambient.

The current decreases during charging as the OC voltage increases which necessitates a lower current to discharge with the same power. Oppositely, the current increases during discharging. These dynamics are however not evident from the joule losses in the figure as their dynamics are largely determined by the significant fluctuations in internal resistance (see Appendix). Indeed, the internal resistance causes the irregular shape of the joule losses which is most evident during the charging period.

As between discharging and charging, the temperature drops slowly at the end of the simulation after charging is done. It is, however, evident that the joule losses far exceed the thermal losses to the ambient at these temperatures. Thus, if the battery is continuously charged and discharged with only short breaks in between, the battery will reach much higher temperatures before the thermal losses to the ambient will even out the joule losses. The total loss of thermal energy to the ambient is 0.507 kWh while the total energy dissipated in the battery due to joule losses is 4.565 kWh. This motivates active cooling which will be introduced in the next section.

The battery discharging and subsequent charging corresponds to cycling the battery 0.886 times as the simulation resulted in a total throughput of 312.7 Ah.

2. c) Maximum temperature and internal resistance of the battery

The maximum temperature of the battery is 58.3°C reached at the end of the charging period (see fig. 2). The lowest and highest internal resistances of the battery are 0.058 and 0.086 p.u. respectively (see fig. 8 in the Appendix).

3 Adding a cooling unit

To simulate the active cooling, a relay is added in the thermal dynamics block. The relay takes the battery temperature as an input, and outputs a constant of 4000 when the temperature reaches 35°C, and turns off when the temperature drops below 25°C.

To measure the energy losses to the surroundings and the heat dissipated by the cooler, an integrator block was added for both of the losses and converted from Joule to kWh by a gain block.

3. a) Dynamic behaviour of the temperature

From fig. 3 it can be seen that there is a small increase in the battery temperature while the battery is discharged, a bigger increase during the charging period, due to the absolute current, and then a decrease when the active cooler is activated. For a short period the joule losses exceed the cooling power and thermal loss, and therefore keeps an almost steady temperature even though the cooler is activated. This correlates well with the bottom graph, which shows the Joule losses, the heat lost to the surroundings, and the heat dissipated by the cooler.

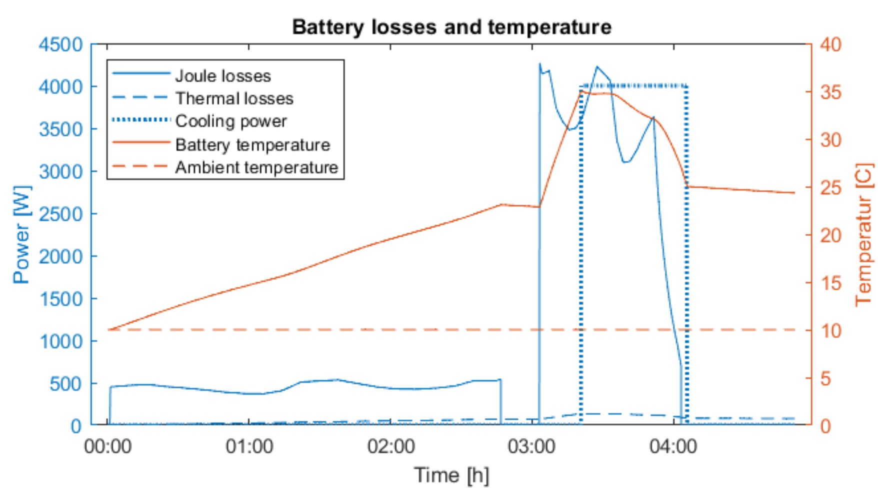

Figure 3: Temperature and battery losses with ambient temperature 10°C

3. b) Process losses improvement from battery cooling

The joule and inverter losses do not change, since they don't depend on the temperature, and the power pattern is the same as previous. The joule and inverter losses would be greater if the energy demand from the cooler was drawn from the battery, but in the current model, the cooler uses "free" energy.
The cooling unit dissipates 2.9 kWh of heat during the simulation, and another 0.3 kWh of heat is dissipated to the surroundings as thermal losses. Since the thermal losses are dependent on the temperature difference between the ambient air and the battery, the thermal losses will in this case be lower than in Task 2, since the battery generally has a lower temperature due to the active cooling.

3. c) Ambient temperature (and initial temperature of battery) of 25°C

When the ambient temperature is increased to 25°C, active cooling is needed earlier, due to the higher battery temperature. It is also worth noticing that the thermal losses are smaller since the temperature difference is smaller than before.
The change in ambient temperature increases the heat dissipated by the cooler to 4.5 [kWh], with a thermal loss of 0.11 [kWh]. As before the joule and inverter losses stay the same. With a given COP of 5 for the cooling unit, it would have a consumption of $\frac{4.454[kWh]}{5} = 0.891[kWh]$, this is the energy consumed by the cooling unit. If the energy is drawn from the battery, it would have to pass an inverter, leading to a greater energy demand from the battery. With an inverter efficiency of 95%, the energy drawn from the battery is $\frac{0.891[kWh]}{0.95} = 0.938[kWh]$.

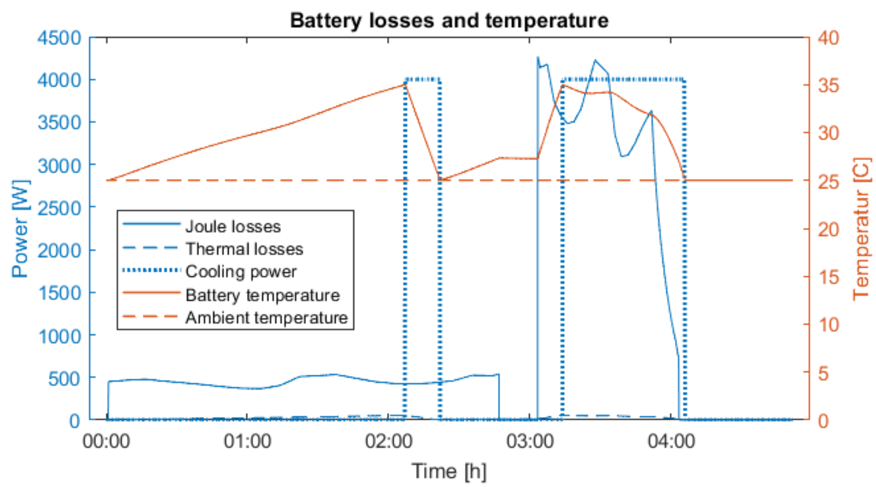

Figure 4: Temperature and battery losses with ambient temperature 25°C

3. d) Cooling unit power usage during battery discharge

When the cooler is connected to the battery during discharging the power consumed by the cooler should be added to the discharging power. Thus, when the cooling power is 4 kW, the COP is 5 and the inverter efficiency is 0.95, then the instantaneous power is increased by $4\,kW/(5 \cdot 0.95) = 0.842\,kW$. Thus, the required power for cooling is inversely proportional to the COP. It should be mentioned that connecting the cooler to the battery results in an increased need for cooling as the current drawn from the battery is increased resulting in higher joule losses and therefore, increased heating of the battery. By simulation, it is determined that the joule losses during discharging increase from 1.255 kWh to 1.260 kWh corresponding to a 0.4 % increase, when the power consumed by the cooler is drawn from the battery. The instantaneous power increase in the simulation is 0.880 kW, which means that the added joule losses imposed by the cooling unit equal 0.038 kW.

4 Assessing the passive cooling characteristics of the battery

Using the battery model without a cooling unit the battery temperature without any charging or discharging is simulated for 96 hours. The initial temperature of the battery is 40°C and the ambient temperature is a constant 10°C.

4. a) Model simplification and findings

Everything except the thermal dynamics subsystem from the model can be removed since no other dynamics are happening or interacting with the battery. This allows us to only simulate a small part of the total system to get a view into the thermal characteristics of the battery. Looking at fig. 5 the decay of the battery temperature over the 96 hour period can be seen. From this simulation the time constant associated with this exponential decay is found to be 16.35 hours. I.e. if we drive the car home from work at 17:00 then the car will not have lost more than 2 thirds of the heat in the battery before it has to drive again at 07:00, 14 hours later.

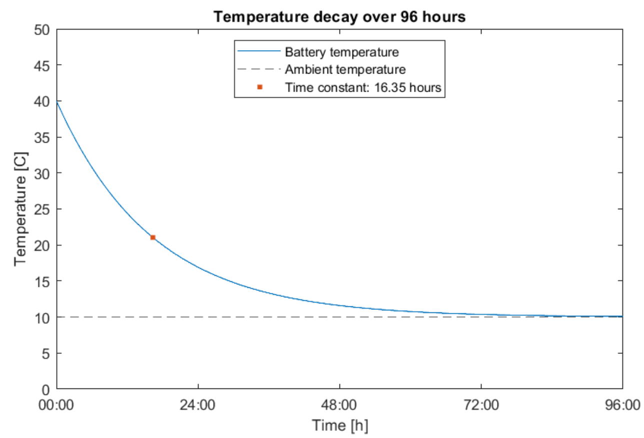

Figure 5: Temperature evolution of the battery over 96 hours.

5 Simulating the dynamic behaviour of the EV battery using data sampled during a trip from Denmark to Italy

5. a) Overview of battery usage during the trip

Fig. 6 illustrates the power profiles (upper) and the SOC and voltage profiles (lower) during the simulation. Evidently, the reference power is met throughout the simulation. However, the model SOC protection needed to be modified slightly to allow this as the relay function was initially too insensitive to follow the power set point even when the battery was not exceeding its maximum SOC - see Appendix fig. 9 to see how the simulation was unable to follow the set point initially. The range of SOC the battery runs through is from 95% (at the very start of the trip) to 53.96% (at the end of the trip). At no point during the trip does the voltage protection need to enforce limits on the battery charging or discharging as the battery is also not charged above 90% during any of the 3 charging periods. The total throughput of the battery during the trip is 410.7 Ah, which corresponds to 1.164 battery cycles for the battery with a capacity of 176.4 Ah. The maximum temperature of the battery during the trip is 35°C, which can also be seen from fig. 10, where drops immediately when the cooling unit sets in since it cools at a much higher power than the joule losses. The consumed energy while driving can be denoted as either the consumed AC power by the motor, the consumed DC power, or the power supplied by the battery. We define it as the energy supplied by the battery while the rpm of the motor is not null. The consumed energy is then 81.18 kWh - the equivalent energy delivered to the motor after losses is 74.12 kWh. The charged energy is specified as the AC energy used to charge the car while parked. This is 59.13 kWh.

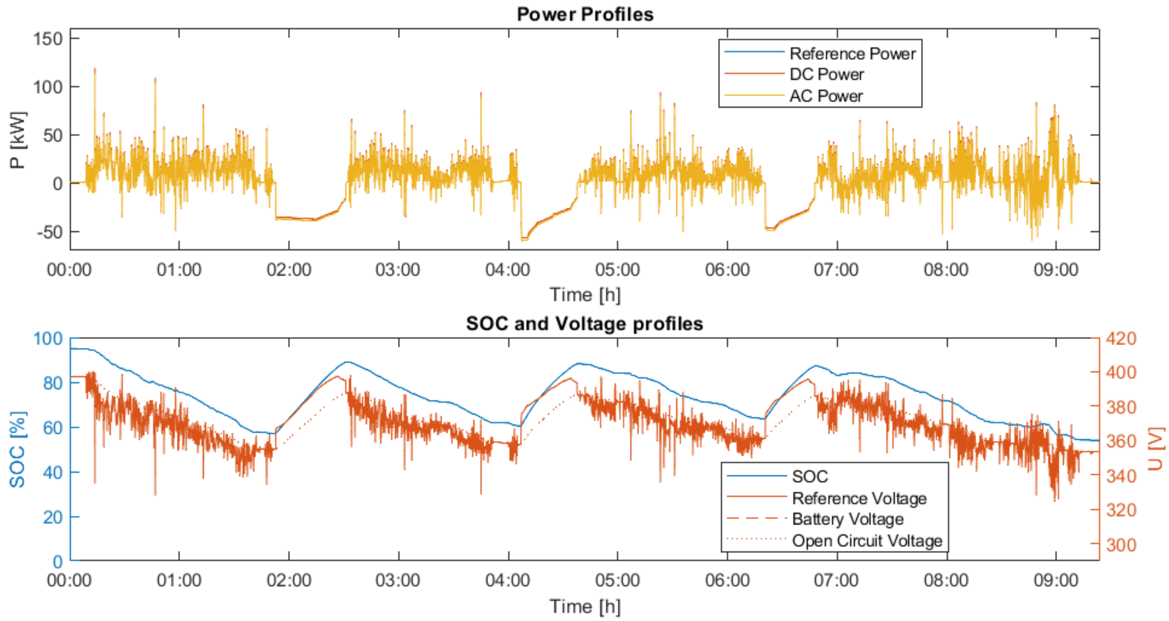

Figure 6: Power flow is observed as positive when the battery is discharging and negative during charging. Voltage profiles and SOC development during the discharging and charging periods.

5. b) Average driving consumption during the trip

The average driving consumption during the trip can be calculated by dividing the earlier identified consumption during driving with the distance driven. The trip was 499.5 km. This makes the average driving consumption 0.163 kWh/km over the duration of the trip. The average AC energy required is 0.148 kWh/km.

5. c) Comparison of power supply to rpm of the electric motor

Fig. 7 illustrates the relationship between the power supplied to and the rpm of the electric motor. The rpm of the motor has a positive correlation with the power reference for the battery. The plot has one noticeable line, the vertical line with almost zero power supplied during driving. This is likely not enough to sustain the high speeds, why there is another cluster which has a more distinct positive correlation with the power. The maximum power drawn from the battery during the 9 hour trip is around 120 kW with the majority of the large power surges being in the range between 40 and 80 kW. Considering the motor has a peak power of 160 kW, it can be concluded that the motor's peak power is oversized compared to the required power outputs from standard driving patterns.

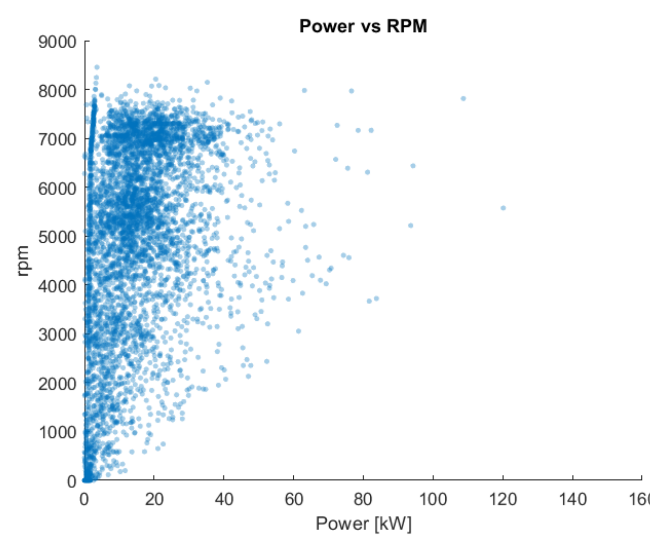

Figure 7: RPM of the electric motor plotted against the power reference from the trip.

A Appendix

Battery specs.	**Value**
Nominal Cell Voltage	3.65 V
Nominal Cell Capacity	58.8 Ah
Nominal Battery Capacity	61.8 kWh
Nominal Battery Voltage	350.4 V
Min.-Max. Cell Voltage	2.9-4.2 V
Min.-Max. SOC	5-95%
Nominal Cell Current (C_{rate}=1)	58.8 A
Battery Mass	309 kg
Specific Heat Capacity (c_p)	1030 J/(kg·K)
Thermal Resistance (R_{th})	0.185 K/W

Table 1

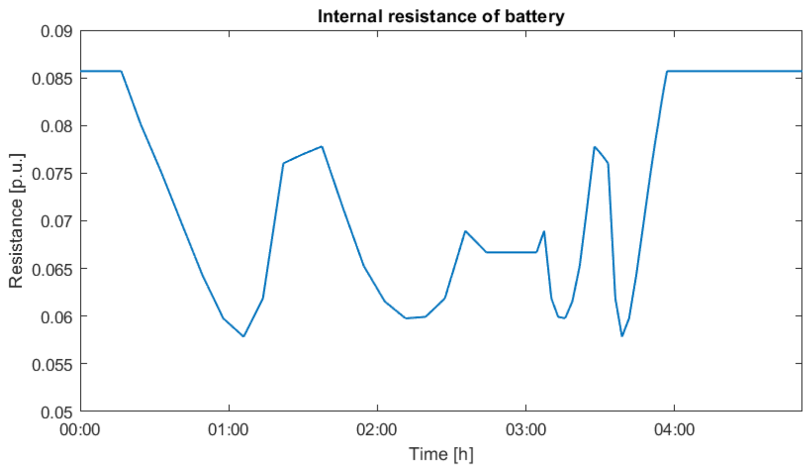

Figure 8: Internal resistance of battery during the simulation.

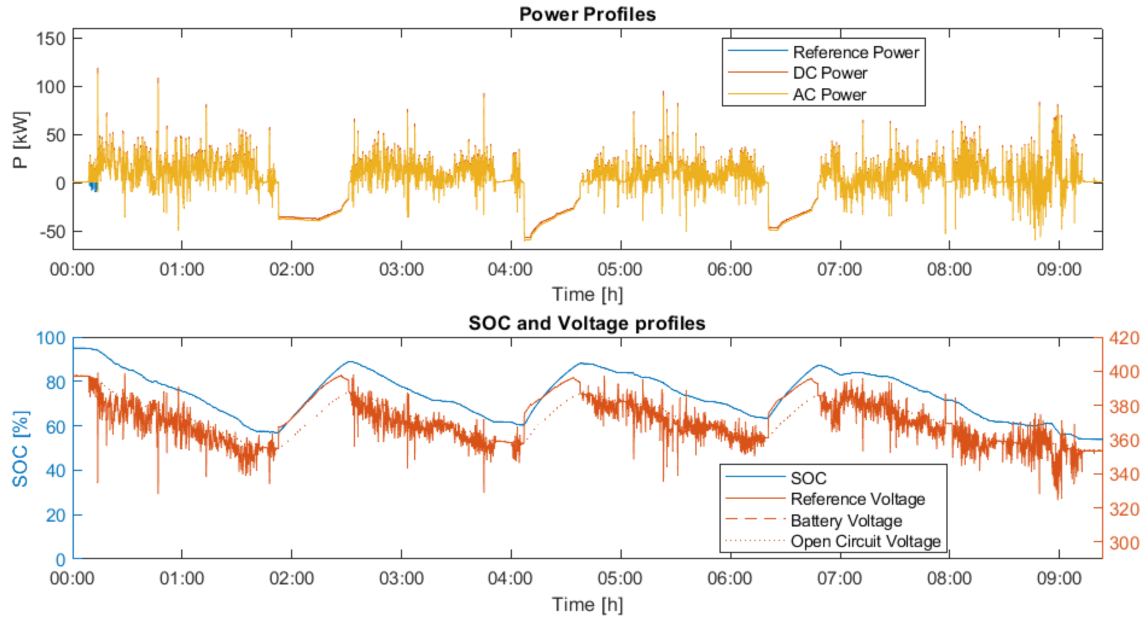

Figure 9: Power flow is observed as positive when the battery is discharging and negative during charging. Voltage profiles and SOC development during the discharging and charging periods.

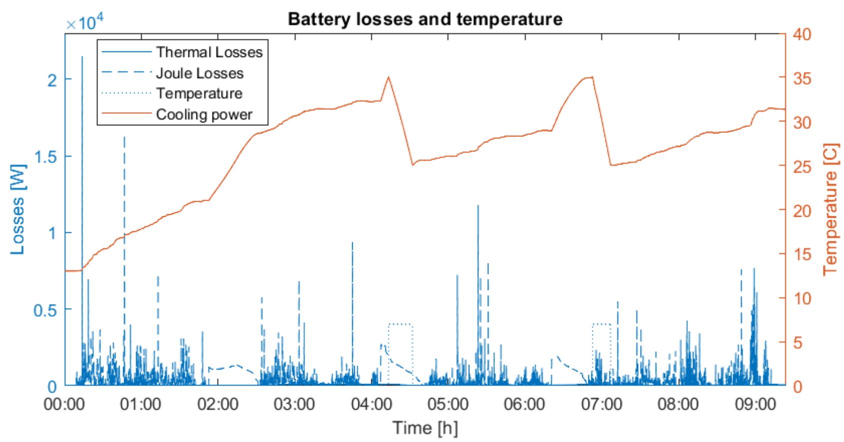

Figure 10: Temperature evolution plotted along with joule losses in the battery and heat dissipation to the ambient.