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Electro-Thermal Modelling of Lithium-Ion Battery

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Symbol Code	Meaning	Symbol in Matlab
OCV	Open Circuit Voltage	Em
R_i	Battery Cell Internal Resistance	R0_LUT
N_s	Number of Cells in Series	Ns
N_p	Number of Cells in Parallel	Np
SOC	State of Charge	SOC_LUT
V_T	Battery Cell Output Voltage	voltVsSOC
V_{out}	Total Output Voltage of the Battery Pack	
P_{batt}	Power Supplied by the battery	
I_b	Battery Discharging Current	I_d
T_b	Uniform Temperature of battery	Tb
P_{th}	Heat Generated Inside Battery by Joule's Effect	Pth
m_b	Battery Cell Mass	Battery.cell_mass
$C_{p,b}$	Specific Heat Capacity of the Battery	Battery.cell_Cp_heat
P_a	Heat Transfer Rate to the Cooling System	Pa
C_b	Battery Thermal Capacity	Cb
h_a	Heat Convection Coefficient of Ambient Air	ha
A_b	Surface Area of the Battery	cell_area
T_{amb}	Ambient Temperature	T_ambient
R_{ba}	Thermal Resistance between Battery and Air	
T_C	Temperature of the Coolant Entering Cooling Plate	Tc
U_f	Overall Heat Transfer Coefficient between Battery and Coolant	
R_{bc}	Thermal Resistance between Battery and Coolant	R_bc
P_C	Heat Transfer Rate to Coolant inside Cooling Plate	Pc
h_f	Convective Heat Transfer Coefficient of Coolant	
Nu	Nusselt Number	
D	Diameter of Cooling System Pipes	

K_f	Thermal Conductivity of Coolant	
m_f	Mass of the Coolant	m_f
$C_{p,f}$	Specific Heat Capacity of Coolant	Cp_f
P_r	Heat Rejected to Ambient Air through Radiator	Pr
K_r	Global Heat Transfer Coefficient of Radiator	Kr
A_r	Frontal Surface Area of Radiator	Ar
C_f	Thermal Capacitance of Coolant	Cf
PTC	Positive Thermal Coefficient Resistor	
P_{PTC}	Heat Generated by PTC	P_PTC
T	Thickness of the Cooling Plate	
k_p	Thermal Conductivity of the Plate and Pipes	
A	Surface Area of the Plate	
D_o	Outer Diameter of the Cooling Pipes	
D_i	Inner Diameter of the Cooling Pipes	
L	Total Length of Cooling Pipes	
$\dot{m}_f$	Mass Flow Rate of Coolant	
$R_{battery\ pack}$	Battery Pack Internal Resistance	Ri_b
ρ_f	Coolant Density	
V_f	Coolant Volume	

Abstract

Electro-thermal modelling of Li-ion batteries is one of the forefront topics due to the increasing interest of automotive industries in electric and hybrid vehicles. To control and manage the behavior of such batteries, reliable models are needed. In this thesis, Li-ion battery is modelled using an equivalent circuit analogy approach to study its behavior and its temperature variation under several charging/discharging tests. The model will be developed from battery cell to battery pack which is enclosed in an insulated box with air circulation to ensure temperature uniformity among its cells. First, electrical behavior is modelled using datasheet battery block found in Simulink library. This model characterizes the battery as an open circuit voltage connected with resistor in series. The main advantage of this model is that its main parameters can be obtained from the data of the battery datasheets. Open circuit voltage, internal resistance, initial capacity, number of cells in series and parallel were all defined to build up the electrical model based on the datasheet of Panasonic NCR18650B battery cell. The resistance of the battery depends on both its temperature and state of charge while open circuit voltage depends only on state of charge. Then, the thermal model of the battery is created according to thermodynamics principle and based on the assumption that the heat generated inside the battery is due only to joule's effect. Thermal model stated that the heat stored inside the battery is the difference between the heat generated due to battery resistance ($P_{th} = RI_b^2$) and heat dissipated into the cooling system. To complete the thermal model, a liquid cooling plate system was designed. The plate is installed at the bottom side of the battery pack and is connected to a pump to deliver the required flowrate and to a heat exchanger that will release the heat absorbed from the battery to the ambient air. The thermal resistance between the battery and the coolant is found to be equal to 0.033 K/W and the global heat transfer coefficient of the radiator is found to be equal to 153.6 W/K based on the assumption that the difference between coolant and air temperature is 5°C and the amount of heat to be removed is equal to the amount of heat generated under 1 C discharge rate. The cooling system is activated when the temperature of the battery crosses 15°C. A PTC heater is also added to the cooling system to increase the temperature of the coolant when battery temperature is below 0°C. After designing the cooling system, the complete model is validated by comparing the results of several tests applied to the model with actual experimental results of the same tests done on 94Ah Samsung prismatic cell. The results revealed the ability of the virtual model to characterize the real behavior of a Li-ion battery up to $\pm$2 V voltage difference and $\pm$4°C temperature difference. The model is then used to simulate the behavior of 138.6 Ah Panasonic battery pack under different continuous/impulse charging/discharging tests. The results of the simulations showed

the effectiveness of the cooling system under low ambient temperature when discharging up to 1.5 C rate where battery temperature didn't exceed its upper limit of 40°C. As the ambient temperature increased, battery temperature started crossing its upper limit so a careful consideration in this case should be given to the amount and duration of discharged current and an implementation of an active cooling system is necessary to limit battery temperature increase. Finally, the 138.6 Ah battery pack model is coupled with vehicle dynamics of Fiat first series vehicle and tested under NEDC and WLTP cycles at different ambient temperatures. The battery was able to deliver required power needed by NEDC drive cycle while it failed to deliver peak power required by WLTP cycle at several points in the cycle and its temperature increased beyond 40°C after 1.5 hours of testing under 25°C ambient temperature.

1. Introduction

With the increased demand on the limited available fossil fuels and due to increasing environmental concerns regarding global warming and climate change, there is a great interest worldwide to shift to an alternative energy and storage systems for electric and hybrid electric vehicles [1]. Nowadays, energy storage systems that are mostly used are the electro-chemical batteries. They convert chemical into electrical energy and are widely used in different sectors of industry (automotive, aerospace, medical, etc.) and in consumer-oriented applications (e.g., electrical appliances, laptops, electronic devices, etc.). There are several types of batteries that are commonly used which are nickel-cadmium, lead-acid, nickel-metal hydride and lithium ion battery. As for what concerns the automotive industry especially in manufacturing of HEV and EVs, the most desired specifications these manufacturers seek in a battery are: high specific power, high specific energy, long life span, high reliability and low manufacturing cost. Hence, Lithium-ion battery is considered a good choice for electric and hybrid vehicles due to its superior properties such as high-power rating, high energy density, and high cycle life [2,3]. In addition, lithium-ion batteries don't include poisonous metals, such as lead, mercury or cadmium. However, these batteries have some problems related to battery thermal management including safety and poor performance at low temperature and their price is still high [4]. Several efforts are being addressed to improve battery technologies to enhance its performance, cycle life and decrease its cost. As for automotive industry, the main challenge that makers face when designing batteries of electric vehicles is to keep the batteries in their optimal working conditions, thus decreasing their losses and protecting them from potential damage such as overheating by high currents, overcharging and over discharging. One of the parameters of the lithium ion battery that must be carefully controlled is its temperature since the working temperature of the lithium ion battery has a great influence on its efficiency, cell degradation, life time and safety [5]. Battery cells generate heat during charging and discharging process due to joule's effect. This heat generation can increase sharply leading to overheating under certain conditions such as high discharge rate, high ambient temperature, overcharging and over-discharging. Overheating, then, will cause premature failure in battery packs in form of thermal runaway or accelerating capacity fading [6,7]. To reduce overheating risk and improve battery performance, the BMS (battery management system) is designed to provide a proper supervision to the battery cells as well as the battery pack. The supervision provided by the BMS include the cell voltage, charging and discharging current, temperature and an interface to the cooling system. Providing optimal working conditions for the cells and gaining critical information such as amount of available energy, State of Charge, life time of the battery and other important information can't be realized by direct measurement through physical sensors, so developing models to simulate battery behavior such as Equivalent Circuit Model (ECM), thermal model, ageing model is necessary. Computer modelling and simulation is an effective tool in the development of battery models to simulate its performance before the prototyping process. To ensure the reliability of the model, it should be validated against measured data.

1.1 Objective of the thesis

The aim of this thesis is to create an electro-thermal model of a lithium-ion battery using equivalent circuit analogy to analyze battery behavior and temperature variation under different charging/discharging cycles. Electrical behavior is modelled by "Datasheet Battery" block found in Simulink software library. The advantage of this model is that its main parameters can be generated from the data of the technical datasheets of the battery. The main key aspects that will be carried in the thesis are as follows:

- Development of an electrical model of the battery pack using Simulink software.
- Development of a thermal model of the battery to measure its temperature.
- Design of a cooling system to the battery to keep its temperature under safe working conditions (below 40 ^{o}C).
- Validation of the electrical and thermal model created for the battery pack by comparing the virtual results obtained by Simulink with actual experimental results.
- Virtual Simulation of the battery pack under study at different charging/discharging tests.

1.2 Structure of the thesis

Besides the general introduction in **chapter 1,** the thesis has 9 major chapters. **Chapter 2** addresses the main components in electric vehicles with the focus on the energy storage. **Chapter 3** illustrates the structure of the battery under modelling starting from the battery cells that will be grouped in series/parallel connection to form the modules and then grouping of the modules to form the battery pack. In **Chapter 4,** the electrical model of the battery will be designed by defining and generating the parameters required to build the model. In **Chapter 5,** the thermal model of the battery is developed according to thermodynamics principle and based on the assumption that heat generated in the battery is due to joule's effect only. **Chapter 6** addresses the design of the cooling system which will be liquid cooling plate system and **chapter 7** estimates parameters of the cooling system as well as the thermal model. In **Chapter 8,** validation of the complete model will take place by comparing its test results with actual experimental results done by Samsung company. **Chapter 9** simulates battery pack under study (Panasonic 138.6 Ah) under different charging/discharging cycles and **Chapter 10** simulates the battery pack under different driving cycles by coupling the battery with vehicle dynamics of Fiat first series car.

2. Energy Storage System of Electric Vehicle

Electric vehicles' production is increasing and EVs are becoming more popular due to their zero emission and high tank-to-wheels efficiency. A proper production of an electric vehicle results from a proper production of its subsystems. The following figure illustrates the main components of the electric vehicle.

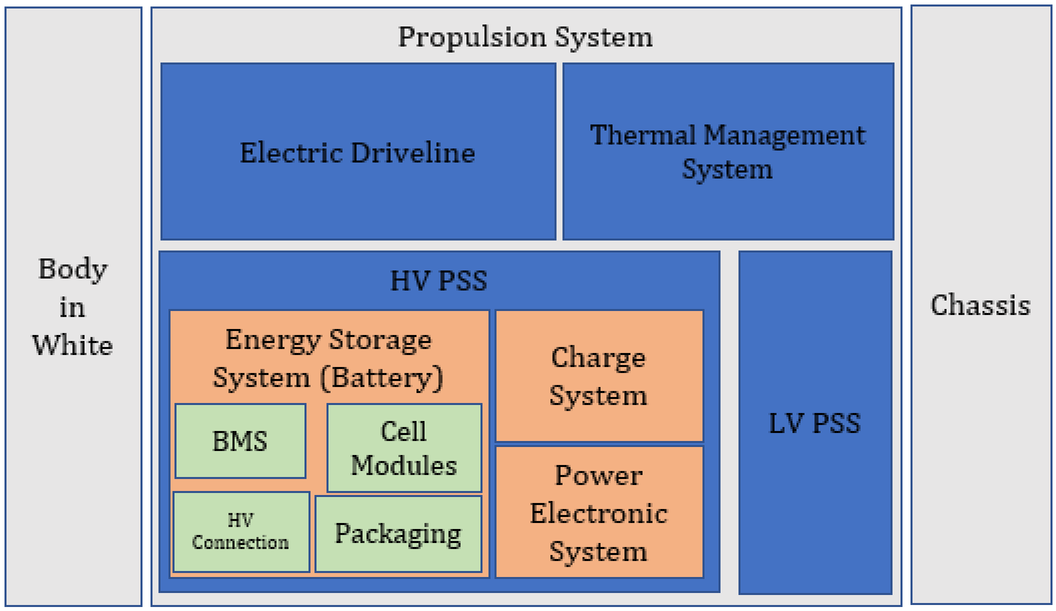


Figure 1: Electric vehicle main components [8].

Energy Storage System (battery) is one of the main important parts in an electric vehicle as it is the primary source of energy for the electric motor that drives the car. Nowadays, lithium-ion batteries are among the most common used types in electric vehicles due to their high energy density, high power density, and long lifespan. However, lithium-ion batteries are facing some challenges, such as ensuring safe operation of the battery-power system when working under various conditions. The safety of battery power system is fundamental, especially when it is grouped by a considerable number of battery cells arranged in series/parallel topology to deliver a higher power density as is the case of EVs. The performance of the battery is affected by the number of charging/discharging cycles, running time and temperature. Therefore, the management of batteries is necessary to optimize its performance when operating at various conditions.

3. Battery Structure

Before proceeding with the battery modelling, it is important to understand the structure and the specifications of the battery pack. To achieve this, certain input data which include battery pack specifications and battery cells' datasheet were provided as shown in the following diagrams.

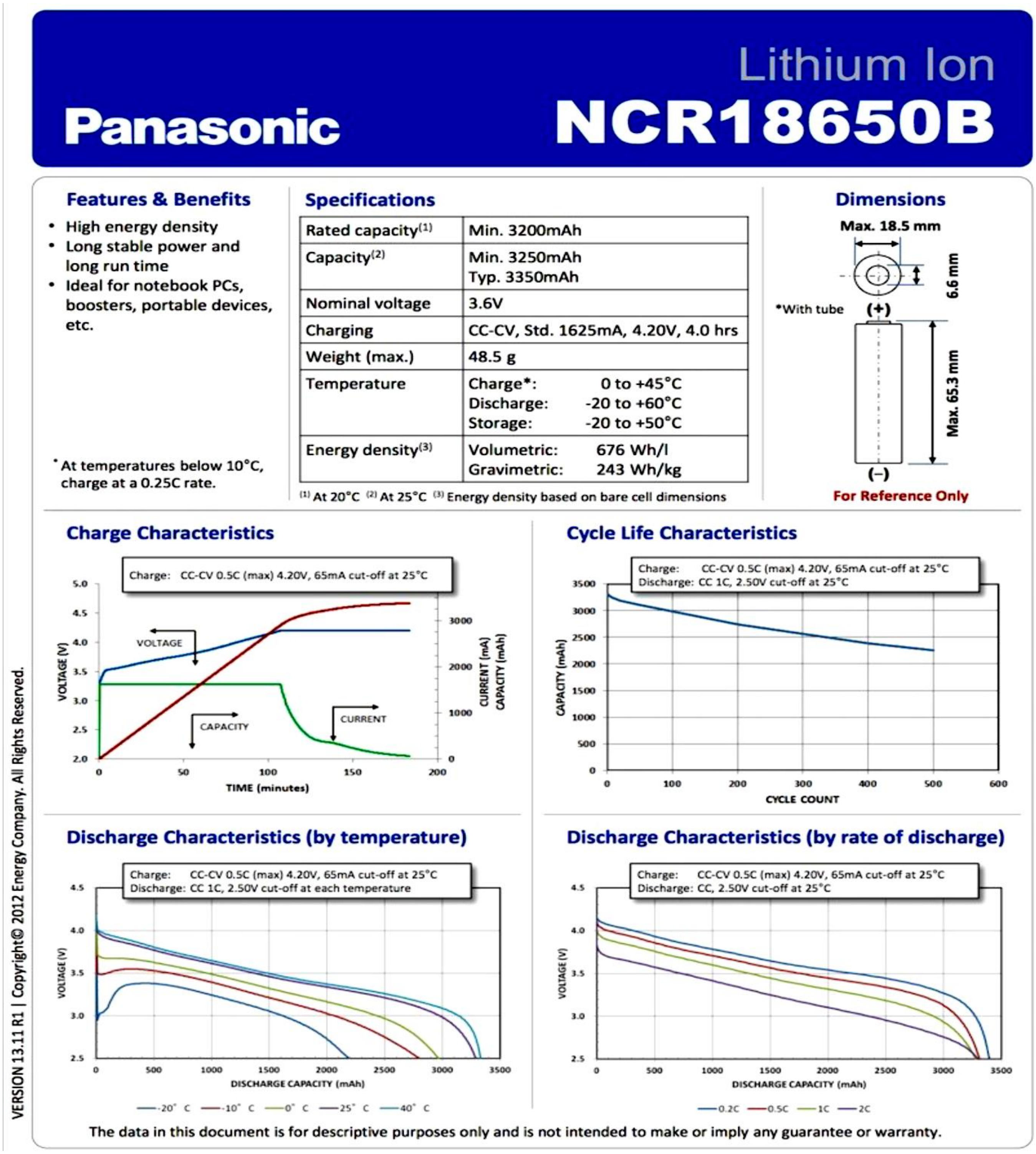


Figure 2: Datasheet of Panasonic NCR18650B battery cell.

Table 1: Battery Pack Specifications.

		Element	Module	Pack
Nominal voltage	*V*	**3.6**	**50.4**	**100.8**
Upper limit voltage	*V*	*4.2*	*58.8*	*117.6*
Lower limit voltage	*V*	*2.7*	*37.8*	*75.6*
Nominal capacity	Ah	**3.3**	**138.6**	**138.6**
Specific capacity	*Ah/kg*	68		
Nominal energy	*kWh*	**0.0119**	**6.99**	**13.97**
Specific energy (Gravimetric)	*Wh/kg*	245	221.63	150.17
Energy density (Volumetric)	*Wh/l*	677		
Continuous discharge current	*A*	**4.87**	**204.54**	**204.54**
Continuous discharge power	*kW*	0.02	10.31	20.62
Specific discharge power	*W/kg*	361	327.08	221.61
Max discharge current (5 s)	*A*	**6.6**	**277.2**	**277.2**
Max discharge power	*kW*	0.024	13.97	27.94
Continuous charge current	*A*	**1.5**	**63**	**63**
Continuous charge power	*kW*	0.01	3.18	6.35
Max charge current (5 s)	*A*	**3.3**	**138.6**	**138.6**
Max charge power	*kW*	0.01	6.99	13.97
Curb weight	*kg*	0.0485	28.518	63.036
Structure weight	*kg*	0	3	30
Total weight	*kg*	**0.0485**	**31.518**	**93.036**
Height	*mm*	65.3		
Width (Diameter)	*mm*	18.5		
Thickness (Diameter)	*mm*	18.5		
Volume	*l*	**0.0175**	***10.32***	***20.63***
Series	---	28	14	2
Parallel	---	42	42	1

Based on the above table, it is worthy to note that the battery pack is composed of a set of battery cells which are arranged in series/parallel configuration. It is assumed that each cell is delivering the same current and has the same thermal capacity. However, the different positions of the cells inside the battery pack lead to a different thermal resistance between each cell and the surrounding air. As a result, each cell has a different temperature and to determine the temperature of the battery pack, we could install temperature sensor at each cell and then take the maximum reading value as the temperature of the battery pack. This approach increases the complexity of the structure of the battery pack due to the presence of high number of temperature sensors. In addition, it requires a lot of pre-processing and high computing power of the battery management system to be able to interpret different temperature readings. To reduce this complexity, battery cells are grouped into modules where each module has an electronic regulator whose function is to keep the battery within its operative range during charge and discharge by monitoring parameters such as temperature, voltage, and current. Each module has a set of temperature sensors (ex: 4 temp. sensors). The figure below shows an illustrative example of the module structure.

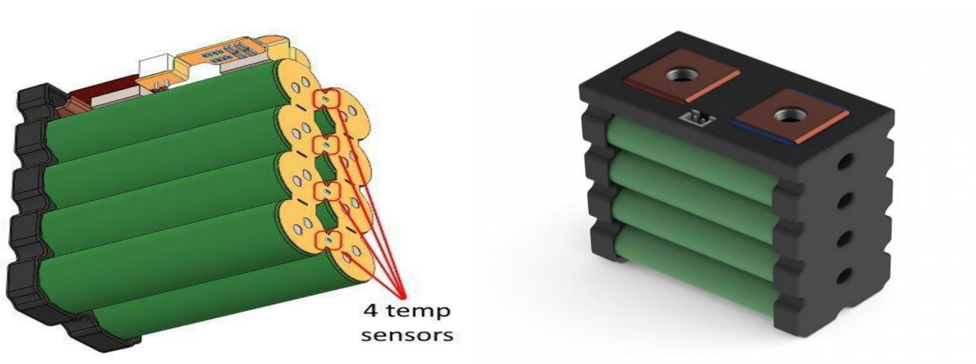


Figure 3: Example of module structure with temperature sensors.

The electronic regulator of the module tracks the temperature reading of the sensors and do the following:

- Measure the differences between the temperature readings to ensure they fall within an acceptable limit defined by experiments.
- Exclude temperature reading outliers, if present, since it is mainly resulting from sensor malfunctioning.
- Communicate the maximum temperature reading to the master electronic regulator of the battery pack.

The temperature of the module is taken as the maximum temperature detected by the sensors installed in the module. In this case, the number of temperature states received by the master electronic regulator is reduced to the number of the modules present in the battery pack.

Then the master electronic regulator tracks the temperature readings received from modules and choose the maximum one to represent the battery pack temperature.

This approach is considered conservative since it is always the maximum temperature reading that will be considered in the development of the electrical and thermal model of the battery pack. The figure below represents an example of a battery pack structure.

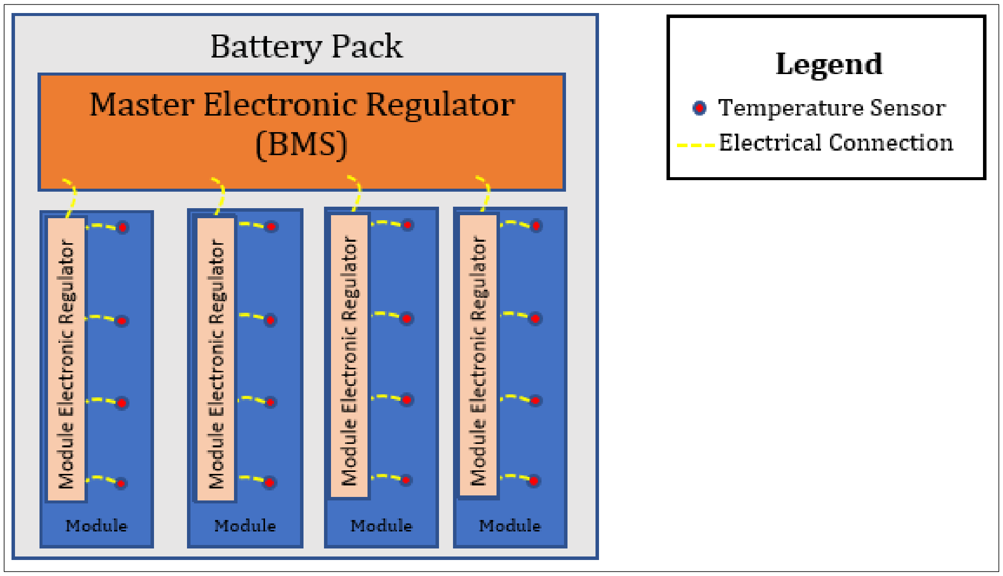


Figure 4: Example of Battery pack structure.

The battery pack is enclosed by an insulated box equipped with fans to properly circulate the air inside it and enhance temperature uniformity among battery cells.

4. Battery Electrical Model

To study the behavior of the battery, it is necessary to build an electrical model that can approximate the actual behavior of the battery. In this thesis, we chose to model the battery using "Datasheet Battery" block found in Simulink software. It is a block inside Simulink library that models a lithium ion battery using manufacturer's datasheet. The main advantage of such model is that it generates the electrical model of the battery pack using datasheet of single battery cell. This block takes as input: battery initial capacity, battery current and temperature and gives as an output: battery voltage, SOC, total power and capacity [9]. The block simply analyzes the battery as an equivalent circuit model that consists of an open circuit voltage and an internal resistance as depicted in the figure below.

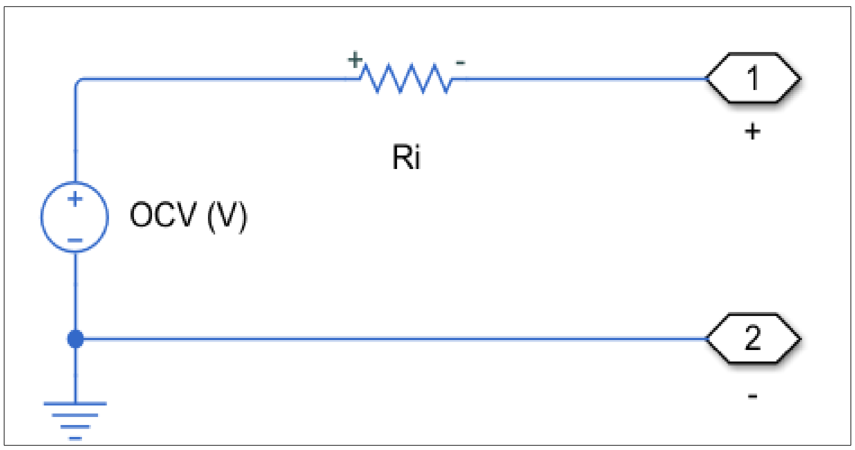


Figure 5: Equivalent Circuit Model of the Battery.

This model decreases the number of temperature states found in a battery pack to only one temperature state thus simplifying modelling process.

The main parameters that are required to build the datasheet battery block are:

- Initial Battery Capacity [Ah]: it is the initial capacity of the battery when start running.
- Open Circuit Voltage table data OCV [V]: open circuit voltage is the voltage measured at the terminals of the battery after enough rest time. OCV varies according to battery state of charge (SOC) and temperature but since its variation due to temperature is low compared to SOC [10], OCV is considered independent of temperature variation in our analysis.
- Internal Resistance R_i [Ohm]: Internal resistance of LiIon battery varies according to temperature and SOC of the battery.
- Temperature breakpoints: is a set of different temperatures at which battery discharging behavior is tested.

- N_s: Number of cells inside battery pack connected in series.
- N_p: Number of cells inside battery pack connected in parallel.

After defining the parameters, the block implements the equations below to generate the required outputs.

$$V_T = OCV - R_i I_b \tag{3.1}$$

$$V_{out} = N_s V_T \tag{3.2}$$

$$SOC = \frac{1}{Cap_{batt}} \int_0^t I_b dt \tag{3.3}$$

$$P_{batt} = V_{out} I_b \tag{3.4}$$

Where:

V_{out}: Total output voltage of the battery pack [V].

N_s: Number of cells connected in series.

N_p: Number of cells connected in parallel.

C_{apbatt}: battery nominal capacity in [Ah].

P_{batt}: Power supplied by the battery [W].

4.1 Parameters Definition of the Electrical Model

To define electrical model parameters of the battery pack, the first step is to import battery datasheet shown in figure 2 into MATLAB and regenerate it. The datasheet contains curves representing discharge characteristics at different temperatures, discharge characteristics at different discharge currents and cycle life characteristics. The curves were tabulated and stored in MATLAB software as matrices. Figure 6 shows the lithium-ion battery discharge characteristics at constant temperature (at four levels of current, shown as C-rate) and at constant current (at five different temperatures).

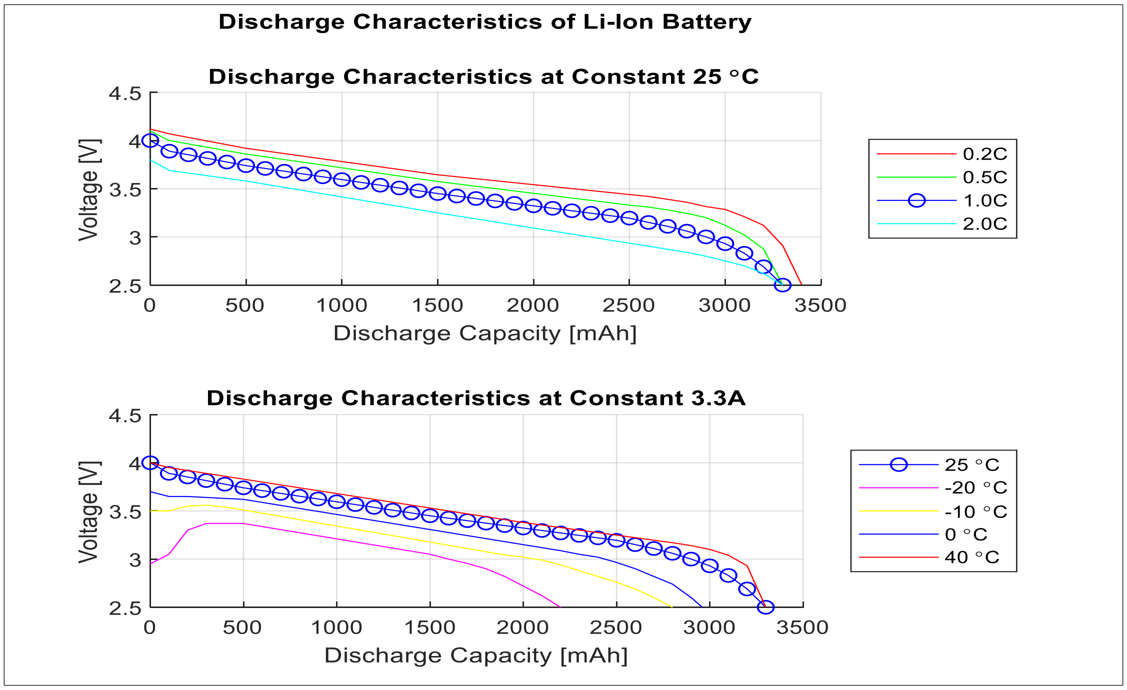


Figure 6: Discharge Characteristics of Panasonic NCR18650B Battery.

After importing battery characteristics into MATLAB, Electrical model main parameters can be defined as follow:

- ***Open Circuit Voltage (OCV) Parameter***

To calculate OCV, a curve fit of the discharge curves at different currents was created using fit function in MATLAB software. This allows discharge curves to be algebraically combined and hence an interpolation/extrapolation process can be easily done. Figure 14 represents voltage versus currents at different SOC levels.

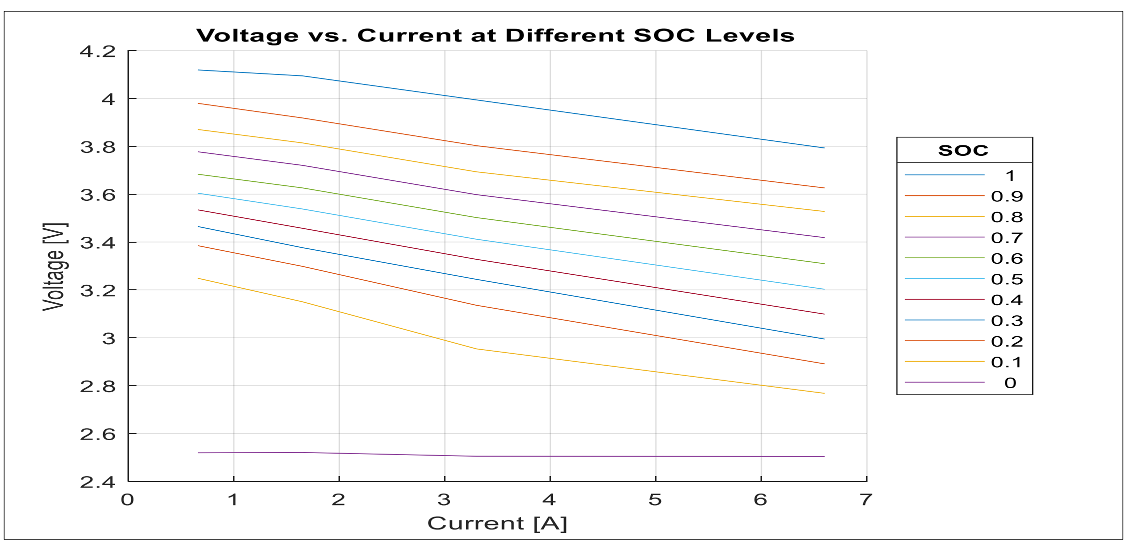


Figure 7: Voltage Vs. Current at Different SOC Levels.

After finding a mathematical relation between voltage and current at different SOC, OCV was calculated by extrapolating each voltage-current line at each SOC level to I=0 A [11]. The result of the extrapolation is a 1-D table of OCV as function of SOC to be imported into the battery block. The figure below shows variation of OCV as function of battery SOC.

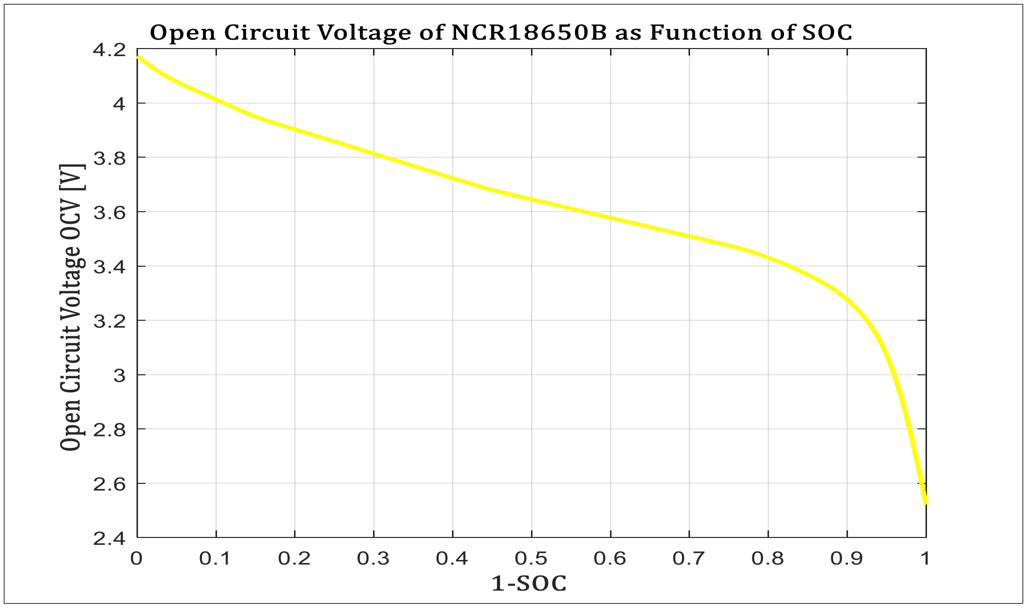


Figure 8: OCV of NCR18650B battery as function of SOC.

- ***<u>Internal Resistance Parameter (R_i)</u>***

Internal resistance in the battery accounts for the voltage drop across battery's terminals when a load is connected compared to no-load voltage. It depends on the battery chemical properties, its ageing behavior, temperature and SOC where its variation is nonlinear. In this paper, the internal resistance is a function of battery temperature and SOC. The internal resistance was calculated according to the following formula:

$$R_i(T_b, SOC) = \frac{OCV(SOC) - V_T(SOC, T_b)}{I_b} \qquad (3.1.1)$$

Where:

$R_i: internal\ resistance\ of\ battery\ [ohm].$

$OCV: open\ circuit\ voltage\ when\ no\ load\ is\ connected\ [V].$

$V_T: voltage\ measured\ at\ battery\ terminals\ when\ a\ load\ is\ connected\ [V].$

$I_b: Battery\ discharged\ current\ [A].$

$T_b: Uniform\ temperature\ inside\ battery\ [K].$

At every test temperature, the internal resistance was calculated for every SOC breakpoint and the result is a 2-D table representing internal resistance as a function of temperature and SOC. Figure 9 shows the variation of internal resistance versus SOC and T_b.

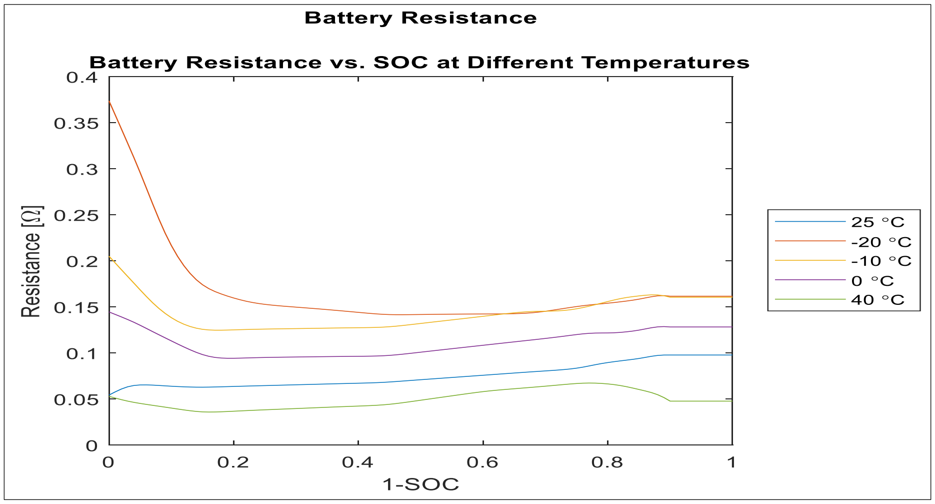


Figure 9: Battery Resistance vs. SOC at different Temperatures.

- ***Initial and nominal battery capacity***

The initial capacity of the battery could be any value between its minimum and maximum capacity which in the case of the cell type shown in figure 2 is between 3.25 Ah and 3.35 Ah. The nominal capacity is the capacity of the battery at nominal temperature (25 °C) which is equal to 3.3 Ah for Panasonic NCR18650B.

The parameters found above where then imported into the datasheet battery block model to generate the electrical model of the battery pack. The diagram below shows battery electrical model represented by Datasheet battery block in Simulink software.

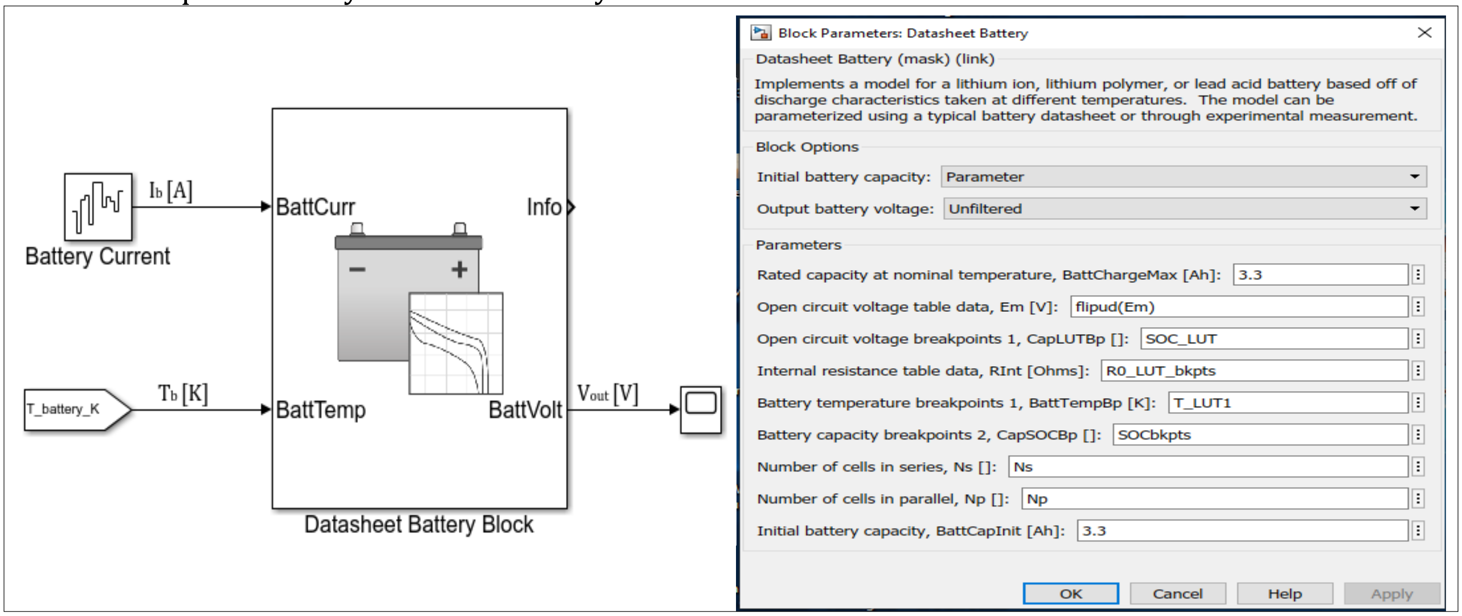


Figure 10: Battery electrical model represented by Datasheet battery block

Note that the electrical model shown above depends on the temperature variation of the battery pack and hence a thermal model of the battery is necessary to run the model.

5. Battery Thermal Model

Heat generation that occurs inside the battery due to its joule heating effect increases its temperature. Excessive increase of this temperature reduces the performance of the battery and effects its SOC and SOH. This temperature can be predicted through a thermal modelling of the battery. The irreversible heat made by joules effect can be expressed as follows:

$$P_{th}(t) = R_i(SOC, T_b) I_b^2(t) \qquad (4.1)$$

The energy balance equation of a battery cell is defined as follows [12]:

$$P_{th}(t) = R_i(SOC, T_b) I_b^2(t) = m_b C_{p,b} \frac{dT_b}{dt} + P_a(t) \qquad (4.2)$$

Where:

m_b: *mass of the battery* [Kg].

$C_{p,b}$: *Specific heat capacity of the battery* [J/Kg.K].

T_b: *Uniform Temperature inside the battery [K].*

P_a: *Heat transfer rate to the cooling system [W].*

The thermal behavior of the battery can be represented by a thermal equivalent circuit (Electrical-Thermal Analogy) as shown in below figure [13].

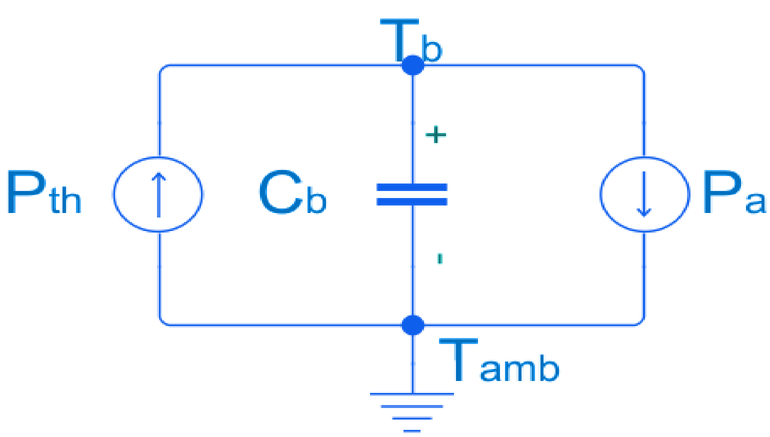


Figure 11: Thermal equivalent circuit of the battery exchanging heat with cooling system.

P_{th} represents the heat generated due to joules effect. The capacitor represents the thermal mass of the battery storing the energy where $C_b = m_b C_{p,b}$ and P_a represents the heat exchange between the battery and the cooling system.

6. Battery Cooling System

The battery pack for safety, performance and lifespan reasons should be stored in a controlled surrounding where the temperature is controlled and there is no risk of thermal runaway. For this reason, the battery should be equipped with an efficient cooling system to control its temperature when it is high and a heating system to heat battery temperature when it is low ($T_b < 0$ °C). Different Heating/Cooling technologies are utilized in electric vehicles. The most common used cooling systems are: Air-Cooling system, Water-Cooling system and Phase change material (PCM) system. In our analysis, two systems were considered:

6.1 Air Cooling System

A simple way to cool the battery pack is to exchange its heat with the ambient air. In this scenario, the heat transfer is done by convection according to the following equation:

$$\dot{Q}_C(t) = P_a(t) = h_a A_b (T_b(t) - T_{amb}) \qquad (5.1.1)$$

Where:

P_a: $Heat\ transfered\ from\ battery\ pack\ to\ the\ ambient\ air\ [W]$.

h_a: *heat convection coefficient of ambient air* [W/m²K].

A_b: *Surface area of the battery* [m²].

T_{amb}: $ambient\ temperature\ [K]$.

The energy balance equations of the system can be written as follows:

$$m_b C_{p,b} \frac{dT_b}{dt} = \dot{Q}_{gen}(t) - P_a(t) = P_{th}(t) - h_a A_b (T_b(t) - T_{amb}) \qquad (5.1.2)$$

$$\frac{dT_b}{dt} = \frac{P_{th}(t)}{m_b C_{p,b}} - \frac{h_a A_b}{m_b C_{p,b}} (T_b(t) - T_{amb}) = \frac{P_{th}(t)}{C_b} - \frac{(T_b(t) - T_{amb})}{C_b R_{ba}} \qquad (5.1.3)$$

Where $C_b = m_b C_{p,b}$ is the thermal capacitance of the battery and $R_{ba} = \frac{1}{h_f A_b}$ is the thermal resistance between battery and air.

The equivalent thermal circuit of the above equation is shown below:

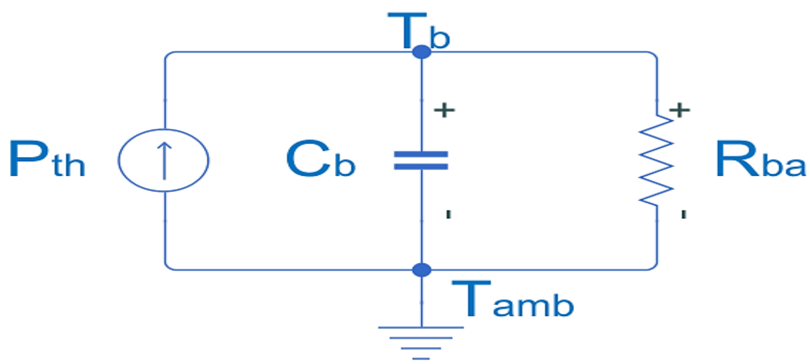


Figure 12: Thermal equivalent circuit of the battery exchanging heat with air.

Eq. 5.1.3 is a linear differential equation where its solution is:

$$T_b(t) = R_{ba}P_{th}\left(1 - e^{-\frac{t}{\tau_{ba}}}\right) + T_{amb} \qquad (5.1.4)$$

Where $\tau_{ba} = R_{ba}C_b$ is the thermal time constant of the system. Eq. 5.1.3 can also be simulated using Simulink block diagrams as shown below:

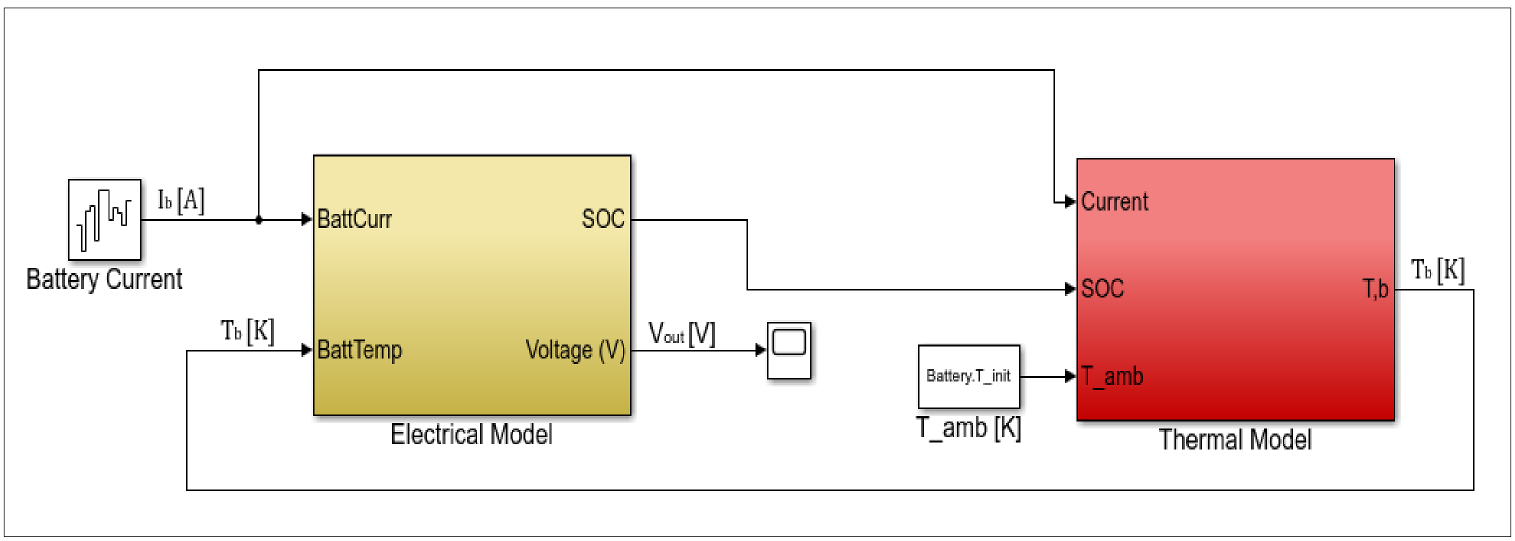


Figure 13: Simulink Diagram Evaluating T_b in case of Air-Cooling System.

This cooling system has several drawbacks:

- Heat transfer coefficient of air is variable and depends on mass flowrate of air and in case of open configuration it is hard to get its value.
- Thermal capacity of air is low compared to water, so it has limited capacity of heat removal.
- In hot weathers where T_{amb} >45 ^{o}C , this system becomes ineffective and an additional A/C system should be connected to ambient air to cool it down before it cools the battery pack.

This system will not be further developed in this paper.

6.2 Liquid Cooling Plate System

A cooling plate with pipes is installed at the bottom side of the battery pack. Figure 14 shows a simple configuration of the system.

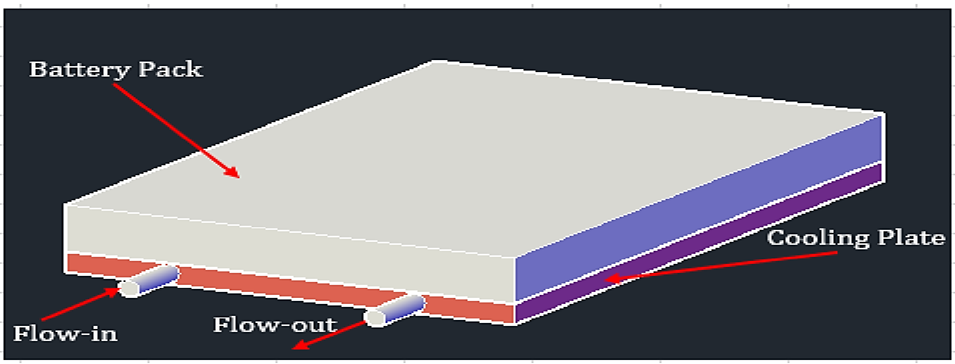


Figure 14: Schematic representation of Battery Pack with Cooling Plate.

The coolant flowing out of the cooling plate will then pass through a radiator. The coolant is circulated by the pump within a closed system where it absorbs heat from battery pack and releases it via a radiator. A fan could be installed behind radiator to increase its efficiency. This system is called a passive cooling system and is represented in figure 15 [14].

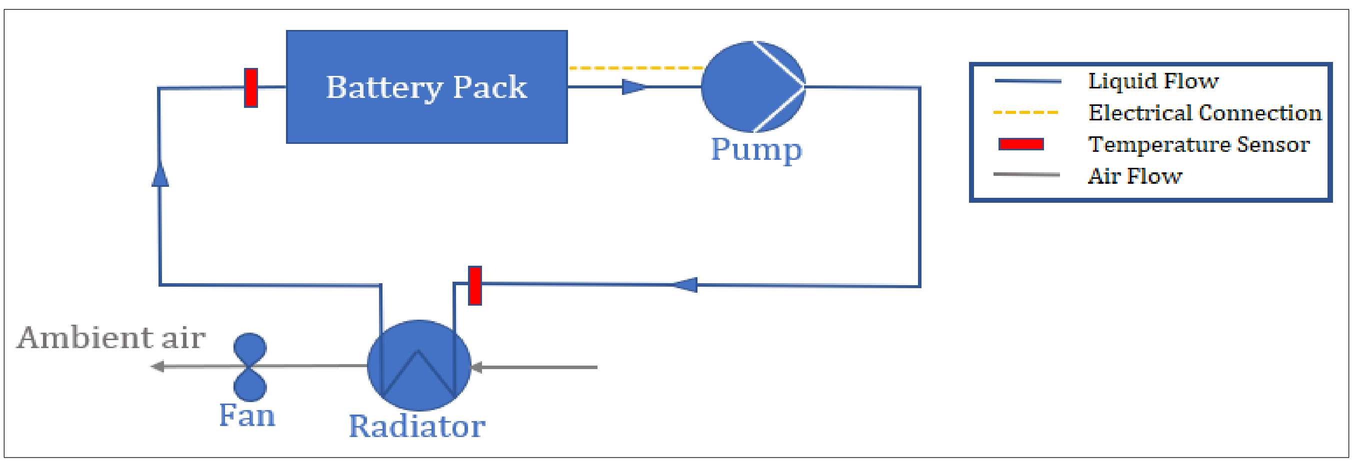


Figure 15: Layout of the Passive Liquid Cooling System.

- **Battery Pack Energy Balance Equations:**

Energy balance equation of the battery pack with cooling plate is as follows:

$$m_b C_{p,b} \frac{dT_b}{dt} = P_{th}(t) - U_f A(T_b(t) - T_C(t)) = P_{th}(t) - P_C(t) \qquad (5.2.1)$$

Where:

$T_C = temperature\ of\ the\ coolant\ entering\ cooling\ plate\ [K].$

$U_f = overall\ heat\ transfer\ coefficient\ between\ battery\ and\ coolant\ [W/m^2K].$

$$P_C(t) = U_f A(T_b(t) - T_C(t)) = \frac{(T_b(t) - T_C)}{R_{bc}} \qquad (5.2.2)$$

Note that it is assumed that the battery exchanges heat with the coolant at uniform temperature T_C measured at the inlet side of the cooling plate.

The convection heat transfer coefficient of the coolant can be calculated from Nusselt number according to equation below:

$$h_f = \frac{Nu.k_f}{D} \qquad (5.2.3)$$

k_f is the thermal conductivity of the coolant in *W/m.K* and D is the diameter of the pipe where fluid is passing. Nusselt number depends on the type of the flow inside the pipe. If the flow is laminar ($R_{ed} \leq 3000$), Nu is constant and is equal to 3.66 while if the flow is turbulent, Nusselt number is calculated as follows (Incorpera,2007):

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \qquad (5.2.4)$$

$$Re_D = \frac{4\dot{m}}{\pi D_h \mu} \qquad (5.2.5)$$

$$f = (0.790 \ln Re_D - 1.64)^{-2} \qquad (5.2.6)$$

- <u>**Radiator Energy Balance Equation:**</u>

Energy stored in the coolant is the difference between energy gained by the coolant at the battery level and energy released by the coolant at the radiator level:

$$m_f C_{p,f} \frac{dT_C}{dt} = P_C(t) - P_r(t) \qquad (5.2.7)$$

Where:

$m_f = mass\ of\ the\ coolant\ [Kg]$.

$C_{p,f} = specific\ heat\ capacity\ of\ the\ coolant\ [J/Kg.K]$.

P_r is the amount of heat rejected to the ambient air through radiator and is equal to:

$$P_r(t) = K_r A_r (T_C(t) - T_{amb}) \qquad (5.2.8)$$

The term K_r represents the global heat transfer coefficient of the radiator that depends on the mass flow rate of both the coolant and air and A_r is the frontal area of the radiator.

The equivalent thermal circuit of the liquid cooling system is shown in the following figure:

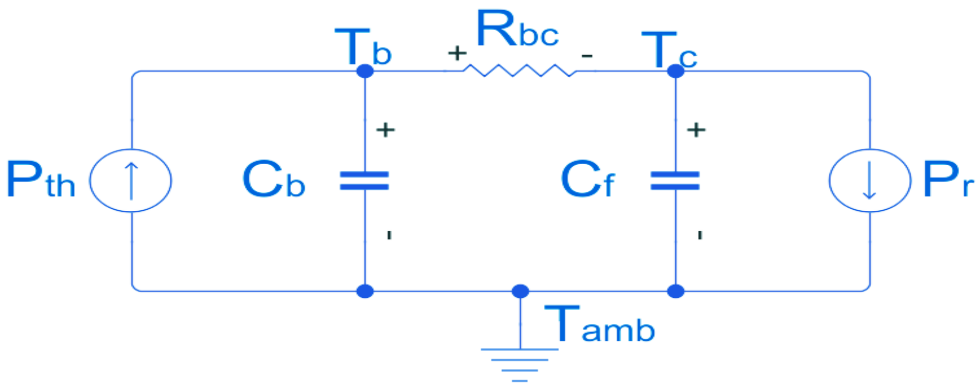


Figure 16: Thermal equivalent circuit of the battery exchanging heat with coolant.

Where:

$C_b = m_b C_{p,b}$ *is the thermal capacitance of the battery* $[J/K]$.

$C_f = m_f C_{p,f}$ *is the thermal capacitance of the coolant* $[J/K]$.

$R_{bc} = \frac{1}{U_f A}$ *is the thermal resistance between the battery and the coolant* $[K/W]$.

6.3 PTC Heating System

In extreme weather conditions where ambient temperature is very low (-20 ^oC to 0 ^oC), a heating system is required to increase the temperature of the battery to its operative range to prevent drastic declination of its performance and degradation of its lifetime. Hence, a PTC heater could be installed along an additional water loop inserted with the cooling system loop as illustrated in the figure below.

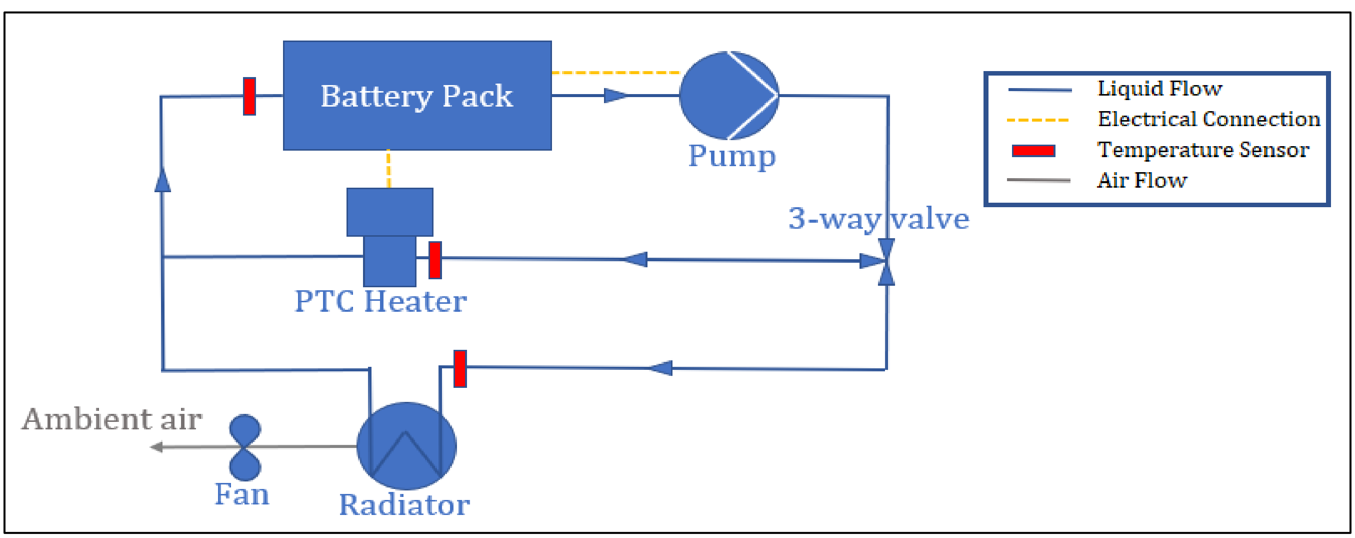


Figure 17: Cooling-Heating System of the Battery Pack.

When the temperature of the battery is below 0 ^{o}C, the battery will pump out certain amount of current to the heater to turn it on allowing for both self-heating and PTC heating and the water will circulate passing through the heater / battery loop. As the temperature crosses 0^{o}C, the heater will be turned off and the coolant will continue circulating in the heater / battery loop. As the temperature of the battery increases above 15 ^{o}C, the coolant will then circulate in the radiator / Battery loop where cooling process starts.

The amount of heat generated by PTC heater is constant and is chosen to be equal to 1000 W. Applying energy balance equation over the coolant in the closed heating system, the equation is as follows:

$$m_f C_{p,f} \frac{dT_C}{dt} = P_C(t) + P_{PTC}(t) \qquad (5.3.1)$$

Where P_{PTC} is the heat generated by PTC heater.

7. Parameters Estimation of Thermal Model with Cooling System

To design the cooling system of the battery pack, it is required to define its parameters that were shown in the thermal equivalent circuit in figure 16. The estimation of the parameters will be based on the battery pack characteristics shown in table 1 of chapter 2 and on the cell's datasheet shown in figure 2.

- **<u>Thermal capacitance of the battery pack C_b</u>**

A test was done by "Thermal Hazard Technology" Company to determine the specific heat capacity of an 18650-lithium ion battery cell which has the same physical parameters as our chosen battery. The test was done over a temperature range of 25 ^oC – 55 ^oC. The table below summarizes the specific heat values at different temperatures.

Table 2: Specific heat capacity of 18650 lithium ion battery at different temperatures [15].

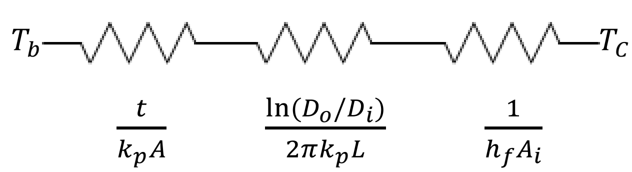
Temperature, T (°C)	Specific Heat Capacity, Cp (J/gK)
30	0.85
35	0.82
40	0.84
45	0.81
50	0.84

Based on the data of the above table, the specific heat capacity of the battery was chosen as the average value which is equal to: $\boldsymbol{C_{p,b} = 830}$ **J/Kg.K**. The mass of the battery pack is given from the data sheet and is equal to **93 Kg**. Hence, the thermal capacity of the battery is:

$$\boldsymbol{C_b = 77190\ J/K}$$

- **<u>Thermal Resistance between Battery and Coolant R_{bc}</u>**

Heat generated inside the battery is transferred to the coolant by conduction through cooling plate, conduction through coolant pipes and convection from internal surface of the pipes to the coolant. The three modes of heat transfer can be represented by a set of three series resistances as shown in the below diagram.



Where:

t = thickness of the cooling plate till pipe surface [m].

k_p = thermal conductivity of the plate and pipes[W/m.K].

A = surface area of the plate[m^2].

A_i = internal pipe surface area [m^2].

D_o = outer diameter of the cooling pipes [m].

D_i = inner diameter of the cooling pipes[m].

L = total length of cooling pipes[m].

h_f = convection heat transfer coefficient of the coolant [W/m^2K].

$$R_{bc} = \frac{t}{k_p A} + \frac{\ln(D_o/D_i)}{2\pi k_p L} + \frac{1}{h_f A_i} \qquad (6.1)$$

This resistance should be designed to have the lowest possible value to ensure that most of the heat generated in the battery is absorbed by the coolant which will later be released to the ambient through the radiator. The first two terms in equation 6.1 depend on the geometry of the chosen cooling plate and the type of material used. As shown in section 5.2, convection heat transfer coefficient h_f depends on mass flow rate of the coolant which can be found as follows:

$$\dot{m}_f = \frac{P_r}{C_{p,f} . \Delta T_w} \qquad (6.2)$$

Where ΔT_w is the difference between temperature of the coolant entering and exiting the radiator.

In ICE vehicles, the temperature difference in the coolant shouldn't be high to avoid thermal stresses that may occur in the engine so ΔT_w is set to be in the range of 5°C – 10°C. The same range will be chosen in our analysis. The specific heat capacity of the coolant which is chosen to be a 50-50% water-glycol mixture is $\boldsymbol{C_{p,f} = 3403\ J/KgK}$ [16]. The amount of heat to be removed by the radiator is chosen to be equal to the amount of heat generated by the battery during constant nominal discharging current (1-C rate) of ***I_{nom} =138.6 A***.

$$P_{r,nom} = R_{battery\ pack} I_{nom}^2 \qquad (6.3)$$

Where $R_{battery\ pack}$ is the internal resistance of the battery pack that is changing with the variation of battery temperature. The value of the resistance was taken at T_b = 25 °C and is equal to:

$$R_{battery\ pack} = \frac{R_i x N_s}{N_p} = \frac{0.06x28}{42} = 0.04\ \Omega$$

$P_{r,nom} = 0.04x138.6^2 = 768\ W$. The mass flowrate of coolant is then: $\dot{\boldsymbol{m}}_{\boldsymbol{f}} = \frac{\mathbf{768}}{\mathbf{3403}x\mathbf{5}} = \mathbf{0.045}\ \frac{\boldsymbol{kg}}{\boldsymbol{s}}$.

The cooling plate that will be installed has the characteristics as illustrated in the table below:

Table 3: Characteristics of Cooling Plate

Material	Aluminum
Thermal Conductivity of Plate(W/m.K)	220
Plate thickness t (mm)	35
Outside pipe diameter D_o (mm)	30
Inside pipe diameter D_i (mm)	25
Plate surface dimensions (LxW)	0.8 m x 0.535 m
Pipe Length L (m)	7
Coolant Dynamic Viscosity at 25°C (Kg/ms)	2.8 x 10^{-3}
Thermal Conductivity of Coolant (W/m.K)	0.37

Using the parameters mentioned in the above table, the following is obtained:

- $Re_D = 821.4 \ll 3000$ (flow is laminar).
- $Nu = 3.66$
- $h_f = 54.17 \frac{W}{m^2 K}$

Hence thermal resistance is equal to ***R_{bc} = 0.033 K/W.***

- <u>**Thermal Capacitance of the Coolant C_f**</u>

The thermal capacitance of the coolant is simply its mass multiplied by thermal capacity. The thermal capacity of the coolant at a reference temperature of 25 °C is *$C_{p,f}$ = 3403 J/Kg.K* as mentioned in the previous section. The mass of the coolant is approximated as follows:

$$m_f = \rho_f V_f \qquad (6.4)$$

Where ρ_f is the density of the coolant that is equal to 1076 Kg/m³ at T_C=25°C and V_f is the volume of the coolant circulating in the cooling system (cooling plate + radiator + connections) which is assumed equal to 3 times the volume of coolant inside cooling plate.

$$V_f = 3x\frac{\pi D_i^2}{4} L \qquad (6.5)$$

Substituting the parameters of eq. 6.5 with their values give **$V_f \approx$ 10 Litres**. Then:

- $\boldsymbol{m_f = 11\ Kg}$
- $\boldsymbol{C_f = 37745\ J/K.}$

- <u>**Global Heat Transfer Coefficient of the Radiator K_r**</u>

The global heat transfer coefficient can be calculated based on the following equation:

$$K_r A_r = \frac{P_r}{T_C - T_{amb}} \qquad (6.6)$$

The temperature of the coolant entering the radiator will be close to the battery temperature that should be kept below 40°C. on the other hand, T_{amb} is in the range of -20°C – 40°C. A temperature difference of 5°C between T_C and T_{amb} is assumed in calculating $K_r A_r$.

$$K_r A_r = \frac{768}{5} = 153.6\ W/K.$$

After estimating all the required parameters, the complete model is built on Simulink along with a monitor that will trace battery current, voltage, SOC, and Temperature. The model is shown in the below figure.

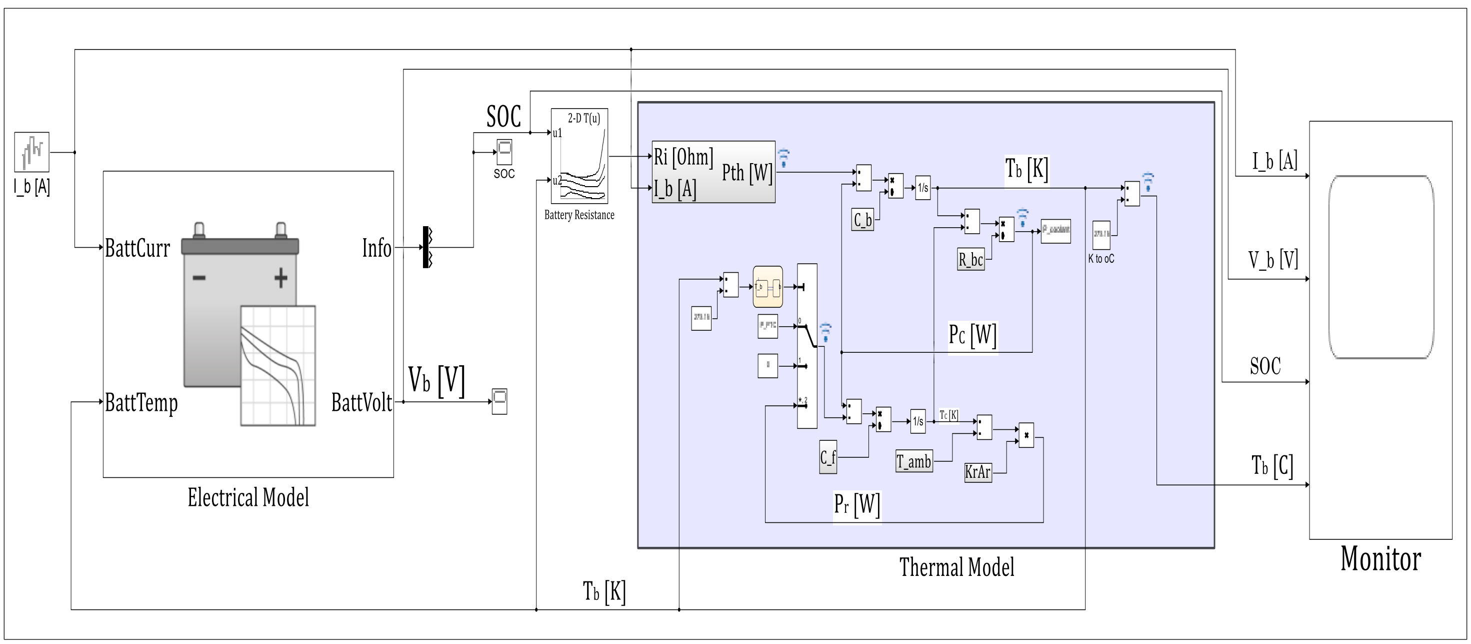


Figure 18: Electrical and thermal model of the battery pack on Simulink.

8. Validation of the Battery Model

After creating the virtual model of the battery, it is important to verify its reliability in representing the real behavior of a lithium-ion battery. To do so, a 94Ah Samsung battery module bench testing experiments have been done and provided to us for reference. All tests were carried out inside a climatic chamber at a testing temperature of 25ºC. The module under testing consists of 10 battery cells grouped in series with its characteristics shown in the below table.

Table 4: Samsung 94 Ah Battery cell and module characteristics.

		Element	Module
Nominal voltage	*V*	**3,7**	**37**
Upper limit voltage	*V*	*4,15*	*41,5*
Lower limit voltage	*V*	*2,7*	*27*
Nominal capacity	*Ah*	**94**	**94**
Specific capacity	*Ah/kg*	46	3
Nominal energy	*kWh*	**0,35**	**3,48**
Specific energy	*Wh/kg*	168,83	126,01
Continuous discharge current	*A*	**188**	**188**
Continuous discharge power	*kW*	0,70	6,96
Specific discharge power	*W/kg*	337,67	252,03
Max discharge current (5 s)	*A*	**282**	**282**
Max discharge power	*kW*	1,04	10,43
Continuous charge current	*A*	**47**	**47**
Continuous charge power	*kW*	0,17	1,74
Max charge current (5 s)	*A*	**188**	**188**
Max charge power	*kW*	0,70	6,96
Life cycle	*#*	4000	
Curb weight	*kg*	2,06	20,6
Structure weight	*kg*	0	7
Total weight	*kg*	**2,06**	**27,6**
Height	*mm*	125	175
Width	*mm*	173	201
Thickness	*mm*	45	486
Volume	*l*	**0,97**	**17,10**
Series	---	90	10
Parallel	---	1	1
Note	---	**All values @25 °C AND SoC 50%**	

The module under testing had no cooling system except for natural convection with the surrounded air. The figure below illustrates the experimental setup of the battery module.

Figure 19: Battery module under test located into the climatic chamber set at 25°C.

To proceed with the validation process, the first step is to import the module characteristics available in the manufacturer's datasheet into the model we created virtually to have an equivalent representation of the battery module under testing. The main parameters that are required to build the electrical model of Samsung 94Ah battery module are:

- Open circuit voltage of the battery versus SOC.
- Internal resistance of the battery versus SOC and battery temperature.
- Number of battery cells inside the module.

The technical datasheet provided by Samsung contained all the required parameters mentioned before. The figures below show OCV and internal resistance of Samsung battery cell.

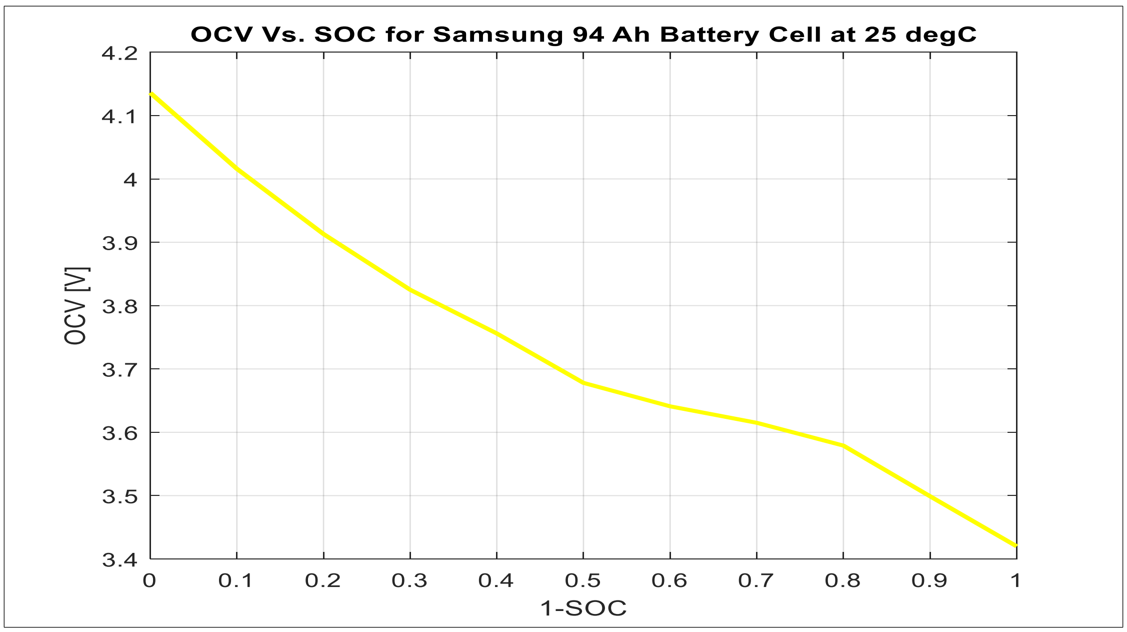


Figure 20: Open Circuit Voltage of Samsung-94Ah Battery cell versus SOC.

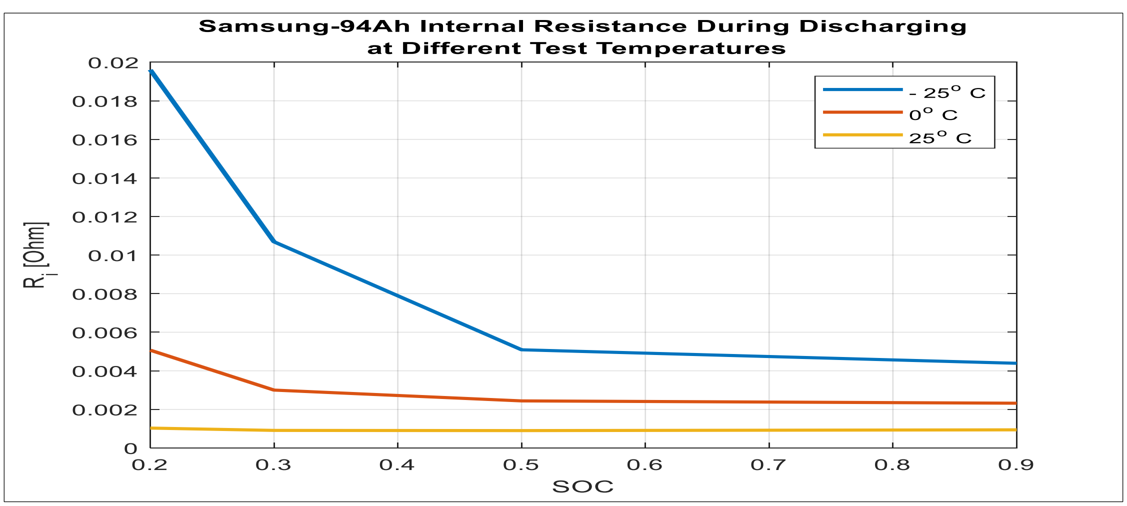


Figure 21: Internal Resistance of Samsung 94Ah Battery cell versus SOC and Battery Temperature.

By importing the parameters mentioned before, the electrical model is ready. As for the thermal model of the battery module, since only natural convection is used in the experimental test then the thermal behavior of the module will evolve according to the energy equation 5.1.2 mentioned before:

$$m_b C_{p,b} \frac{dT_b}{dt} = P_{th}(t) - P_a(t) = R_i(T_b, SOC) I_b^2 - h_a A_b (T_b(t) - T_{amb})$$

The model of the battery module (attached in Appendix D) is ready to run charging/discharging tests as those made during bench testing to compare its results with the real ones. Note that during the simulation, since convective heat transfer coefficient of the air inside climatic chamber was not known, its value was varied until the behavior of the virtual model followed the same behavior of the real battery module. Below is the output of the virtual simulations along with the output of the real experiments under defined charging/discharging cycles.

<u>1st Test: Full "rated" 1/2 C Charge and 1 C & 3/2 C Discharge</u>

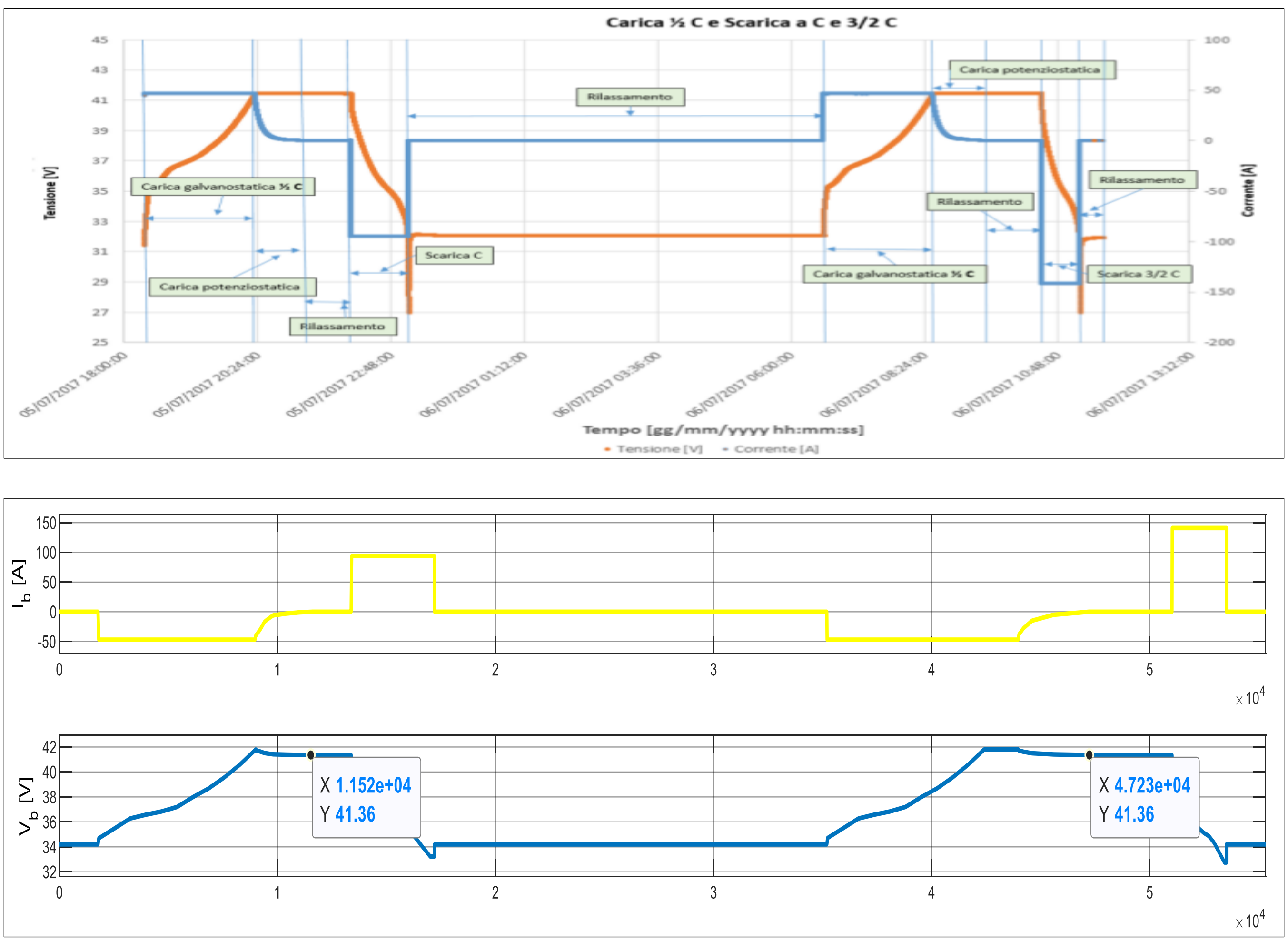


Figure 22: Voltage and Current of Battery Module during 1st Test. 1: Real Experiment, 2: Virtual Test.

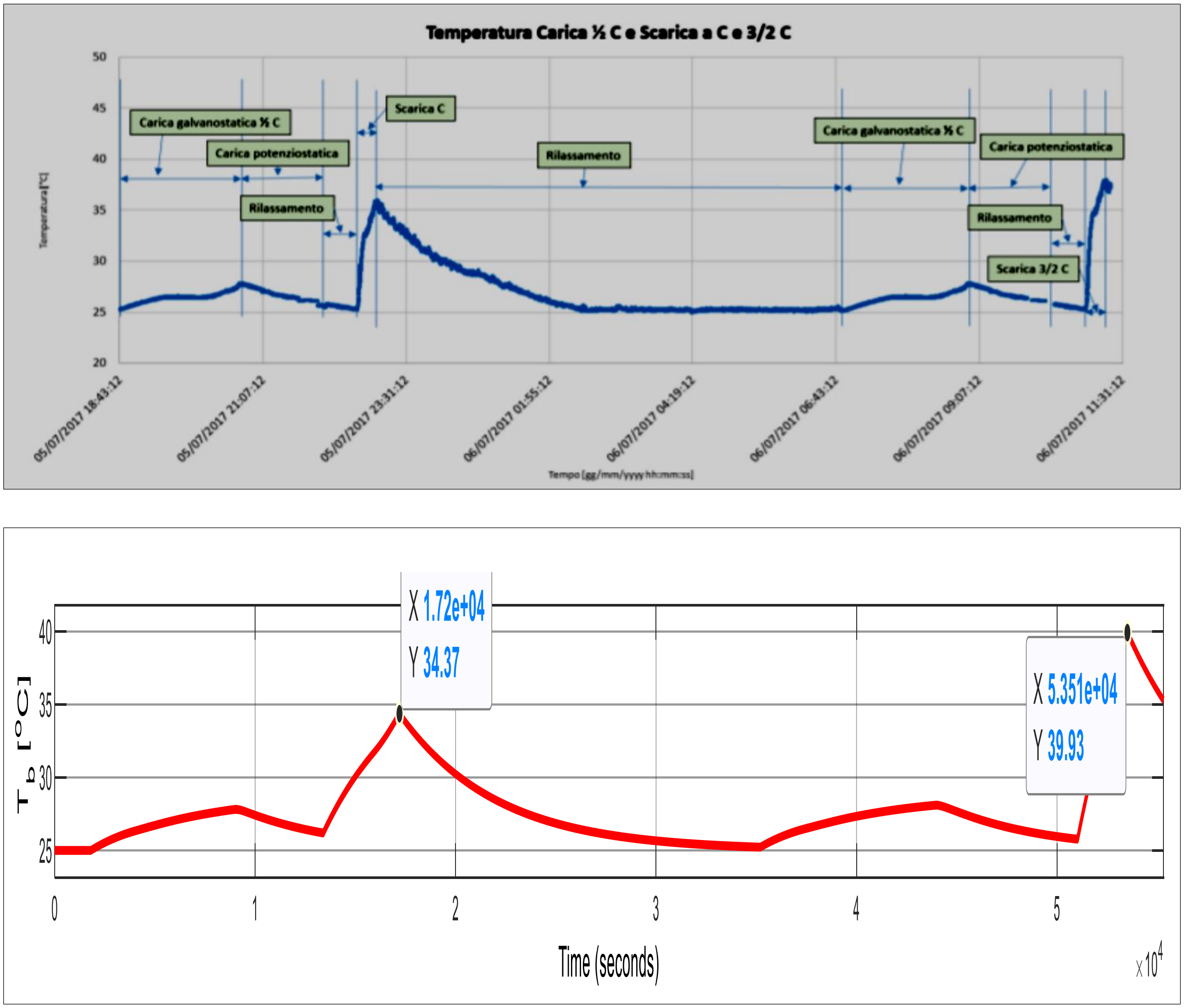
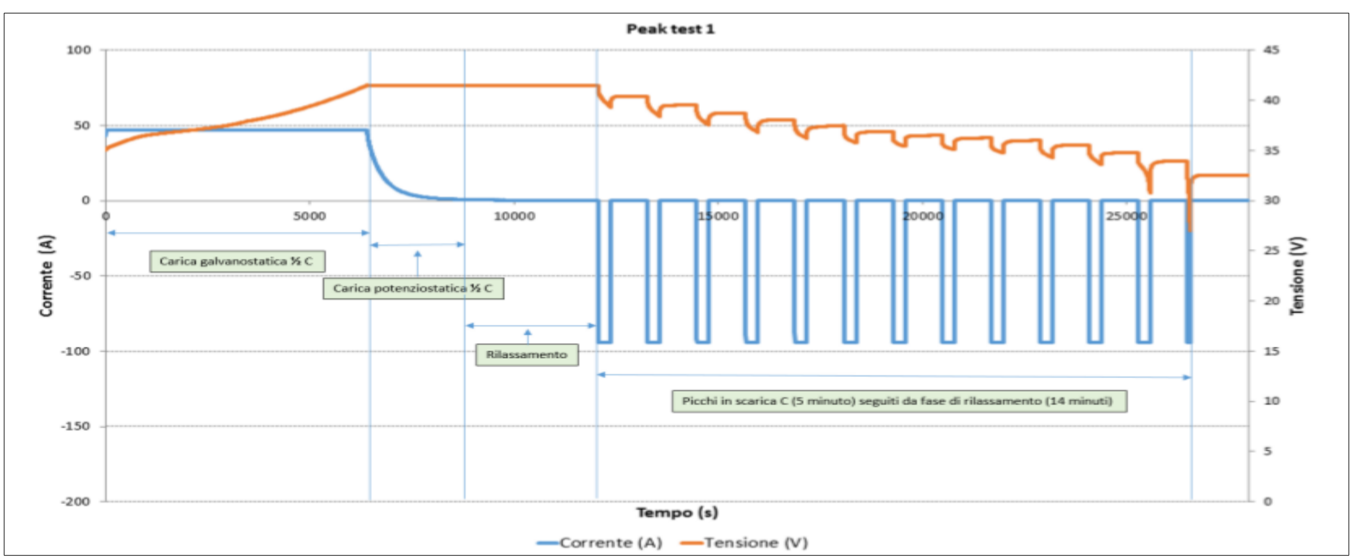


Figure 23: Temperature of Battery Module during 1st Test. 1: Real Experiment, 2: Virtual Test.

2nd Test: Full "rated" 1/2 C Charge and Impulse Train 1 C Discharge



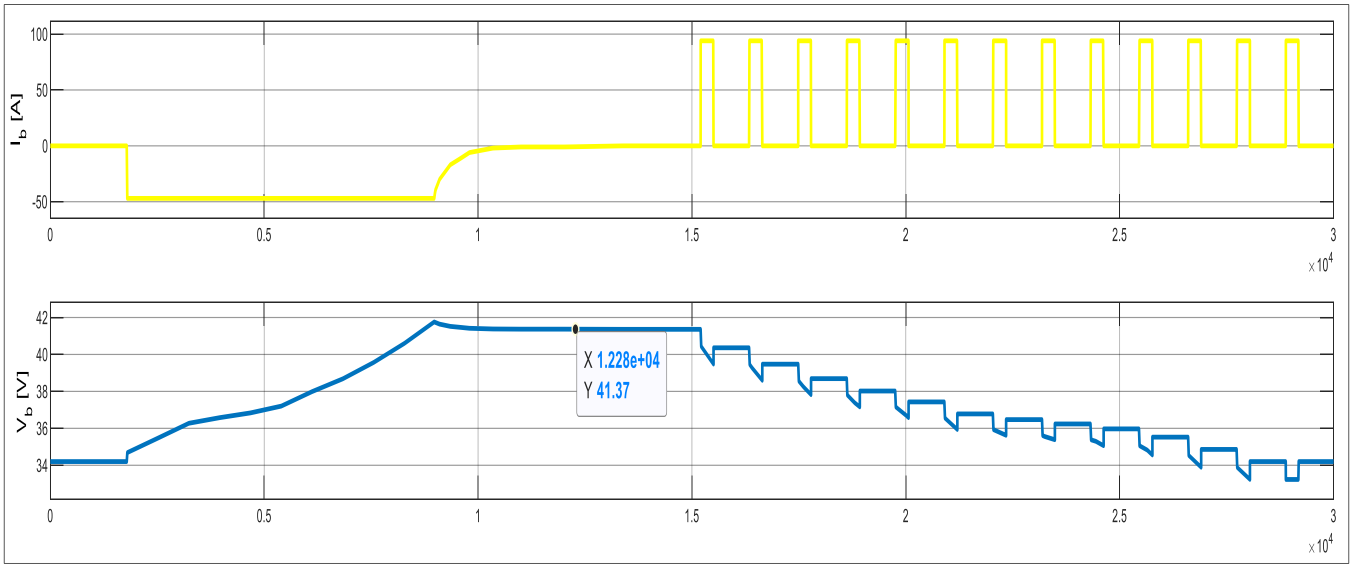


Figure 24: Voltage and Current of Battery Module during 2nd Test. 1: Real Experiment, 2: Virtual Test.

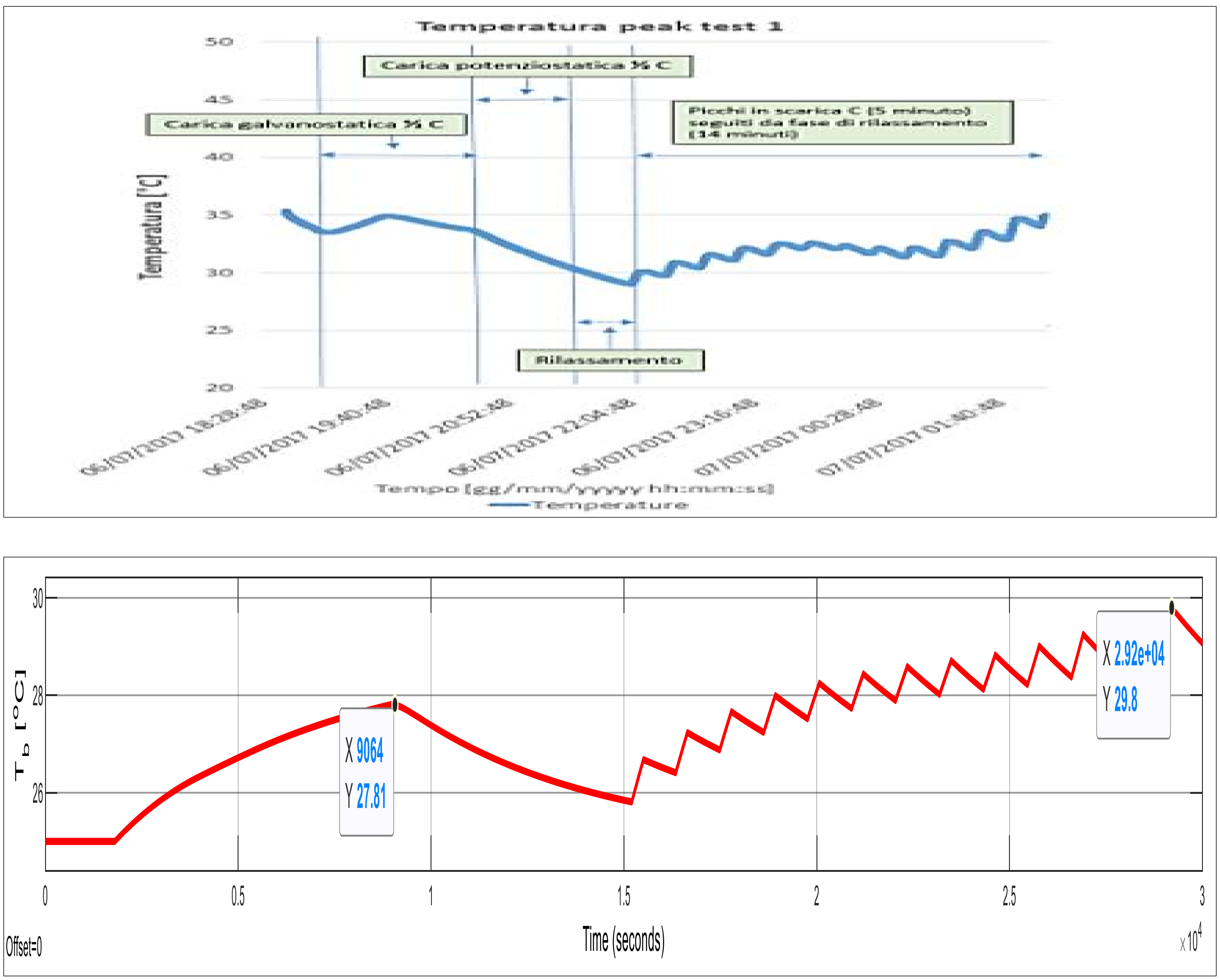


Figure 25: Temperature of Battery Module during 2nd Test. 1: Real Experiment, 2: Virtual Test.

It should be noted from the temperature graph of the real experiment that the starting temperature of the battery module was higher than 25°C (around 35°C) so by comparing the increase of temperature during discharging, we notice an increase of 5°C in the real experiment and 4°C in the virtual experiment with 1°C difference.

3rd Test: Impulse Train 1/2 C Charge and Impulse Train ½ C, 1 C, 3/2 C, 180A Discharge

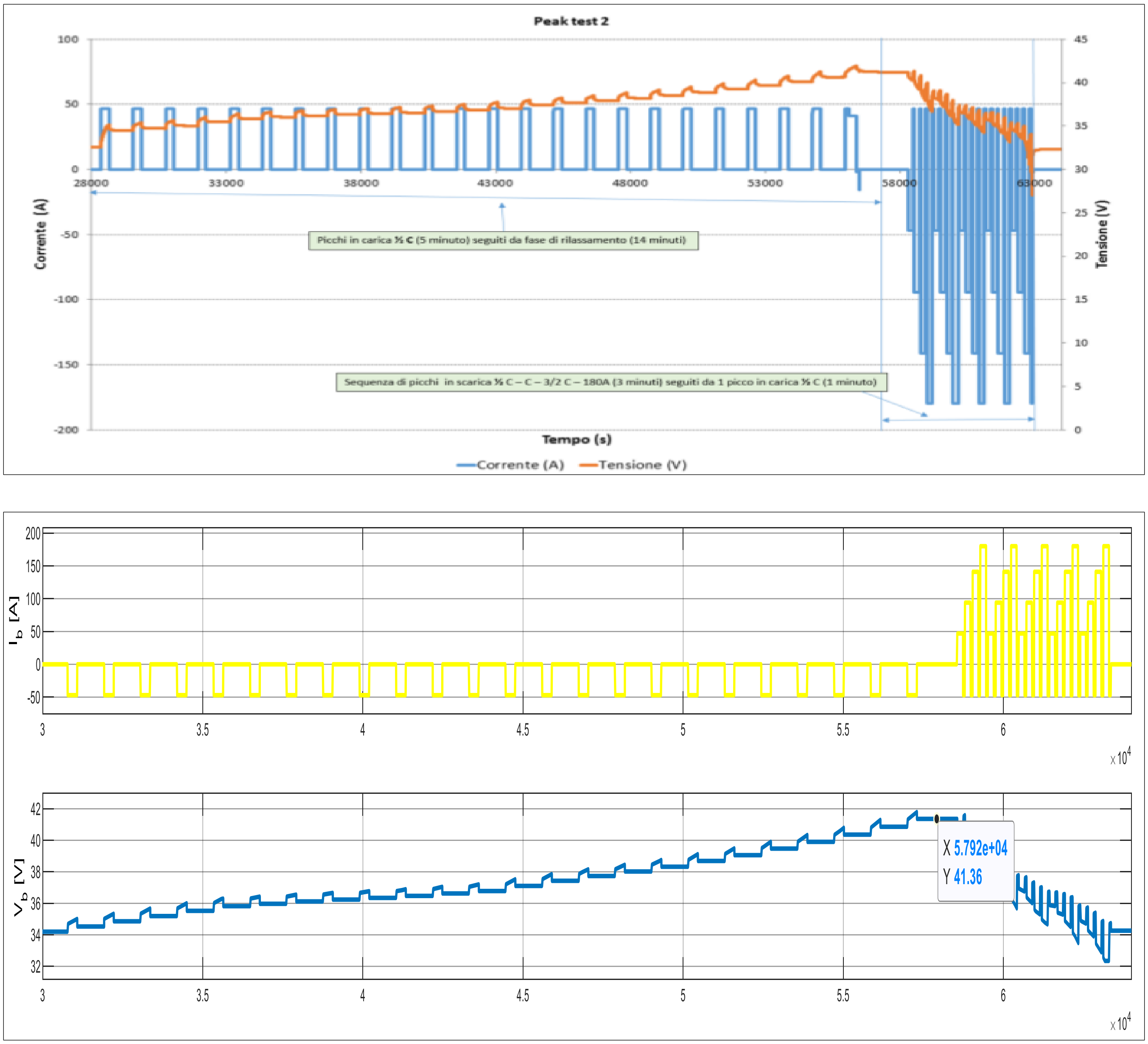


Figure 26: Voltage and Current of Battery Module during 3rd Test. 1: Real Experiment, 2: Virtual Test.

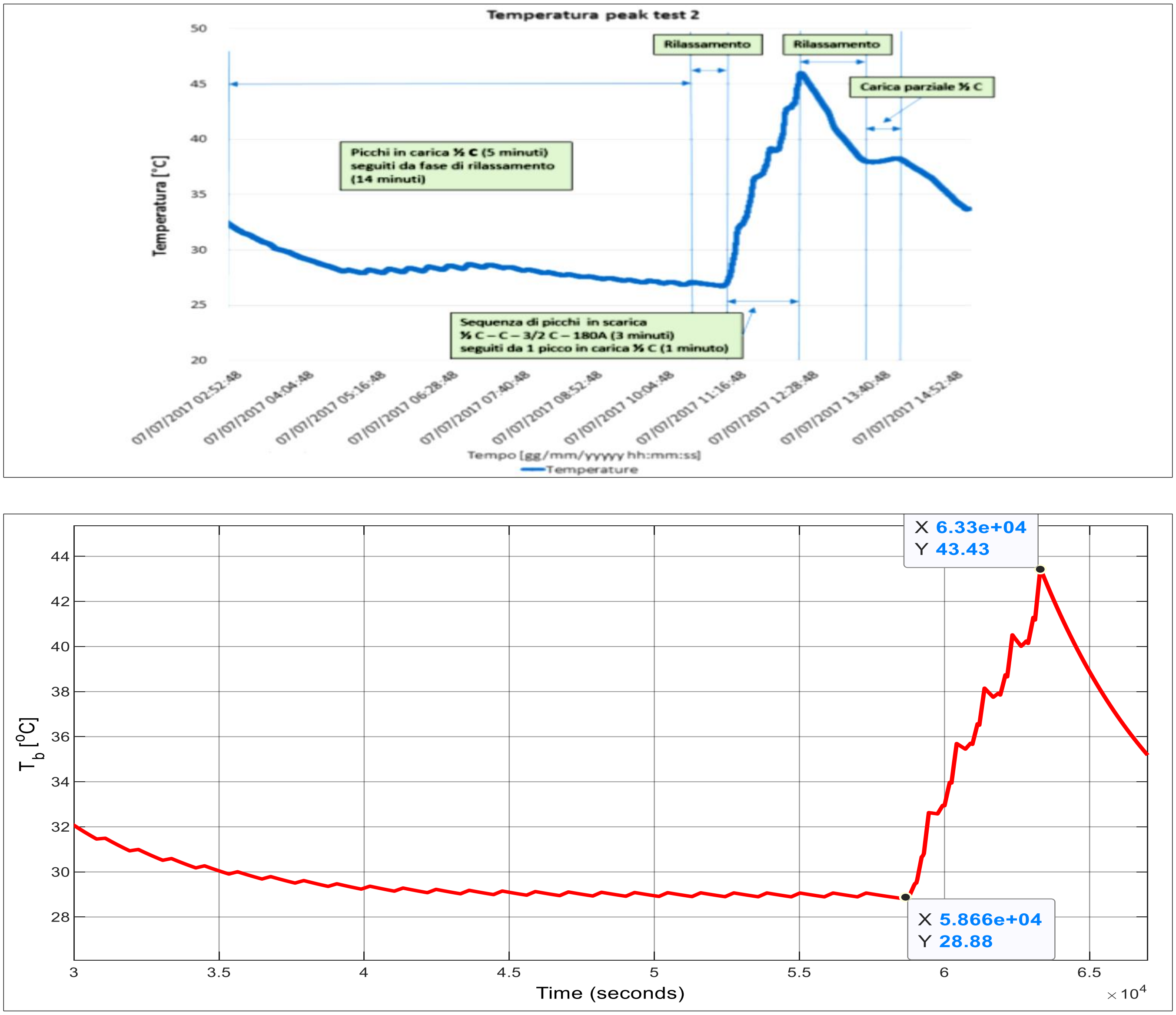


Figure 27: Temperature of Battery Module during 3rd Test. 1: Real Experiment, 2: Virtual Test.

The figures above show that the virtual model was able to provide similar results as real model with around $\pm 2\ V$ difference on battery voltage and $\pm$ 4°C difference on battery temperature. Hence the virtual model built created on Simulink using battery datasheet block could be used to simulate battery behavior under different charging/discharging cycles up to acceptable margins.

9. *Simulation of 138.6 Ah Panasonic Battery Pack Model*

After validating the ability of the virtual model to represent the behavior of lithium-ion battery, different simulation tests could be done on the 138.6 Ah battery pack model. Note that the electro-thermal model of the battery pack is found in **appendix B.** The aim of the tests is to analyze the behavior of the battery pack regarding its voltage, SOC and temperature under different charging/discharging cycles and under different operating conditions.

The battery pack will be tested under 5 different ambient temperatures (-20^{o}C, -10^{o}C, 0^{o}C, 25^{o}C and 40^{o}C) and at each temperature, 3 different charging/discharging cycles will be applied.

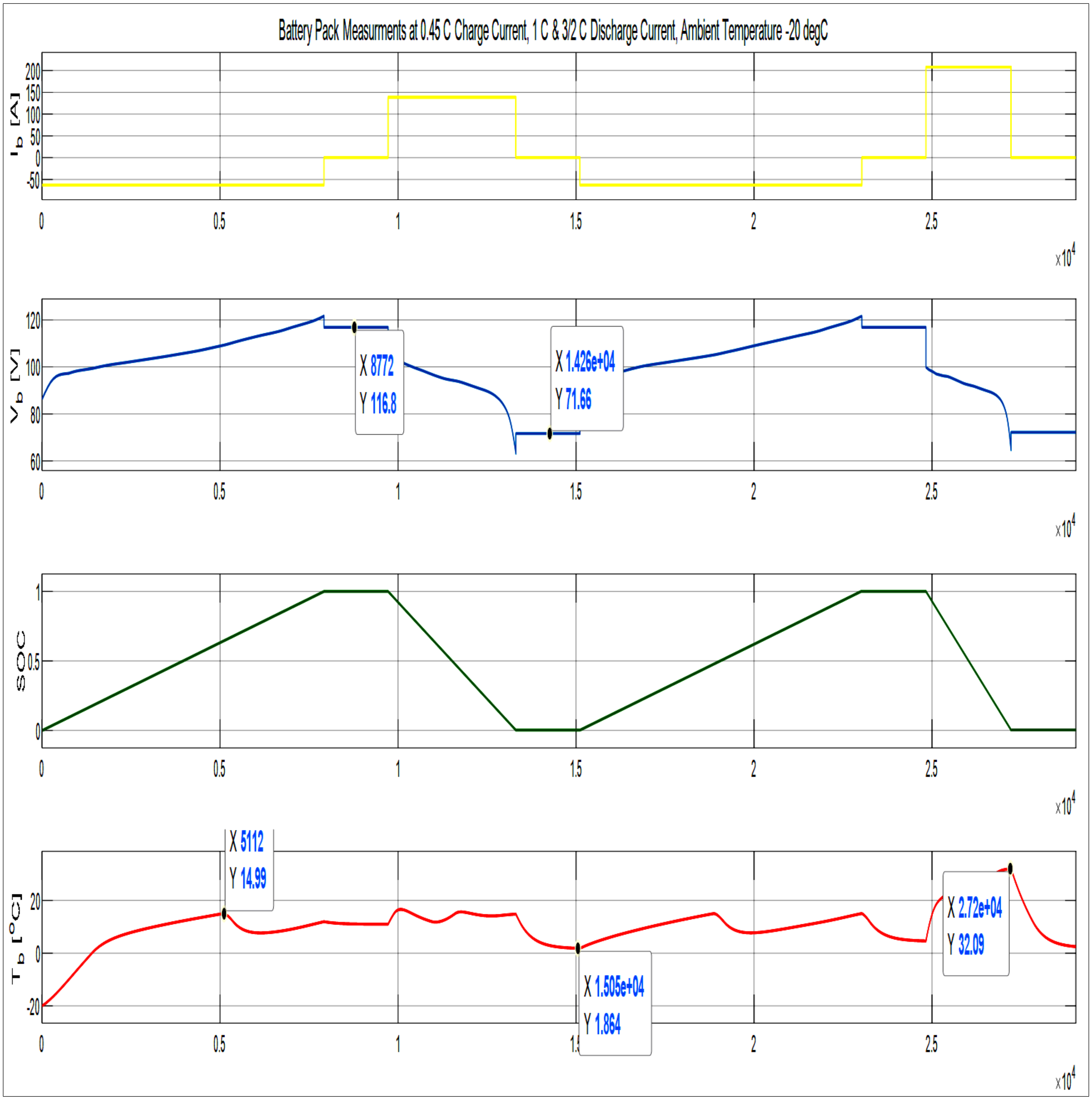
All tests will be done taking into consideration the following conditions:

- The battery pack initial temperature is stabilized with the ambient temperature through enough time of resting before each test.
- The allowable continuous charging current of the battery is 0.45C (63A).
- The initial SOC of the battery pack is 0%.

Full 0.45 C Charge and 1 C & 3/2 C Discharge Test

Step		Parameter		Criteria to Stop
1	Battery Temperature Stabilization	T_{amb}	C-rate	$T_b = T_{amb}$
2	Constant Current Charging	I_b = - 63 A	0.45 C	V_b > 117.6 V
3	Resting Phase	I_b = 0 A	-	t = 30 min
4	Constant Current Discharging	I_b = 138.6 A	1 C	V_b < 70 V [cut-off]
5	Resting Phase	I_b = 0 A	-	t = 30 min
6	Constant Current Charging	I_b = - 63 A	0.45 C	V_b > 117.6 V
7	Resting Phase	I_b = 0 A	-	t = 30 min
8	Constant Current Discharging	I_b = 207.9 A	3/2 C	V_b < 70 V [cut-off]
9	Resting Phase	I_b = 0 A	-	t = 30 min

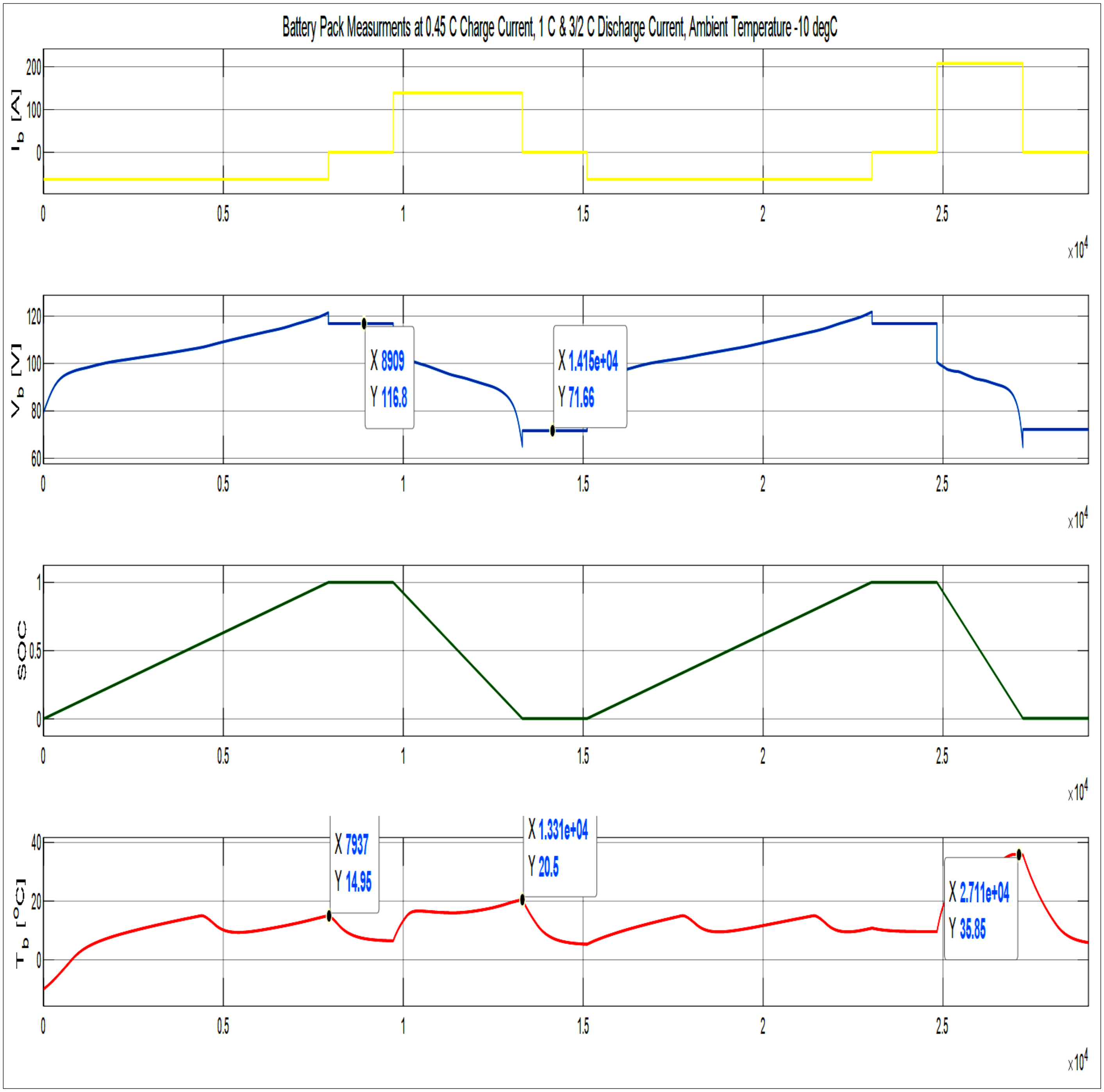
a) T_{amb} = -20°C



Output:

Testing at an ambient temperature of -20°C, battery pack temperature reaches a maximum of 32.1°C when discharging at 1.5 C rate while it reaches 15°C when discharging at 1 C rate. Throughout successive test cycles, battery temperature varies between 1.8°C and 32°C.

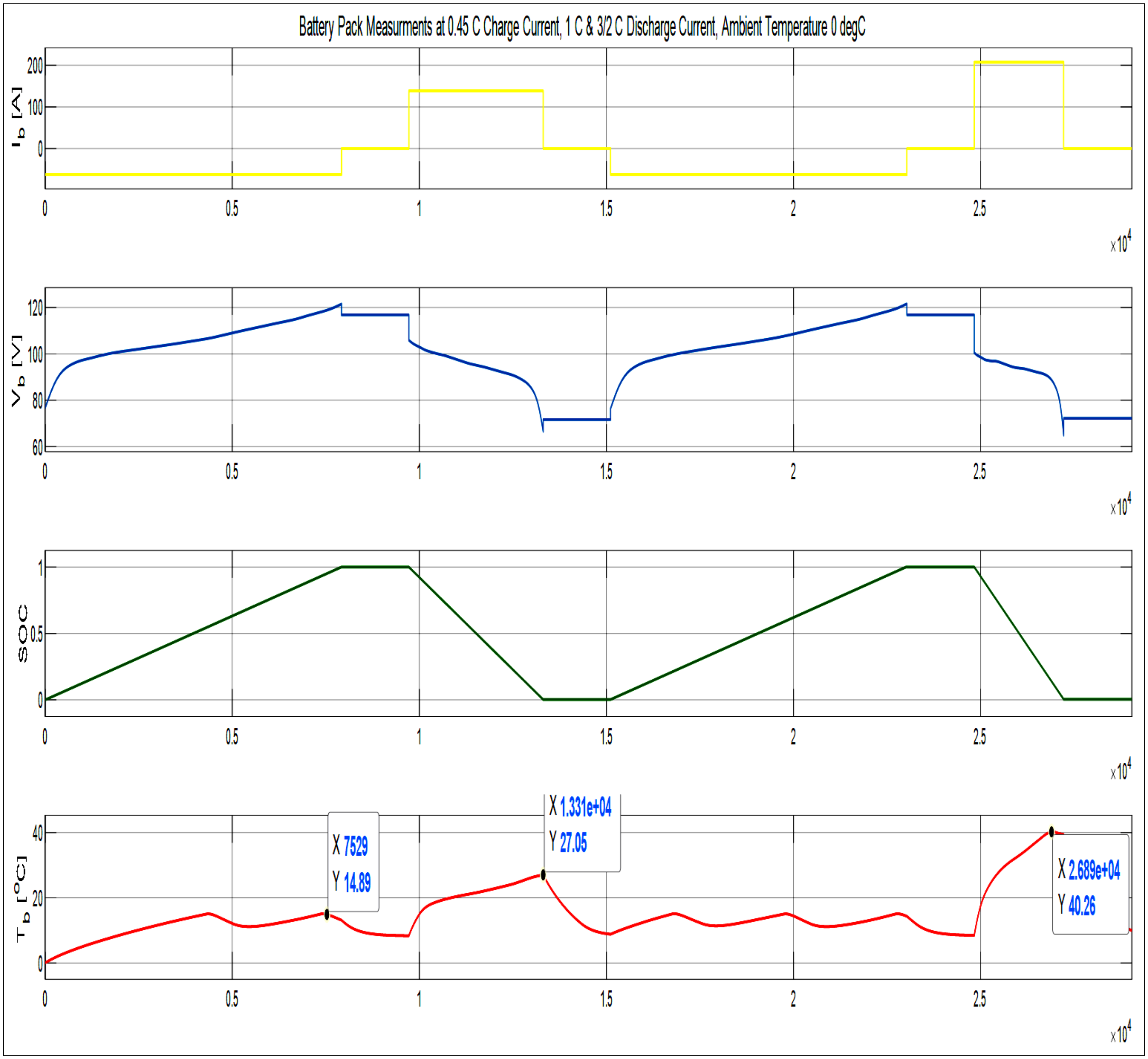
b) $T_{amb} = -10^oC$



Output:

Increasing test temperature to -10°C leads to an increase in battery pack maximum temperature of 4°C reaching a value of 36°C when discharging at 1.5 C rate. Battery pack temperature varies between 7°C and 36°C throughout successive test cycles.

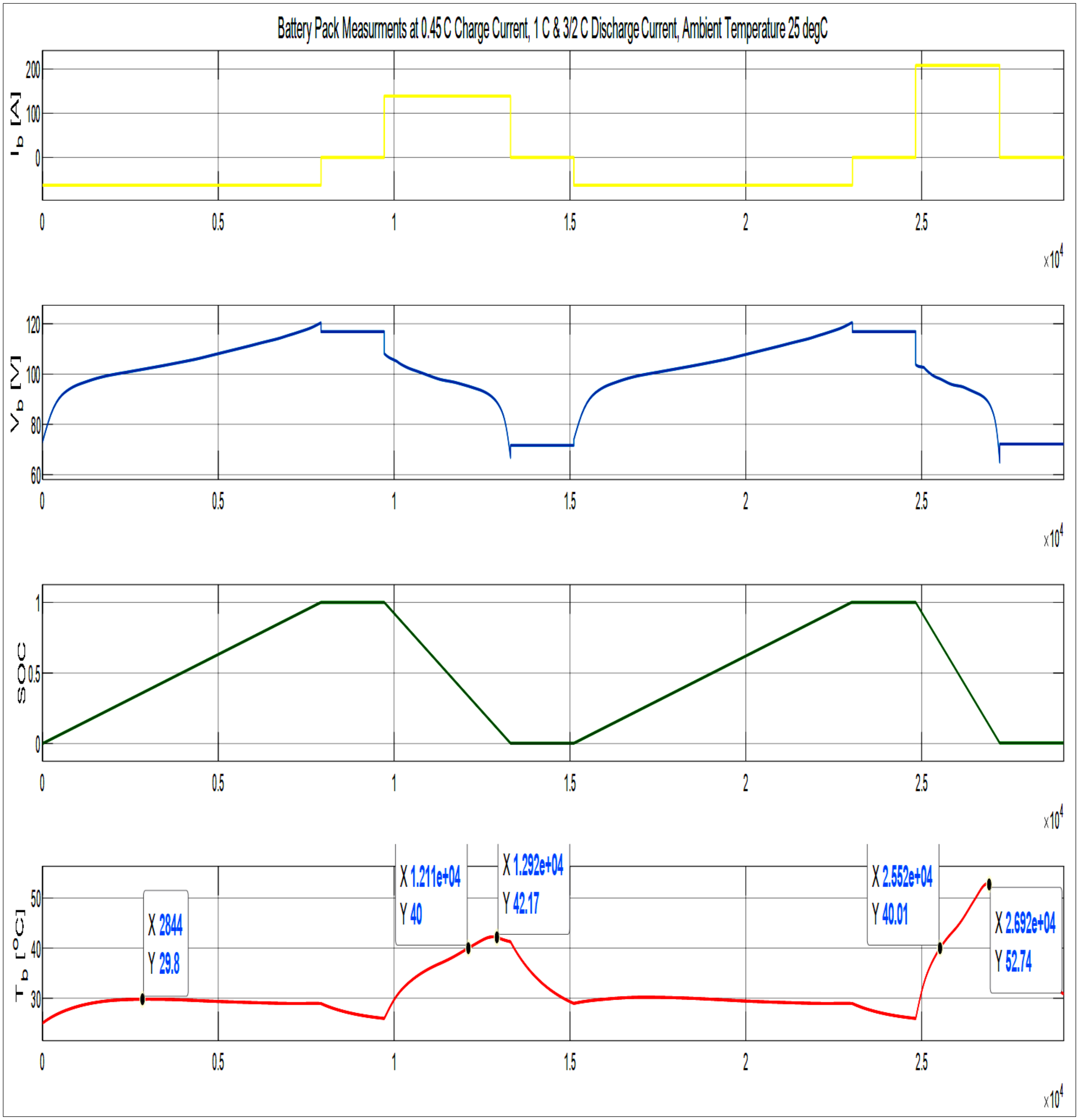
c) $T_{amb} = 0^oC$



Output:

As ambient temperature increases, battery pack temperature increases to reach a maximum of 40.3°C exceeding its upper operating temperature when discharging at 1.5 C rate. To prevent this temperature rise, a decrease of the discharging current could be applied when battery temperature starts approaching its upper limit hence reducing heat produced due to joule's effect. If the demand of the current is necessary, active cooling system should be turned on where coolant of the battery exchange heat with A/C cooling system instead of passive radiator hence increasing amount of extracted heat.

d) $T_{amb} = 25^oC$



Output:

Testing at ambient temperature of 25ºC, battery pack temperature exceeds 40ºC both when discharging at 1 C reaching 42.2ºC and when discharging at 1.5 C reaching 52.7ºC. hence, a limitation on the duration of continuous discharging at 1 C and 1.5 C rate is applied. To keep battery temperature below 40ºC, the amount of discharged current should be decreased as temperature starts approaching upper limits.

e) $T_{amb} = 40^oC$

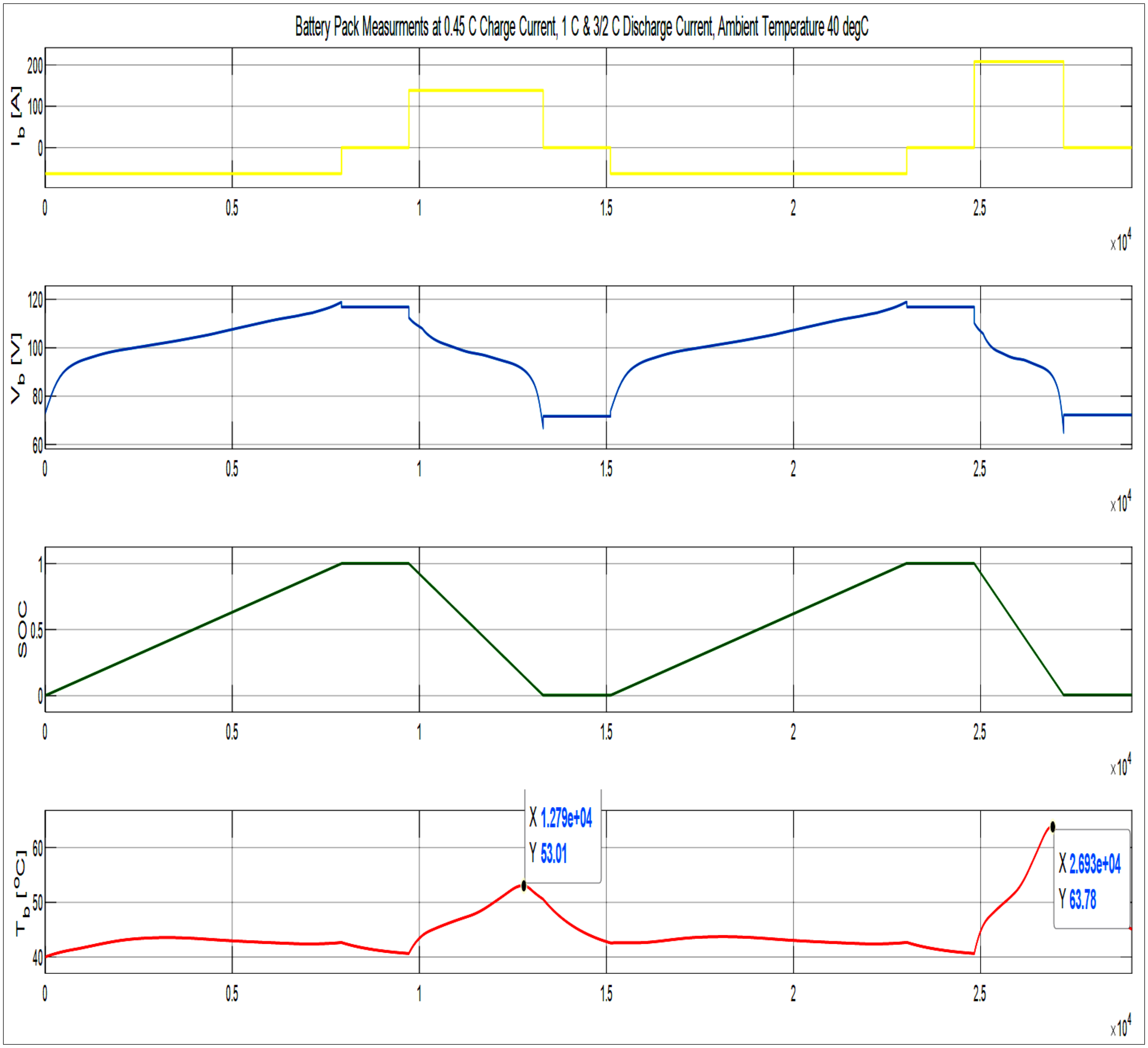


Figure 28: Battery Pack Behavior under 0.45 C Charging, 1 C and 3/2 C Discharging.

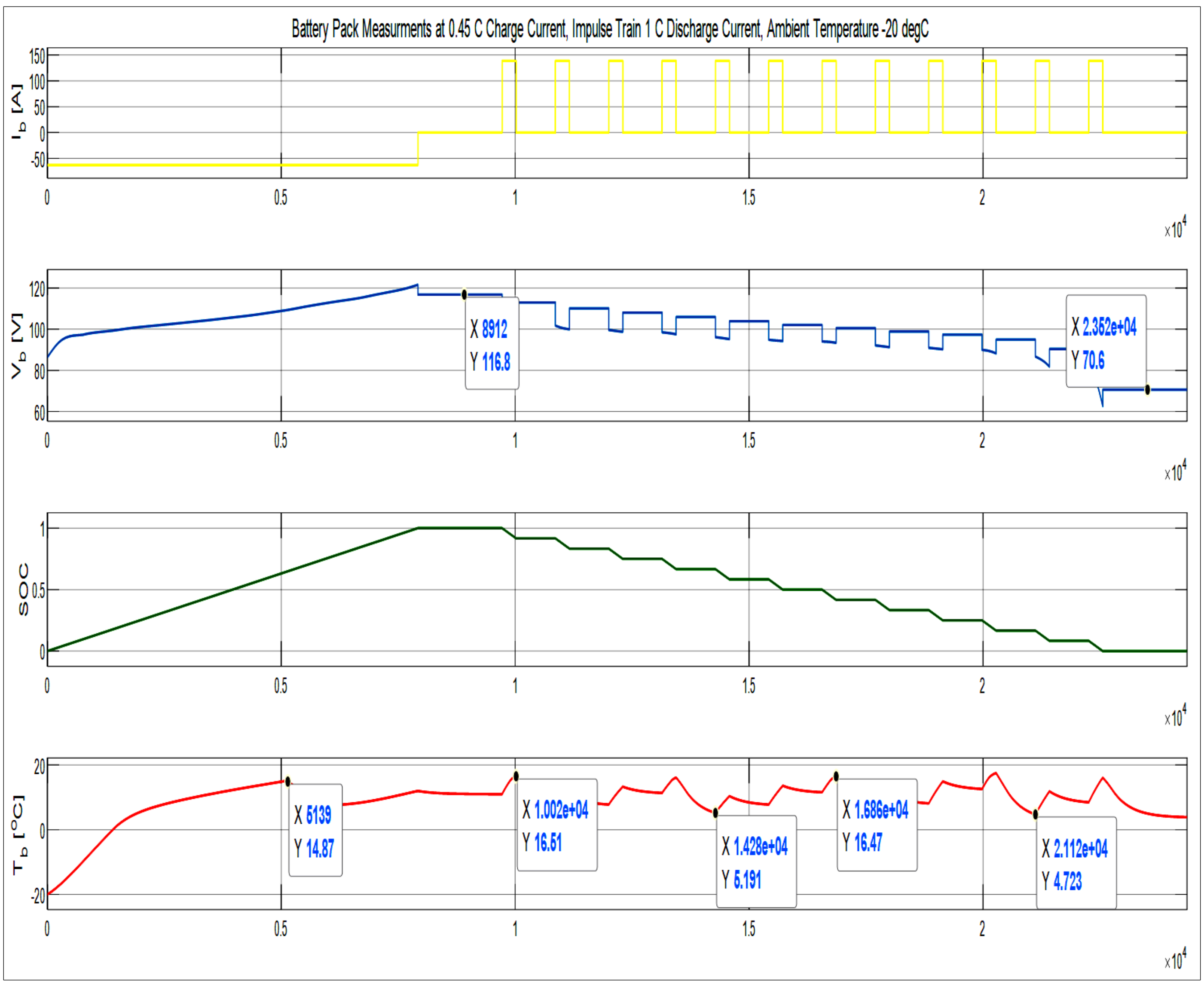
Output:

Batter pack temperature reaches 53°C under 1 C discharging and 64°C under 1.5 C discharging. When ambient temperature is high (>40°C), passive cooling system lacks the ability to keep battery temperature below its upper limit and an active cooling system is necessary to extract heat from battery.

Full 0.45 C Charge and Impulse Train 1 C Discharge Test

Step		Parameter		Criteria to Stop
1	Battery Temperature Stabilization	T_{amb}	C-rate	$T_b = T_{amb}$
2	Constant Current Charging	I_b = - 63 A	0.45 C	V_b > 117.6 V
3	Resting Phase	I_b = 0 A	-	t = 30 min
4	Impulse Constant Current Discharging	I_b = 138.6 A for 5 mins. I_b = 0 A for 14 mins.	1 C	V_b < 70 V [cut-off]
5	Resting Phase	I_b = 0 A	-	t = 30 min

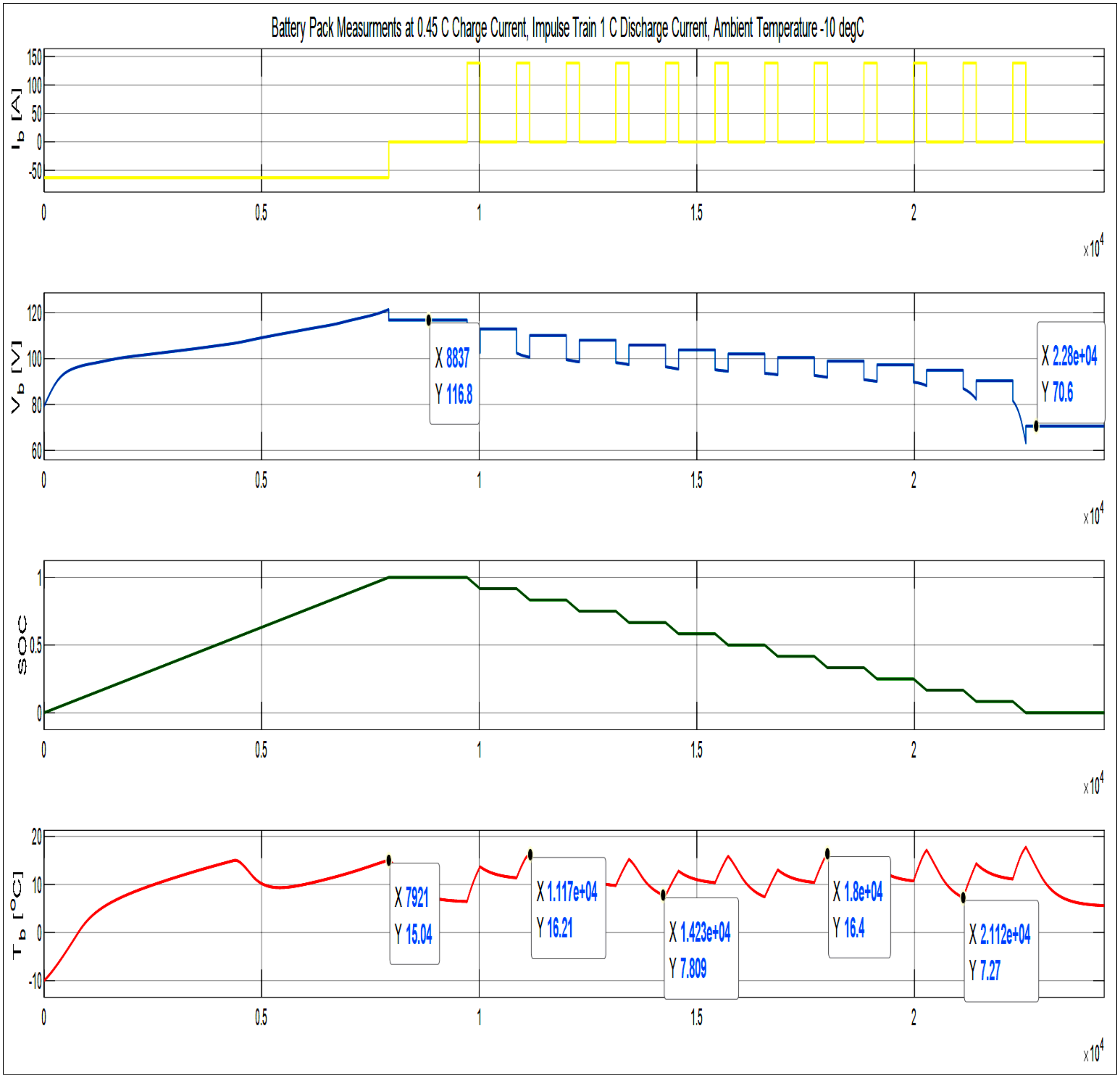
a) T_{amb} = -20°C



Output:

Battery pack temperature varies between 4.7°C and 16.5°C under impulse discharging of 1 C rate keeping its value within normal operating range.

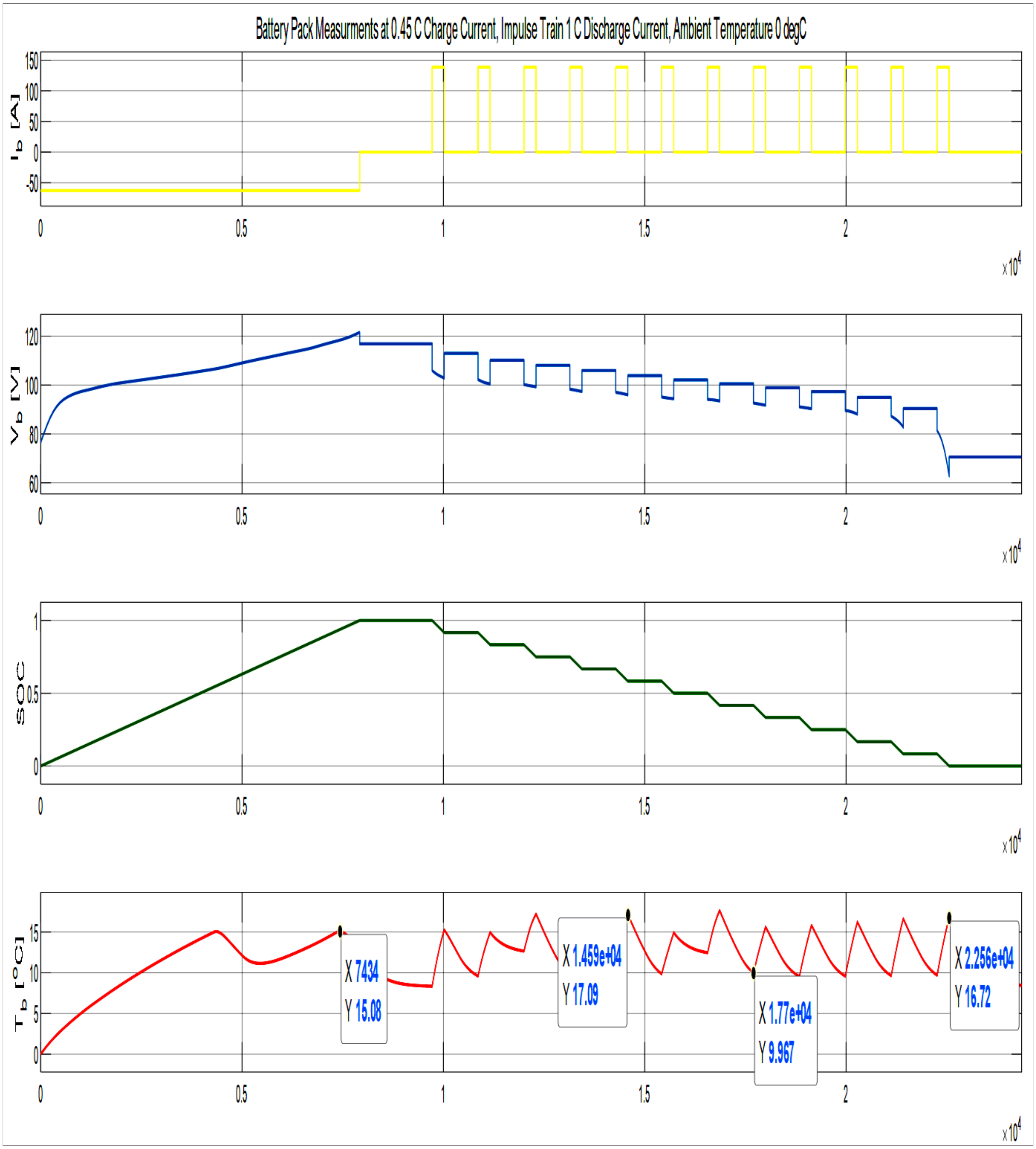
b) T_{amb} = -10°C



Output:

Battery pack temperature varies between 7.3°C and 16.5°C under impulse discharging of 1 C rate keeping its value within normal operating range.

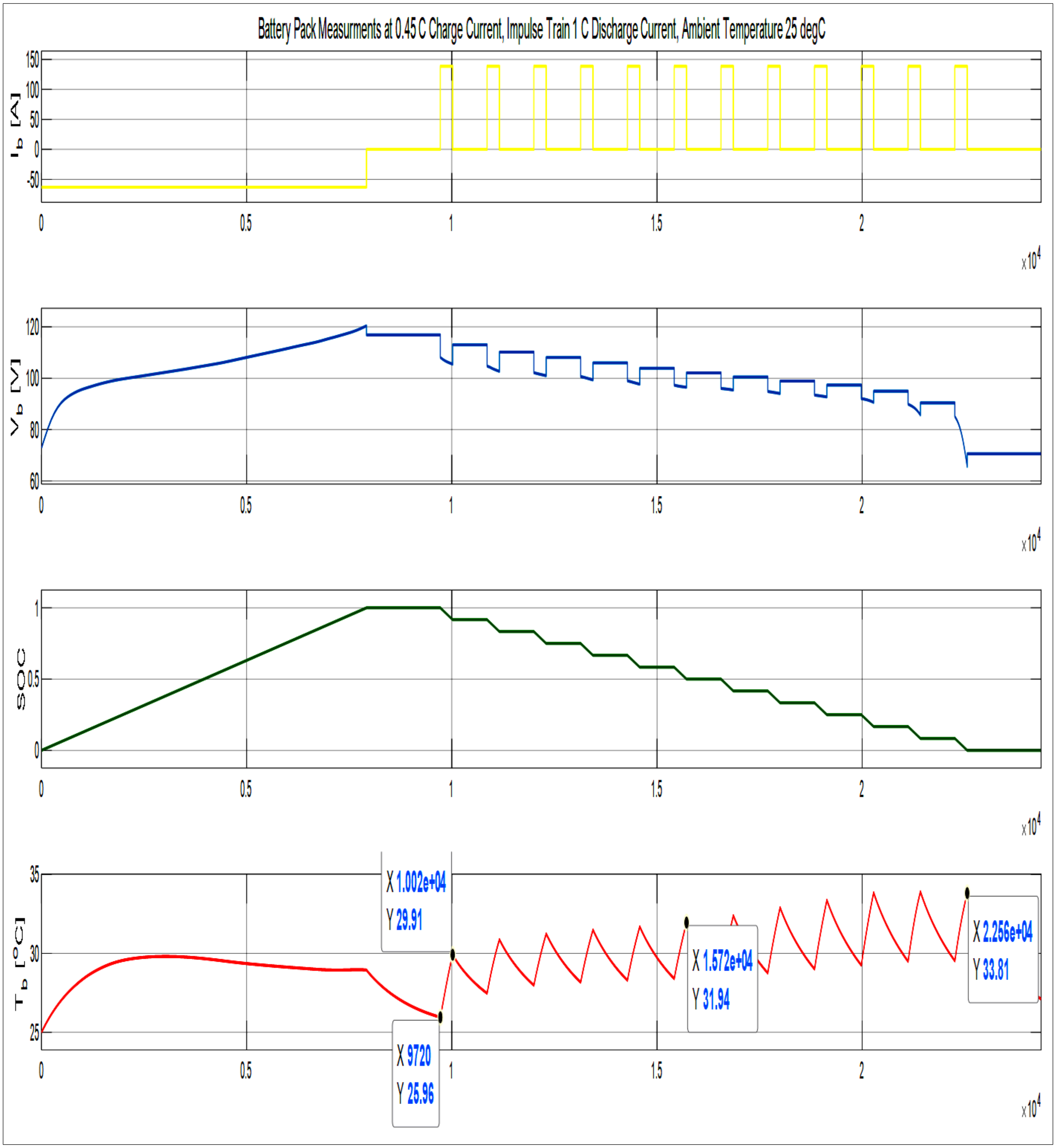
c) $T_{amb} = 0^oC$



Output:

Battery pack temperature varies between 10°C and 17°C under impulse discharging of 1 C rate keeping its value within normal operating range.

d) $T_{amb} = 25^oC$



Output:

Battery pack temperature varies between 26°C and 34°C under impulse discharging of 1 C rate keeping its value within normal operating range.

e) $T_{amb} = 40^oC$

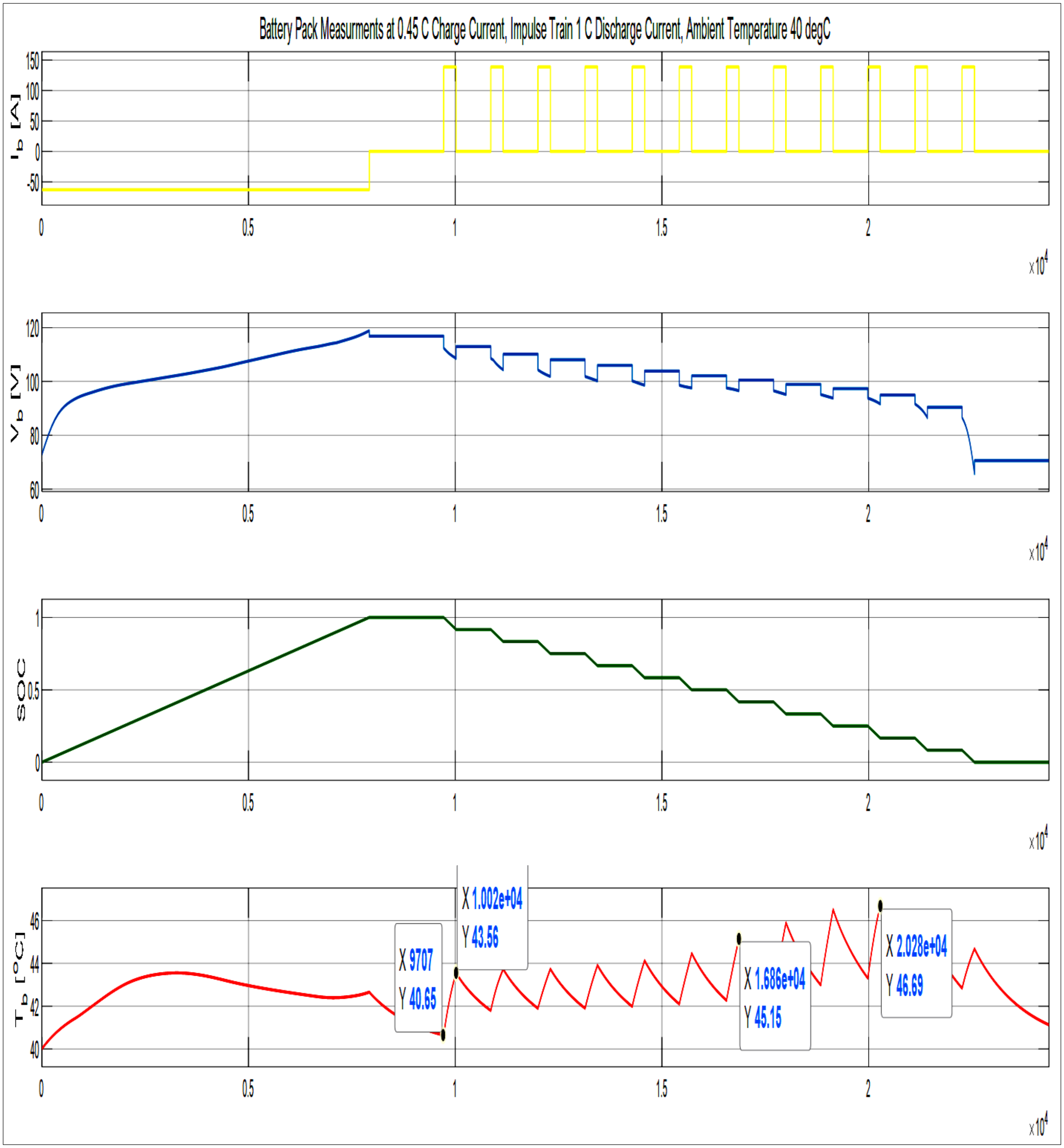


Figure 29: Battery Pack Behavior under 0.45 C Charging, Impulse Train 1 C Discharging.

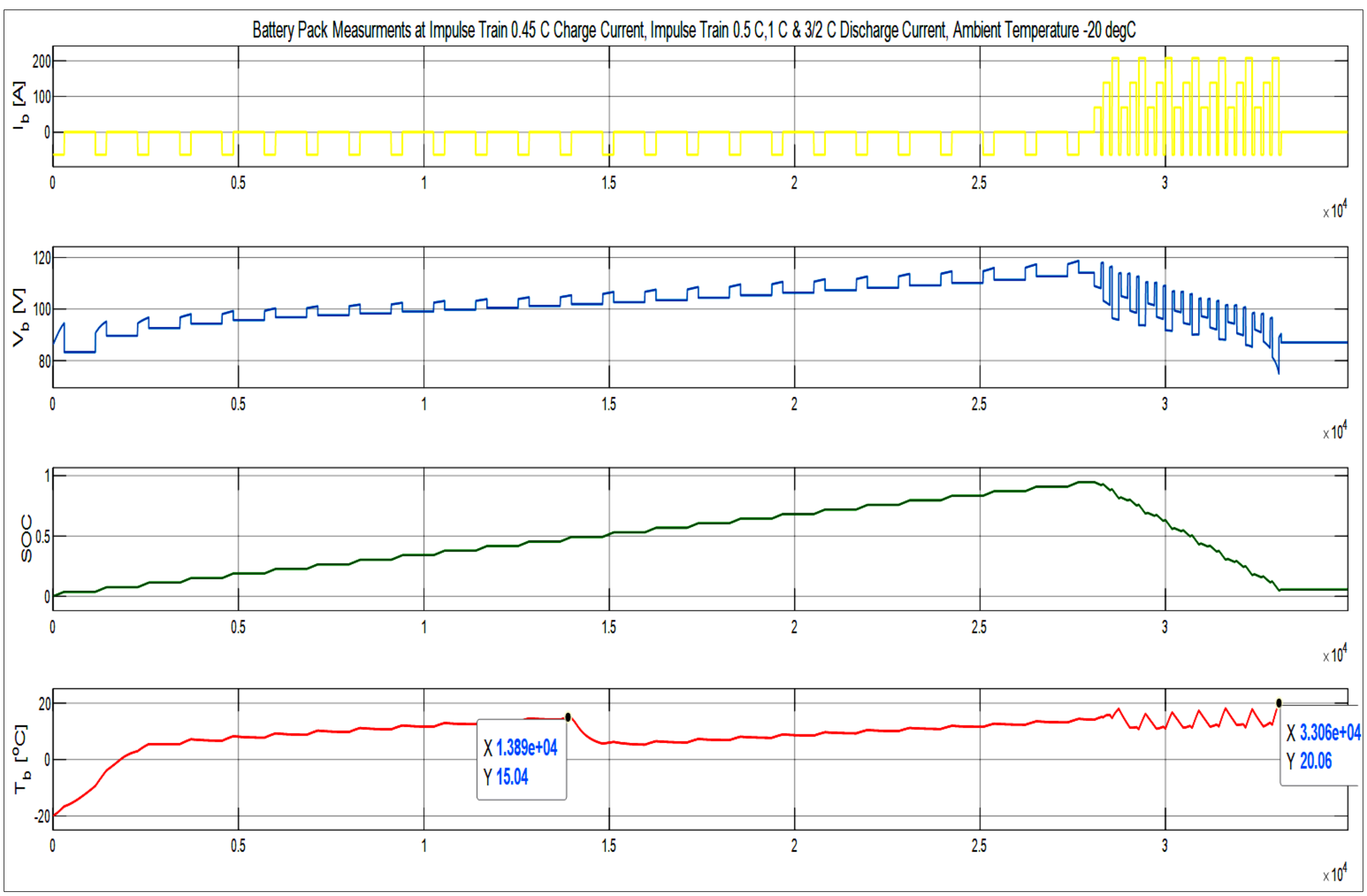
Output:

Testing at an ambient temperature of 40^{o}C, battery temperature increases from 40^{o}C to 46.7^{o}C.

Impulse Train 0.45 C Charge and Impulse Train 0.5 C, 1 C & 3/2 C Discharge Test

Step		Parameter		Criteria to Stop
1	Battery Temperature Stabilization	**T_{amb} = -20°C**	C-rate	T_b = -20°C
2	Impulse Constant Current Charging	I_b = - 63 A for 5 mins. I_b = 0 A for 14 mins.	0.45 C	V_b > 117.6 V
3	Impulse Constant Current Discharging	I_b = 69.3 A for 180 sec. I_b = -63 A for 60 sec. I_b = 138.6 A for 180 sec. I_b = -63 A for 60 sec. I_b = 207.9 A for 180 sec. I_b = -63 A for 60 sec.	0.5 C 0.45 C 1 C 0.45 C 3/2 C 0.45 C	V_b < 70 V [cut-off]
4	Resting Phase	I_b = 0 A	-	t = 30 min

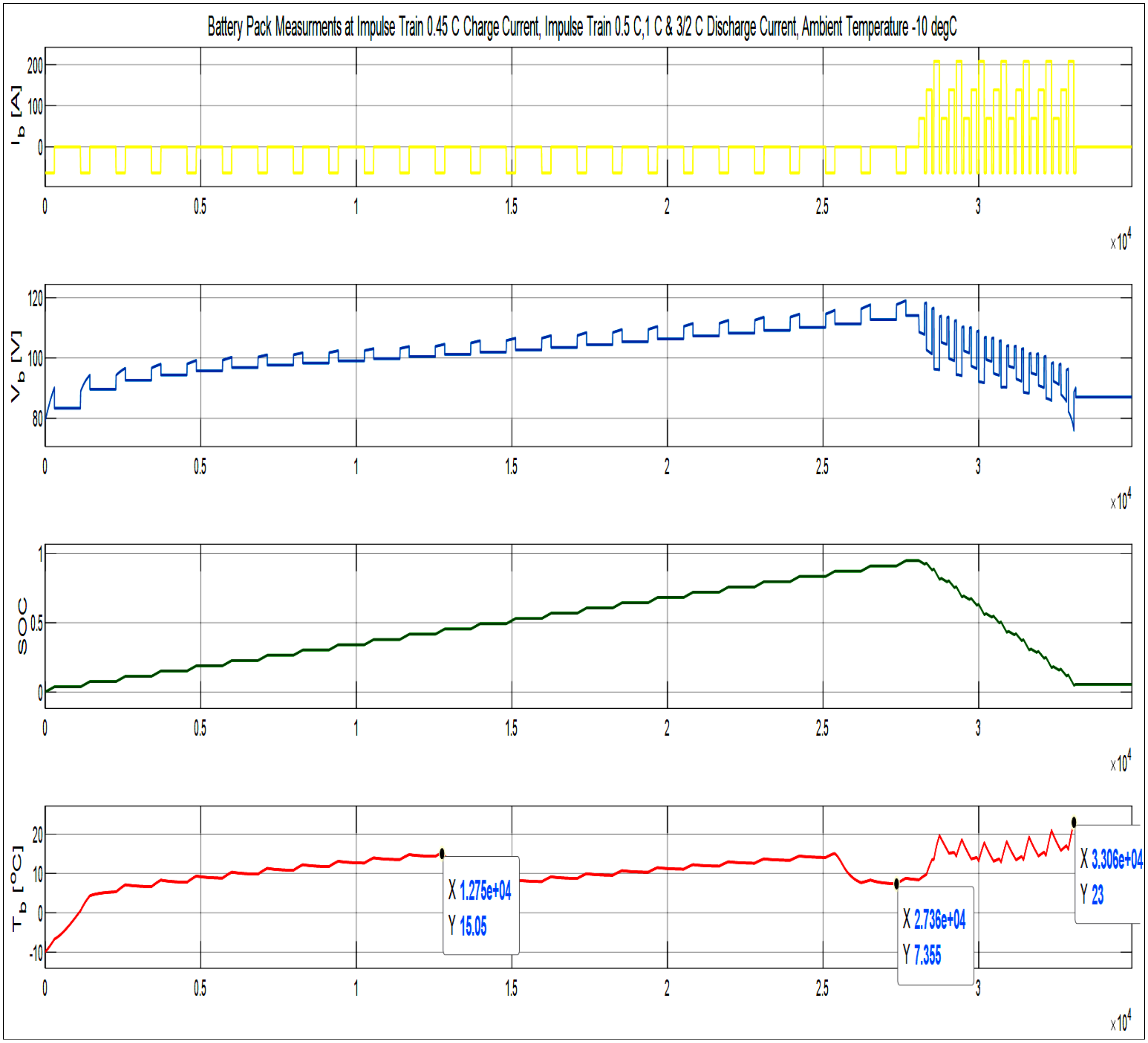
a) **T_{amb} = -20°C**



Output:

Battery pack temperature reaches 15°C during impulse charging and a maximum of 20°C during impulse discharging which is within its normal operating range.

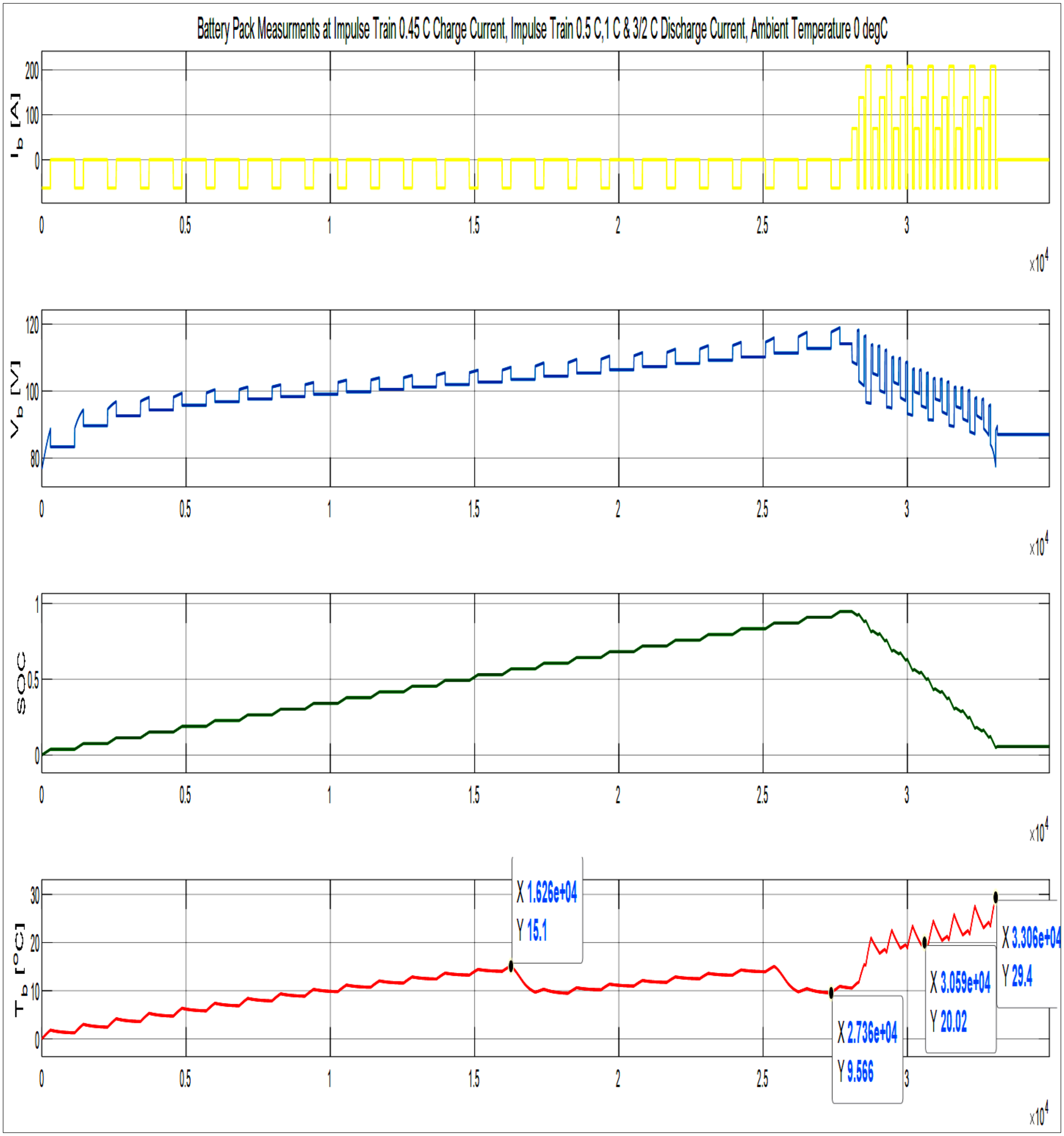
b) T_{amb} = -10°C



Output:

As the ambient temperature increased to -10°C, the maximum battery pack temperature increases by 3°C reaching a value of 23°C during impulse discharging at 1.5 C rate. Also, in this test, the temperature remains within its normal operating range.

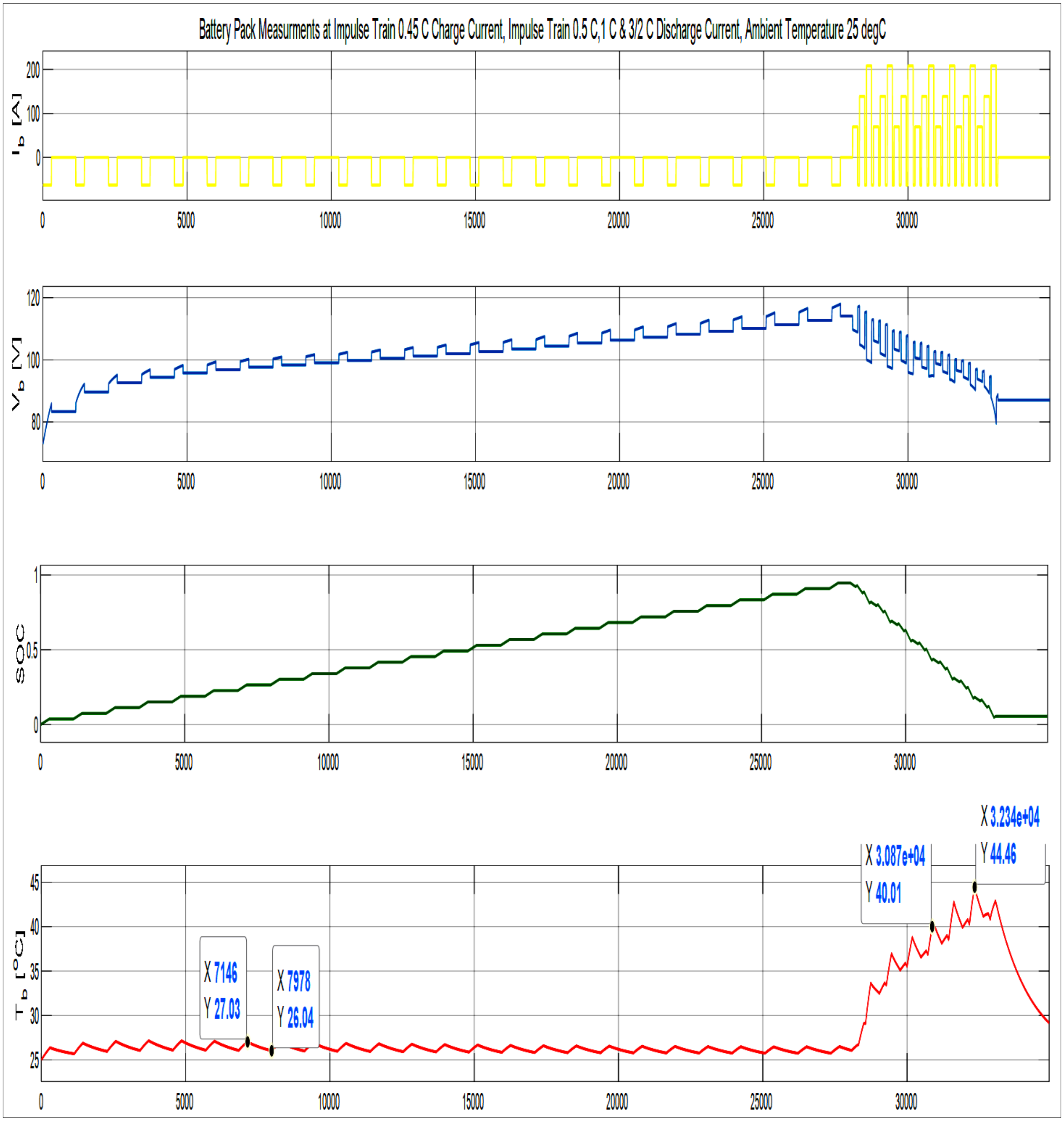
c) $T_{amb} = 0^oC$



Output:

Battery pack temperature reaches a maximum of 29.4°C during last 1.5 C impulse of the test cycle. The temperature is kept within its normal operating range, so no restrictions exist on current profile tested.

d) $T_{amb} = 25^oC$



Output:

Battery pack temperature exceeds 40°C after 8.75 hrs of testing during the third impulse discharging of 1.5 C rate. The temperature increases to reach a maximum of 44.5°C. Hence, for an ambient temperature above 25°C, amount of discharged current should be controlled to keep battery temperature below its upper limit.

e) $T_{amb} = 40^oC$

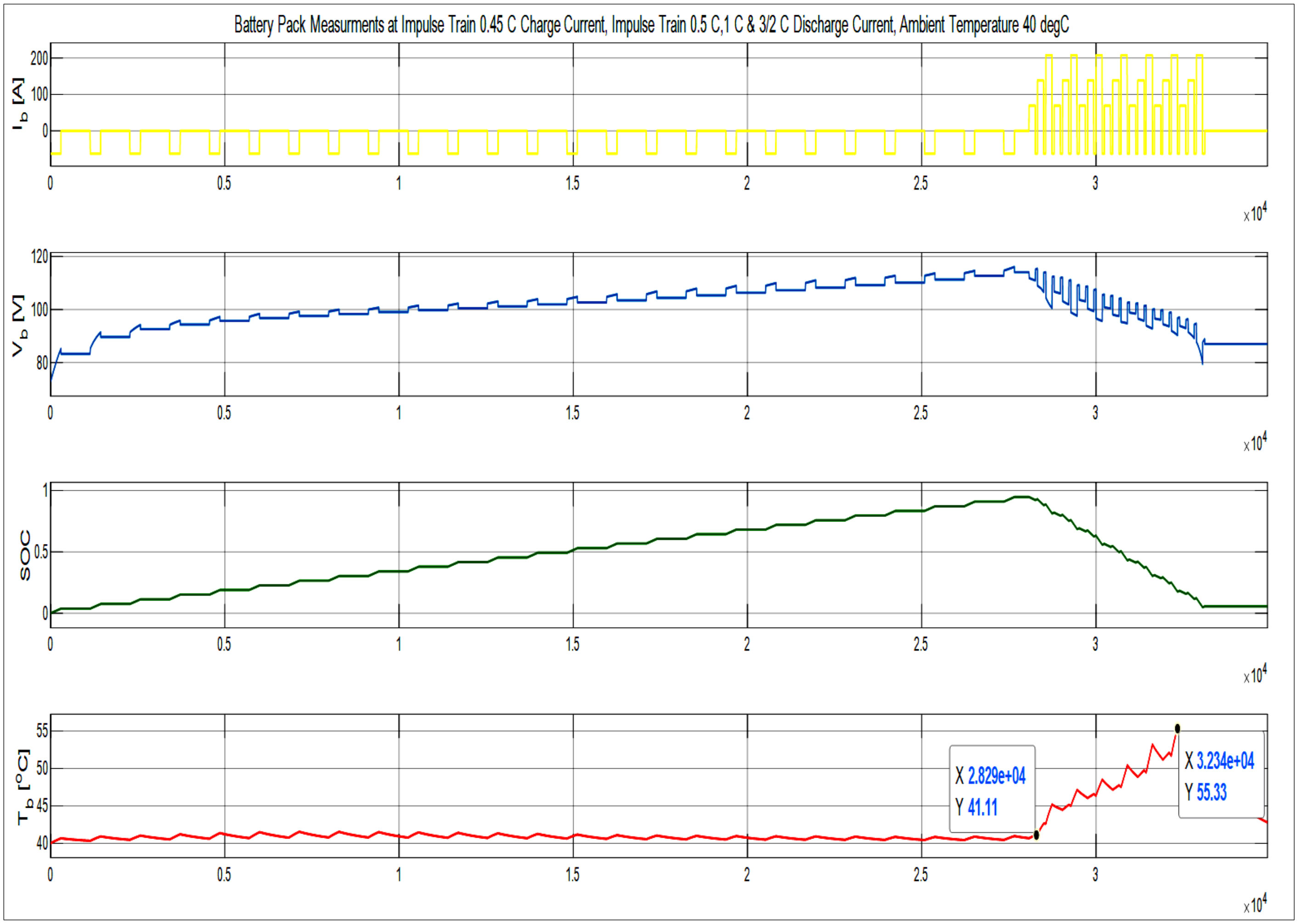


Figure 30: Battery Pack Behavior under Impulse Train 0.45 C charging, Impulse Train 0.5 C, 1 C and 1.5 C Discharging.

Output:

Testing at an ambient temperature of 40°C, battery pack temperature increases from 40°C to reach a maximum of 55.3°C.

Test Results Analysis:

As shown in the tests done early, a continuous cyclic discharging at 1 C and 1.5 C rate is possible for an ambient temperature below 0°C as the battery pack temperature didn't exceed 40°C. However, when discharging at an ambient temperature above 0°C, a limitation should be considered on the time of discharging at both 1 C and 1.5 C rates to avoid temperature increase to a value above 40°C. Consecutive Impulse charging and discharging cycles at ambient temperature below 25°C could be applied without risking battery performance while at high ambient temperature, careful consideration should be taken on the duration and amplitude of such impulses and an active cooling system should be implemented when necessary.

10. Simulation of Battery Pack Model Over Different Driving Cycles

The model of the battery pack will be coupled with the vehicle dynamics model of Fiat Panda first series and tested under the following driving cycles:

- NEDC Cycle
- WLTP Cycle

Note that the complete model of the vehicle has already been done and provided as a Simulink model as illustrated in the following figure.

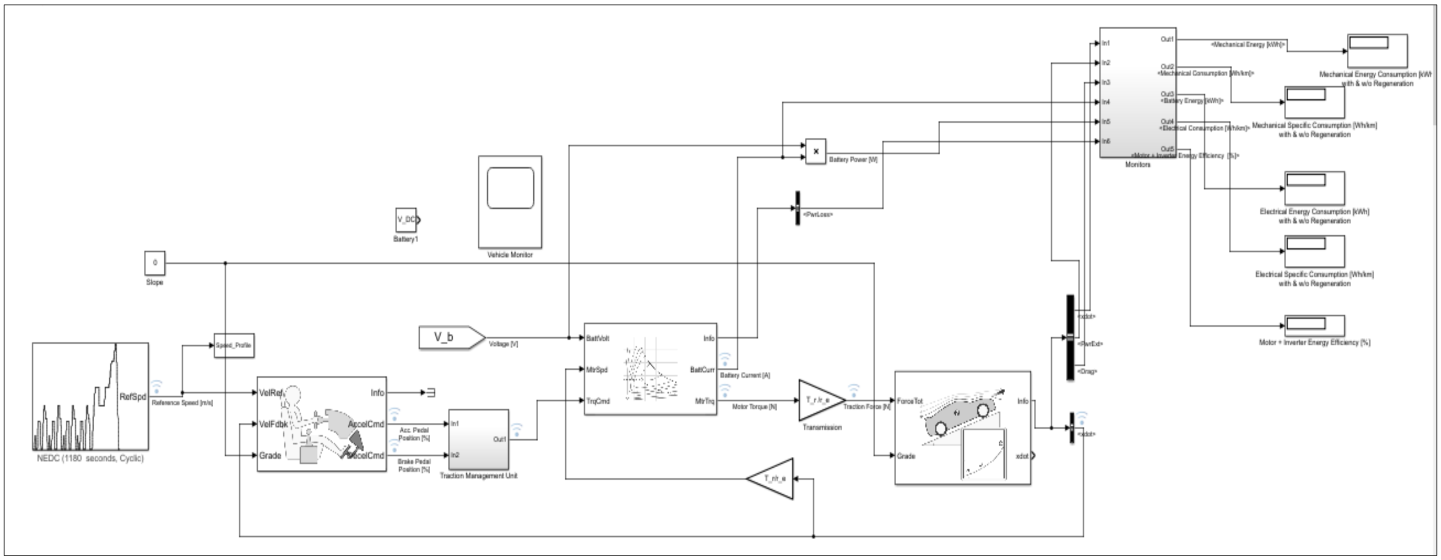


Figure 31: Vehicle Dynamics Block Diagram.

The figure below shows the coupling between the traction system and the accumulation system (battery pack).

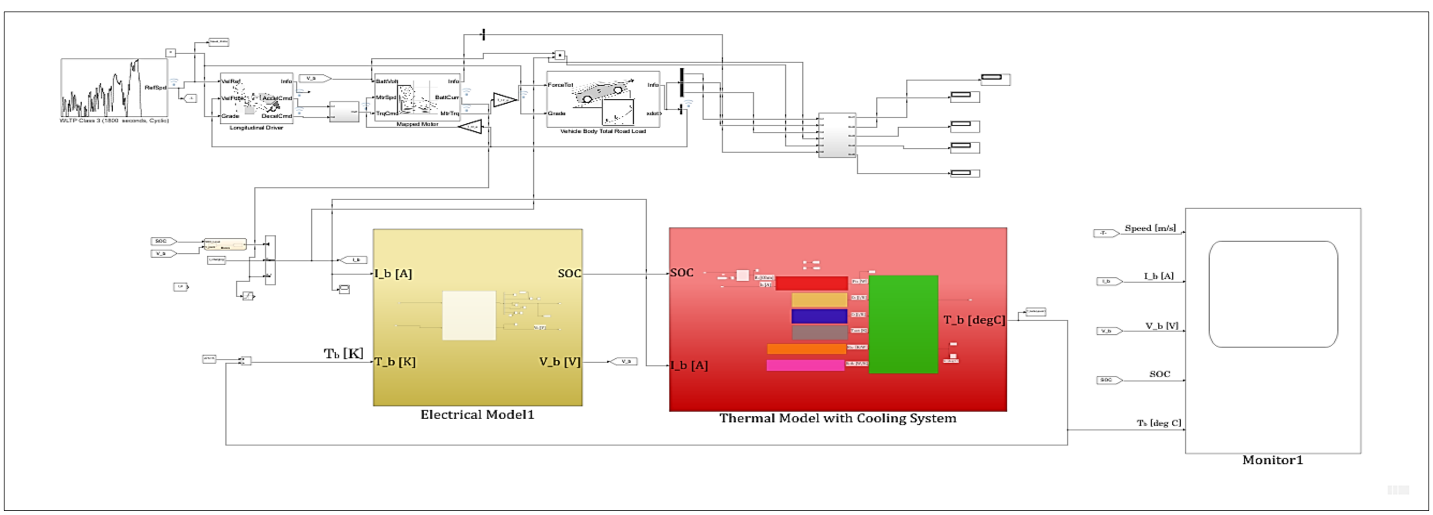


Figure 32: Traction and Accumulation Systems' Coupling.

A) Testing Under NEDC Drive Cycle:

Ambient Temperature: **0°C**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

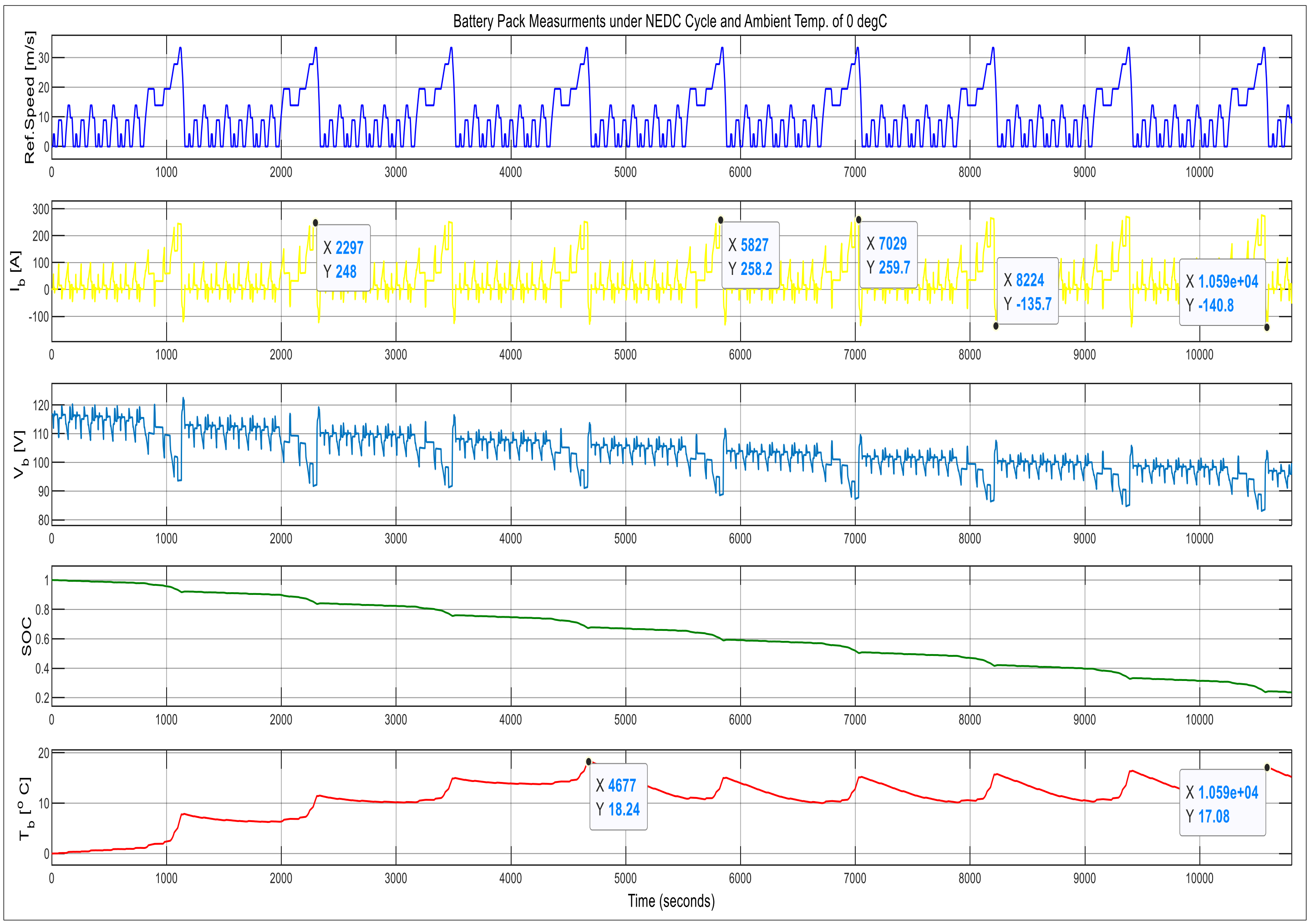


Figure 33: Battery Pack Behavior under NEDC Drive Cycle and Ambient Temperature of 0 degC.

Driving under NEDC cycle with regenerative breaking, the temperature of the battery pack increases from 0°C to reach 18.2°C after 1.3 hours of testing. Note that regenerative breaking leads to a charging current of 140.8 A which is higher than the maximum allowable charging current of the battery pack so a controller should limit the charging current received by regenerative breaking or release it if the temperature of the battery is reaching its upper limit.

Ambient Temperature: **25^{o}C**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

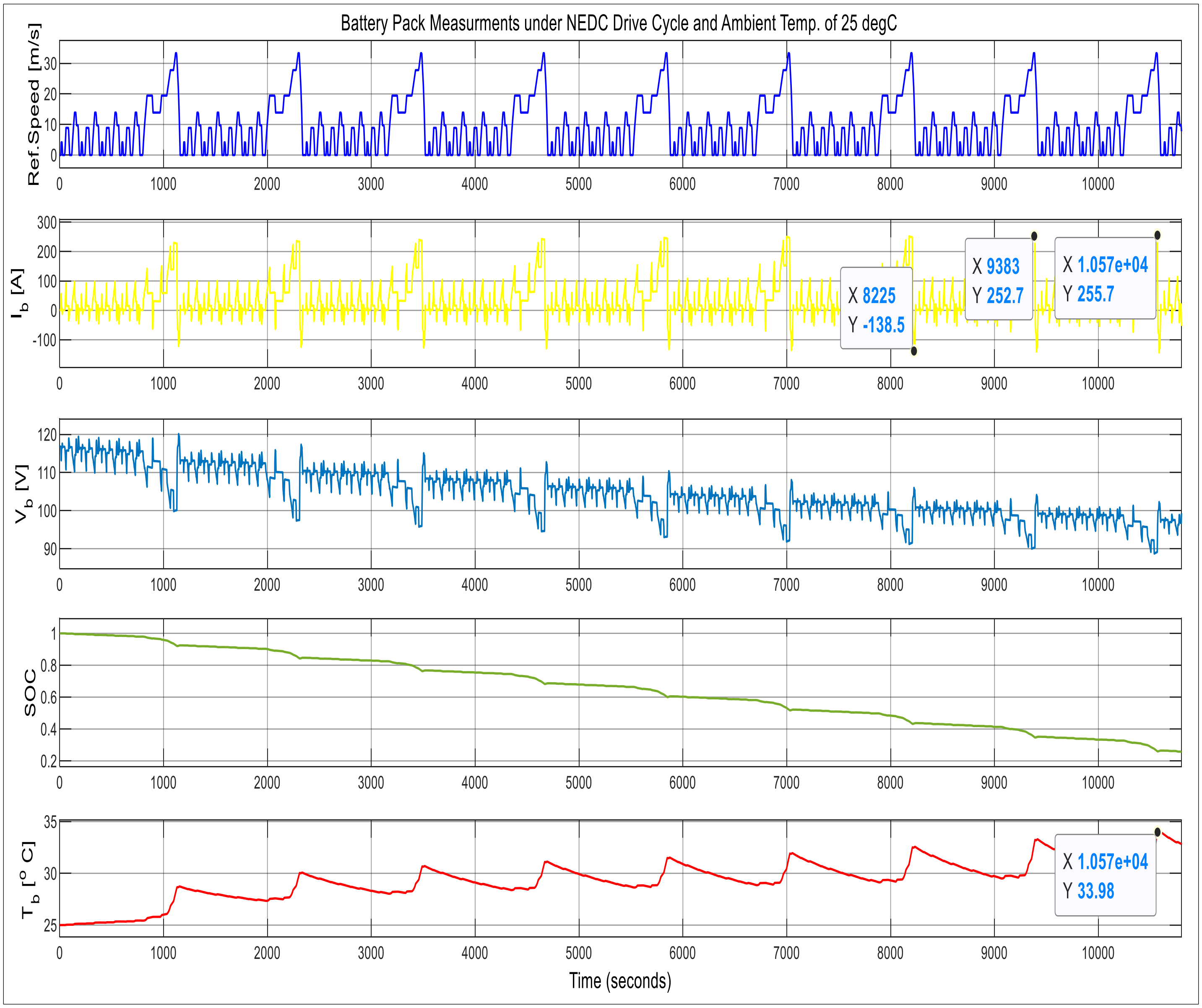


Figure 34: Battery Pack Behavior under NEDC Drive Cycle and Ambient Temperature of 25 degC.

Driving under NEDC cycle with regenerative breaking, the temperature of the battery pack increases from 25^{o}C to reach 34^{o}C after 3 hours of testing. The temperature is kept under its normal operating temperature range.

Ambient Temperature: **40°C**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

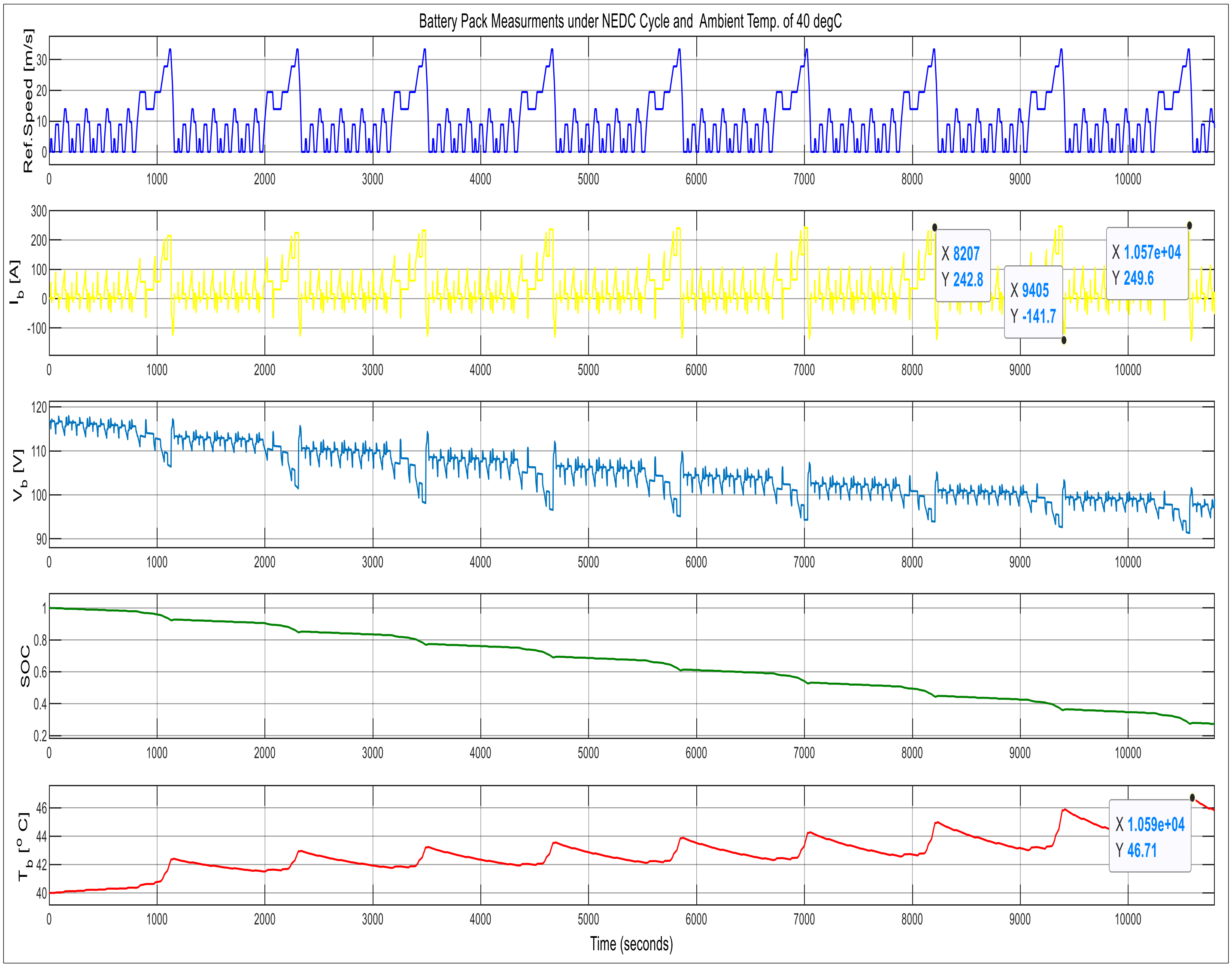


Figure 35: Battery Pack Behavior under NEDC Drive Cycle and Ambient Temperature of 40 degC.

Testing under 40°C, battery pack temperature increases to reach a maximum temperature of 46.7°C after 2.94 hours of testing. To reduce this temperature, an active cooling system is required to extract more heat from the battery and a management of the amount and duration of discharged current should be taken into consideration.

B) <u>Testing Under WLTP Drive Cycle:</u>

Ambient Temperature: **0°C**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

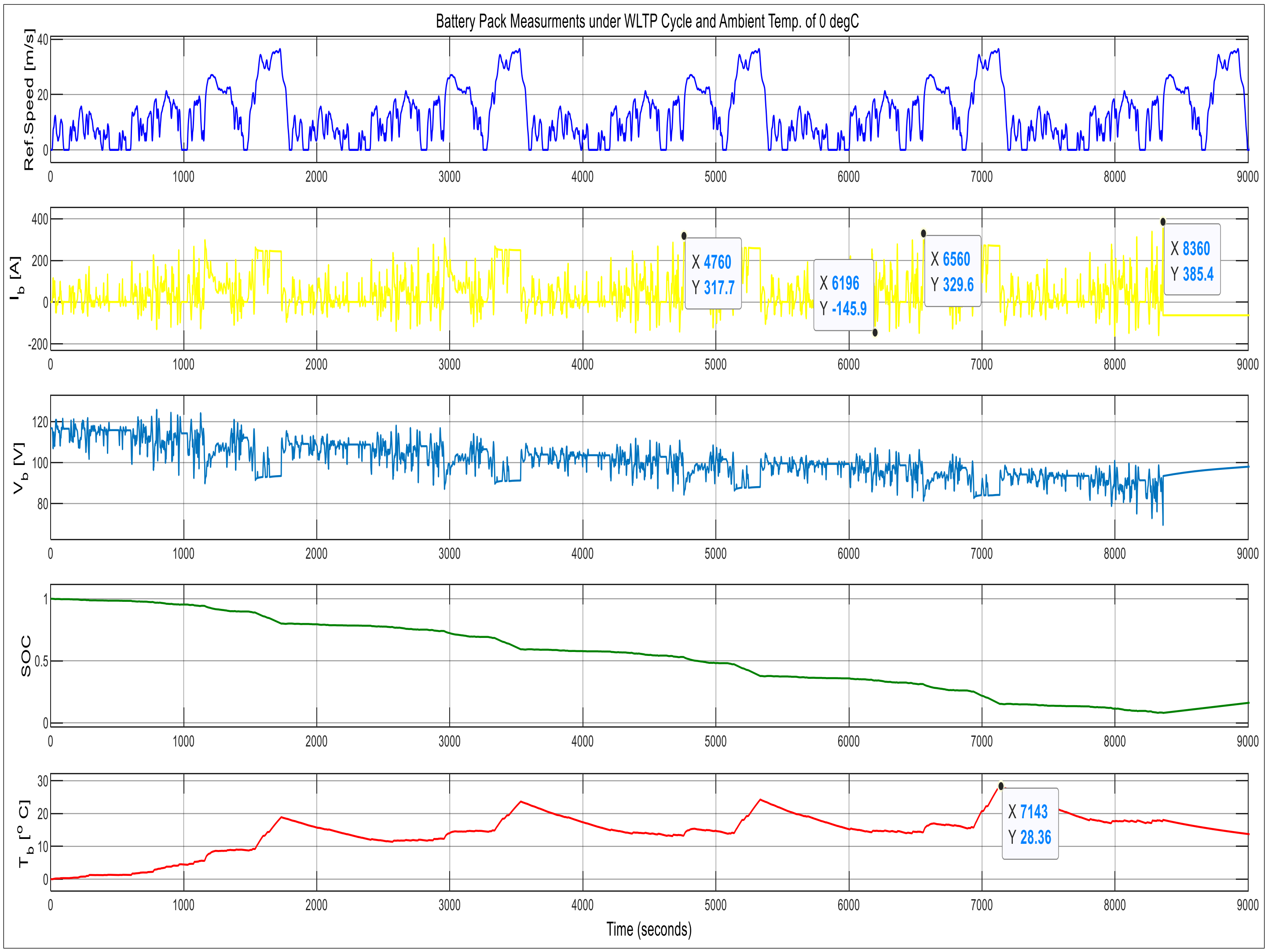


Figure 36: Battery Pack Behavior under WLTP Drive Cycle and Ambient Temperature of 0 degC.

Testing under an ambient temperature of 0°C, battery pack temperature reaches a maximum of 28.6°C to stay under normal temperature operating range. Note that the amount of needed current during certain points in the cycle exceeds the maximum capability of the battery which will limit the acceleration requirements of the vehicle.

Ambient Temperature: **25ºC**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

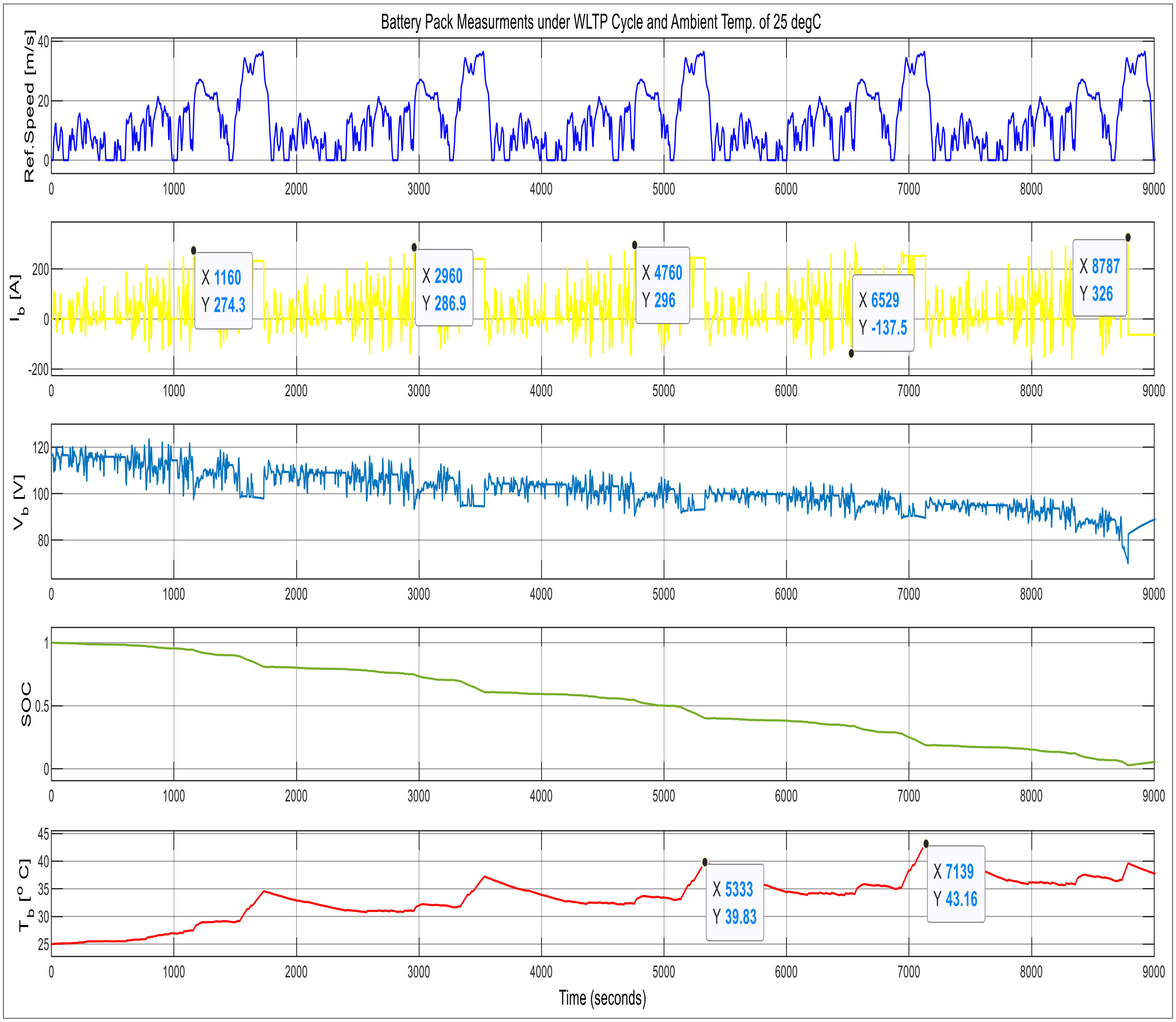


Figure 37: Battery Pack Behavior under WLTP Drive Cycle and Ambient Temperature of 25 degC.

Driving under WLTP cycle with regenerative breaking, the temperature of the battery pack crosses 40ºC after 1.5 hours of testing and reaches a maximum of 43.2ºC after 1.98 hours.

Ambient Temperature: **40°C**

Initial SOC: 100%

Discharging Current: Variable according to the load demand of the vehicle.

Charging Current: Variable based on regenerative braking when SOC>0 and fixed at 0.45 C when battery is fully discharged.

Time of the test: 3 hours (10,800 seconds)

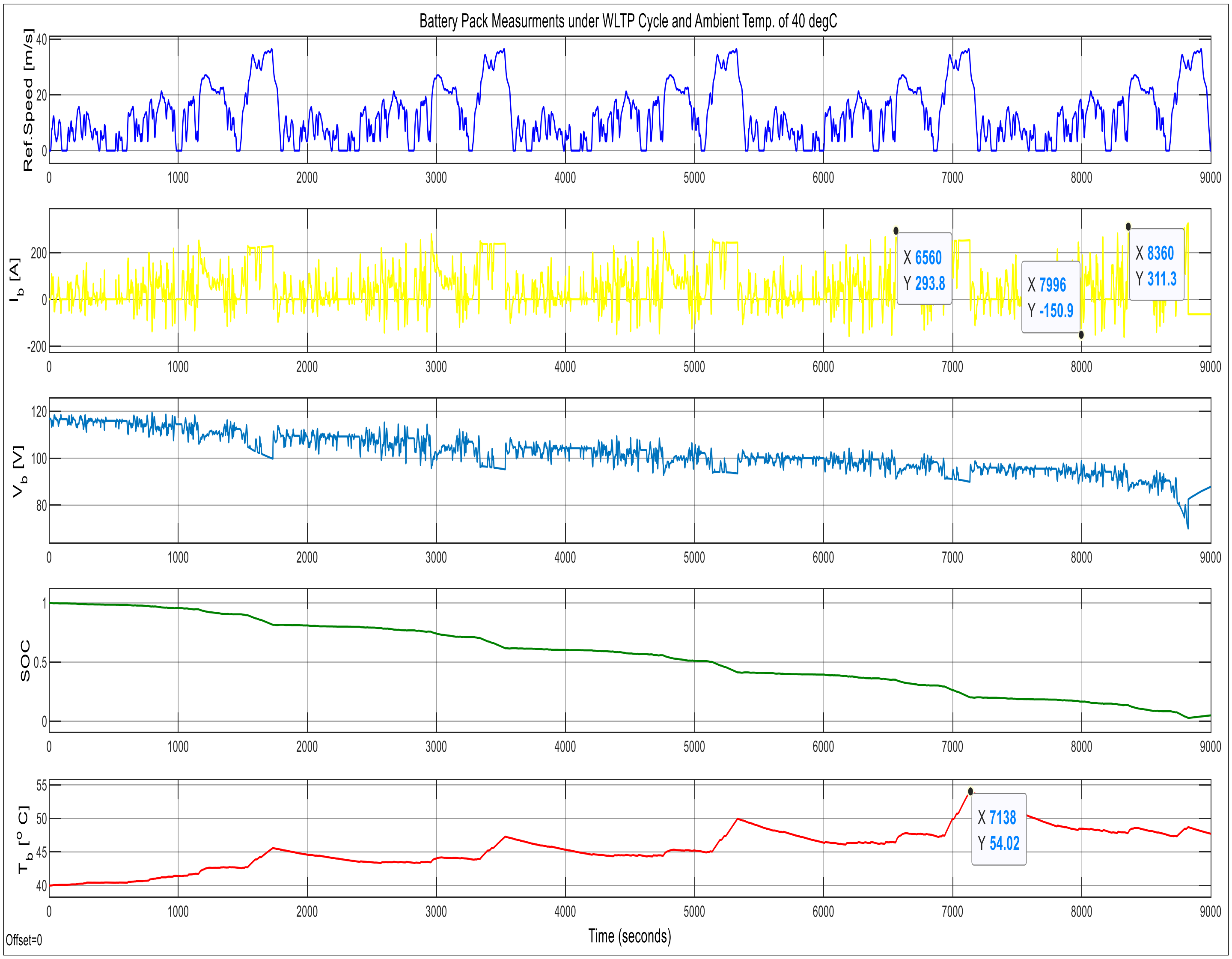


Figure 38: Battery Pack Behavior under WLTP Drive Cycle and Ambient Temperature of 40 degC.

As the ambient temperature increased to 40°C, battery pack temperature reached a maximum of 54°C. As mentioned earlier, with high ambient temperatures, careful consideration should be taken on the amount and duration of the pumped out current of the battery and an active cooling system is required to overcome passive cooling system limitations.

11. Summary

In this paper, electrical/thermal modelling of Lithium-ion battery pack was created on Simulink software to analyze battery behavior under different charging/discharging cycles. The electrical model was based on "Battery Datasheet" block found in Simulink library. The advantage of this block is that it estimates the behavior of Li-ion battery based on the basic data found in batteries' datasheet. Panasonic NCR18650B battery cell was used to estimate parameters of the electrical model and so OCV and internal resistance were generated from the datasheet and imported in the electrical model. Thermal model was then created based on the assumption that heat generated inside battery was only due to joules effect, so the energy stored inside the battery was simply the amount of heat generated by the battery subtracted by the heat dissipated to the cooling system. The cooling system designed was liquid plate cooling system installed at the bottom side of the battery pack with its parameters estimated based on a nominal heat generation of 768 W at 1-C discharge rate. A coupling between electrical and thermal model was then done to create the full model of the battery pack. To validate the model, Samsung SDI 98.6 Ah battery experimental tests were provided as a reference to compare its results with the results obtained using our virtual model. The comparison showed that the virtual model was able to represent actual battery behavior up to $\pm 2\ V$ difference on battery voltage and $\pm$ 4^{o}C difference on battery temperature. After validating the model, several charging/discharging tests were done on Panasonic 138.6 Ah battery pack to analyze its behavior. The results showed that at low ambient temperature, impulse and continuous discharging at a rate below 1.5 C rate was possible without exposing the battery to reach its upper limit temperature whereas at high ambient temperature, careful consideration should be taken on the amount and duration of discharged current to keep battery temperature within its acceptable limits. At the end, Panasonic battery pack model was coupled with vehicle dynamic model of Fiat Panda first series to analyze its behavior under NEDC and WLTP drive cycles at different ambient temperatures. It was noticed that for an ambient temperature below 25^{o}C, driving for three hours under NEDC cycle didn't expose battery temperature to exceed its upper limit while under WLTP cycle, the temperature exceeds 40^{o}C after 1.5 hours. Another notification was that when driving under WLTP cycle, the amount of required discharge current at certain points of the cycle exceeds the maximum capacity of the battery pack which in its turn will lead to a decrease in the acceleration requested by the car. A possible future project would be design of a predictive control algorithm to predict the temperature of the battery when a certain current is required to approve the amount and duration of discharged current that the battery can deliver without exposing its performance.

Appendix A: Matlab Code – Parameters Generation of 138.6Ah Battery

```
clc
clear all
close all
% Note: The following line should be changed to the directory where "exp_data.mat"
file is located in the PC drive
load(fullfile('','Panasonic DataSheet','exp_data.mat'))
batt_id = 'Lithium Ion High Energy Density 3.3Ah';
label = 'LiIon';
current_label = {'0p66A','1p65A','3p3A','6p6A','3p3A','3p3A','3p3A','3p3A'};
current = [0.66 1.65 3.3 6.6 3.3 3.3 3.3 3.3];
temperature_label = {'25C','25C','25C','25C','N20C','N10C','0C','40C'};
temperature = [25 25 25 25 -20 -10 0 40];
line_colors = {'r','g','b','c','m','y','b','r'};
markerType1 = {'none', 'none', 'o', 'none', 'none', 'none', 'none', 'none'};
figure(1);
grid on ;
subplot(2,1,1);hold on;
for j=1:4
data = ['LiIon_' current_label{j} '_' temperature_label{j} '_Panasonic'];
plot(exp_data.(data)(:,1),exp_data.(data)(:,2),'color',line_colors{j},'Marker',mark
erType1{j});
end
title(['Discharge Characteristics of LiIon Battery' sprintf('\n\n') 'Discharge
Characteristics at Constant 25 \circC']);
xlabel('Discharge Capacity [mAh]')
ylabel('Voltage [V]');
legend({'0.2C','0.5C','1.0C','2.0C'},'Location','EastOutside')
grid on
hold off;

subplot(2,1,2);hold on;
for j=[3 5:8]
data = ['LiIon_' current_label{j} '_' temperature_label{j} '_Panasonic'];
plot(exp_data.(data)(:,1),exp_data.(data)(:,2),'color',line_colors{j},'Marker',mark
erType1{j});
end
title('Temperature Characteristics at Constant 3.3A');
xlabel('Discharge Capacity [mAh]')
ylabel('Voltage [V]');
ylim([2.5 4.5]);
legend({'25 \circC','-20 \circC','-10 \circC','0 \circC','40
\circC'},'Location','EastOutside')
grid on
hold off;

%% Step 2: Normalize State-of-Charge (SOC) Data
ref_exp = 3;
val_exp = logical([1 0 0 0 1 0 0 0]);
ref_curr = current == current(ref_exp);
ref_temp = temperature == temperature(ref_exp);

[sort_current, sort_index_current] = sort(current(ref_temp));
[sort_temp, sort_index_temp] = sort(temperature(ref_curr));
N = length(current); % Number of experiments
```

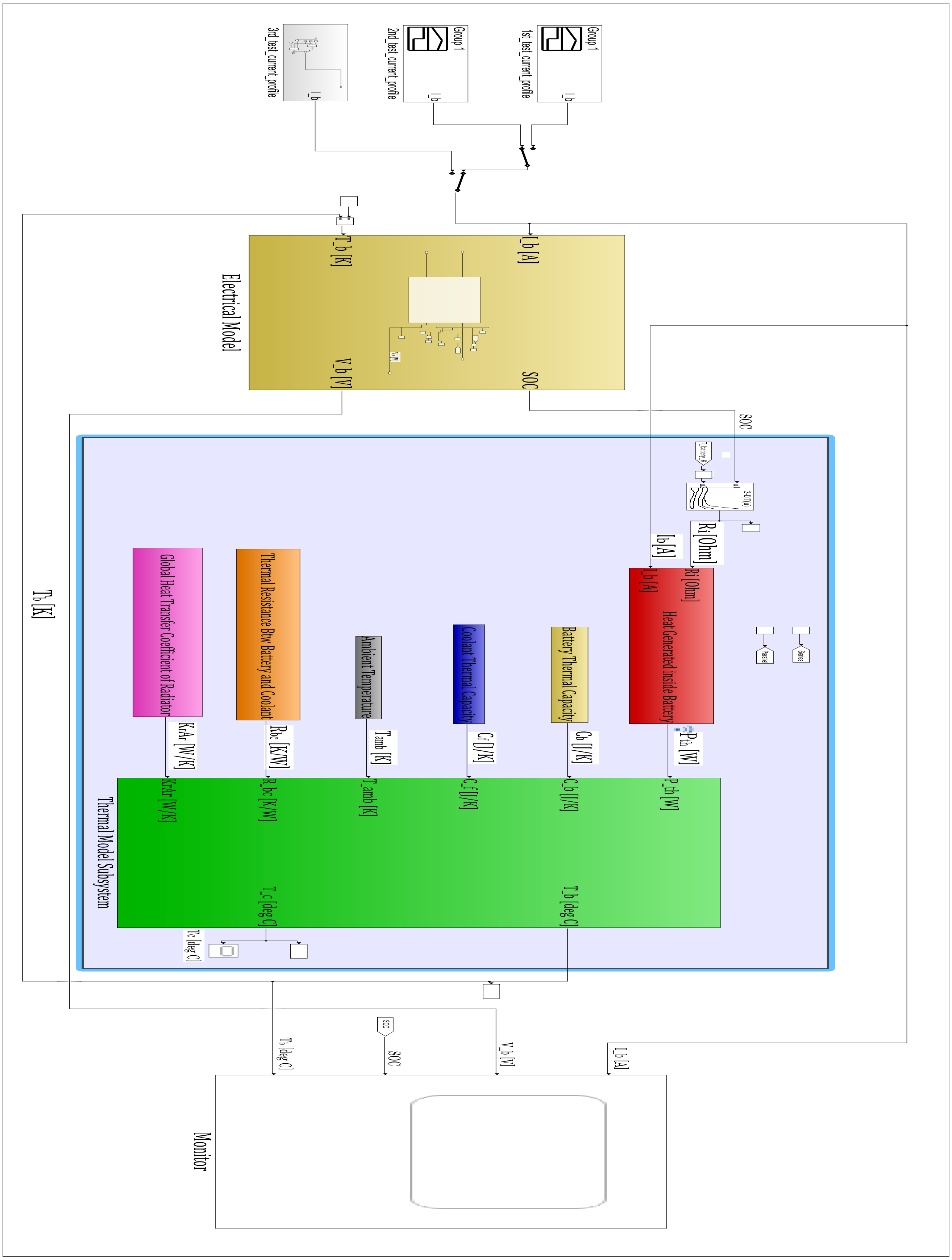
```
for i=1:N
    x.(['curr' current_label{i} '_temp' temperature_label{i}]) = ...
            exp_data.([label '_' current_label{i} '_' temperature_label{i}
'_Panasonic'])(:,1)/...
            exp_data.([label '_' current_label{i} '_' temperature_label{i}
'_Panasonic'])(end,1);
    % Calculate actual capacity for each datasheet
    correct_cap.(['curr' current_label{i} '_temp' temperature_label{i}]) = ...
            exp_data.([label '_' current_label{i} '_' temperature_label{i}
'_Panasonic'])(end,1);
end
%% Normalized SOC Data
figure(2);
count = 1;
hold on
for i=find(ref_temp)
    p1 = plot(x.(['curr' current_label{i} '_temp' temperature_label{i}]),
exp_data.([label '_' current_label{i} '_' temperature_label{ref_exp}
'_Panasonic'])(:,2));
    leg{count}=['I = ' num2str(current(i)) ' A'];
    count = count+1;
end
legend(leg,'Location','EastOutside');
xlabel('1-SOC'); xlim([0 1]); ylabel('Voltage [V]');ylim([2.5 4.2]);
title(['Normalized SOC Data' sprintf('\n\n') batt_id ' '
temperature_label{ref_exp}]);
%% Step 3: Fit Curves
SOC_LUT = (0:.01:1)';
SOCbkpts = 0:.2:1;
for i=find(ref_temp)
    fitObj.(['fit' current_label{i}]) = ...
        fit(x.(['curr' current_label{i} '_temp' temperature_label{i}]),...
        exp_data.([label '_' current_label{i} '_' temperature_label{ref_exp}
'_Panasonic'])(:,2),'smoothingspline');
end
for i=find(ref_curr)
    fitObj.(['fit' temperature_label{i}]) = ...
        fit(x.(['curr' current_label{i} '_temp' temperature_label{i}]),...
        exp_data.([label '_' current_label{ref_exp} '_' temperature_label{i}
'_Panasonic'])(:,2),'smoothingspline');
end
Em_MAT = [];
for i=find(ref_temp)
    Em_MAT = [Em_MAT fitObj.(['fit' current_label{i}])(SOC_LUT)];
end
figure(3)
hold on
for i=1:10:length(SOC_LUT)

plot(sort_current,Em_MAT(i,sort_index_current))%,colorV{i},'Marker','o','MarkerFace
Color',colorF{i})
end
xlabel('Current [A]')
ylabel('Voltage [V]')
legend(num2str(flipud(SOC_LUT(1:10:end))),'Location','eastoutside')
title(['Curve Fitting' sprintf('\n\n') batt_id sprintf('\n') ...
    'Em Matrix of Cell/Module Voltage vs. Discharge ' ...
    sprintf('\n') 'Current at Different SOC']);
%% Step 4: Extrapolate Open Circuit Voltage
R0_refTemp = [];
for i=1:length(SOC_LUT)
    % Fit a line to V=f(I)
```

```
    fitSOC.(['SOC' num2str(i)]) =
fit(sort_current',Em_MAT(i,sort_index_current)','poly1');
end
Em = [];
for i=1:length(SOC_LUT)
    % Em = f(0)
    Em = [Em fitSOC.(['SOC' num2str(i)])(0)];
end
Em = Em';
%% Step 5: Determine Battery Voltage and Resistance at Different Temperatures
%Plot discharge curves at different temperatures
figure(4)
hold on
for i=find(ref_curr)
    plot(x.(['curr' current_label{i} '_temp' temperature_label{i}]), ...
        exp_data.([label '_' current_label{ref_exp} '_' temperature_label{i}
'_Panasonic'])(:,2));
end
legend(temperature_label(find(ref_curr)),'Location','eastoutside');
xlabel('1-SOC'); xlim([0 1]); ylabel('Voltage [V]'); title([batt_id ' '
current_label{ref_exp}]);
title(['Figure 4 - Battery Voltage' sprintf('\n\n') 'Battery Voltage at Different
Temperatures Under Constant Load']);
%%
R0_LUT = [];
for i=find(ref_curr)
    % Create fit object for V vs. SOC
    voltVsSOC.(['temp' temperature_label{i}]) = fitObj.(['fit'
temperature_label{i}])(SOC_LUT);
    % Calculate R0(SOC,T) assuming linear behavior R0 = DeltaV / I
    R0.(['temp' temperature_label{i}]) = (Em - voltVsSOC.(['temp'
temperature_label{i}]))./current(ref_exp);
    % Construct LUT
    R0_LUT = [R0_LUT R0.(['temp' temperature_label{i}])];
end
if ~isempty(find(SOC_LUT==0.9, 1))
    R0_LUT(SOC_LUT>0.9,:) = repmat(R0_LUT(SOC_LUT ==
0.9,:),length(R0_LUT(SOC_LUT>0.9,:)),1);
else
    [closestTo0p9, locClosestTo0p9] = min(abs(SOC_LUT-0.9));
    R0_LUT(SOC_LUT>closestTo0p9,:) = repmat(R0_LUT(locClosestTo0p9,:),...
                                    length(R0_LUT(SOC_LUT>closestTo0p9,:)),1);
end
R0_LUT = max(R0_LUT,0);
T_LUT = 273.15 + temperature(ref_curr);
[T_LUT1,idx] = sort(T_LUT);
xtmp=R0_LUT';
R0_LUT1(1:length(T_LUT),:) = xtmp(idx,:);
% Plot battery resistance at different temperatures

figure(5)
grid on ;
plot(SOC_LUT,R0_LUT)
legend({'25 \circC','-20 \circC','-10 \circC','0 \circC','40
\circC'},'Location','eastoutside');
xlabel('1-SOC'); xlim([0 1]); ylabel('Resistance [\Omega]');
title(['Battery Resistance' sprintf('\n\n') 'Battery Resistance vs. SOC at
Different Temperatures']);
```

```
%% Step 7: Fit Battery Resistance

R0_brkpoints=[];
for q=1:length(SOCbkpts)
    R0_brkpoints=[R0_brkpoints find(SOC_LUT==SOCbkpts(q))];
end
R0_LUT_bkpts = [];
counter = 1;
for i=find(ref_curr)
    R0_LUT_bkpts = [R0_LUT_bkpts;R0_LUT1(counter,R0_brkpoints)];
    counter = counter+1;
end
%%
%% Lookup Table Breakpoints

Battery.SOC_LUT = [SOC_LUT]';
Battery.Temperature_LUT = T_LUT1;

%% Em Branch Properties (OCV, Capacity)

% Battery capacity
Battery.Capacity_LUT = [2.2 2.8 2.96 3.3 3.3]; %Ampere*hours

% Em open-circuit voltage vs SOC rows and T columns
Battery.Em_LUT = [Em Em Em Em Em]; %Volts
Battery.Em_LUT = flipud(Battery.Em_LUT);

%% Terminal Resistance Properties

% R0 resistance vs SOC rows and T columns
Battery.R0_LUT = R0_LUT1'; %Ohms

%% Thermal Properties

% Cell dimensions and sizes
cell_thickness = 18.5*10^-3; %m
cell_width = 18.5*10^-3; %m
cell_height = 65.3*10^-3; %m

% Cell surface area
cell_area = (2*pi()*(cell_width/2)^2) + (pi()*cell_width*cell_height); %m^2

% Cell volume
cell_volume = pi()* (cell_width/2)^2 * cell_height; %m^3

% Cell mass
Battery.cell_mass = 0.0485; %kg

% Volumetric heat capacity
% assumes uniform heat capacity throughout the cell
% ref: J. Electrochemical Society 158 (8) A955-A969 (2011) pA962
cell_rho_Cp = 2.04E6; %J/m3/K

% Specific Heat
% Battery.cell_Cp_heat = (cell_rho_Cp * cell_volume)/Battery.cell_mass; %J/kg/K
Battery.cell_Cp_heat =830; %J/Kg/K
```

```matlab
%% Initial Conditions

% Heating Power
P_PTC = -1000; % Watt

% Charge deficit
Battery.Qe_init = 0; %Ampere*hours

% Initial Temperatures
Battery.T_init = 40 + 273.15; %K
T_ambient= 40 + 273.15; %K
T_coolant_initial= 40 + 273.15; %K

% Cells in series
Ns=28;
% Cells in parallel
Np=42;
% Mass of Coolant
m_f= 11; %Kg

%m_f= 14.78904742; % in case of additional cooling plate from above

% Specific heat of Coolant
cp_f= 3403; %J/Kg/K

% Thermal Resistance between battery and coolant.
R_bc=0.033; %K/W
%R_bc=0.009253239; % in case of additional cooling plate from above

% Global Heat Transfer Coefficient of the Radiator
Kr_Ar=153.6; % W/K

% Max Battery Voltage
V_b_max=(Em(1)*Ns)+4;

% Battery Discharge Current in Amperes
I_d= 1*138.6;% Amperes
I_charging= -63; % Amperes
```

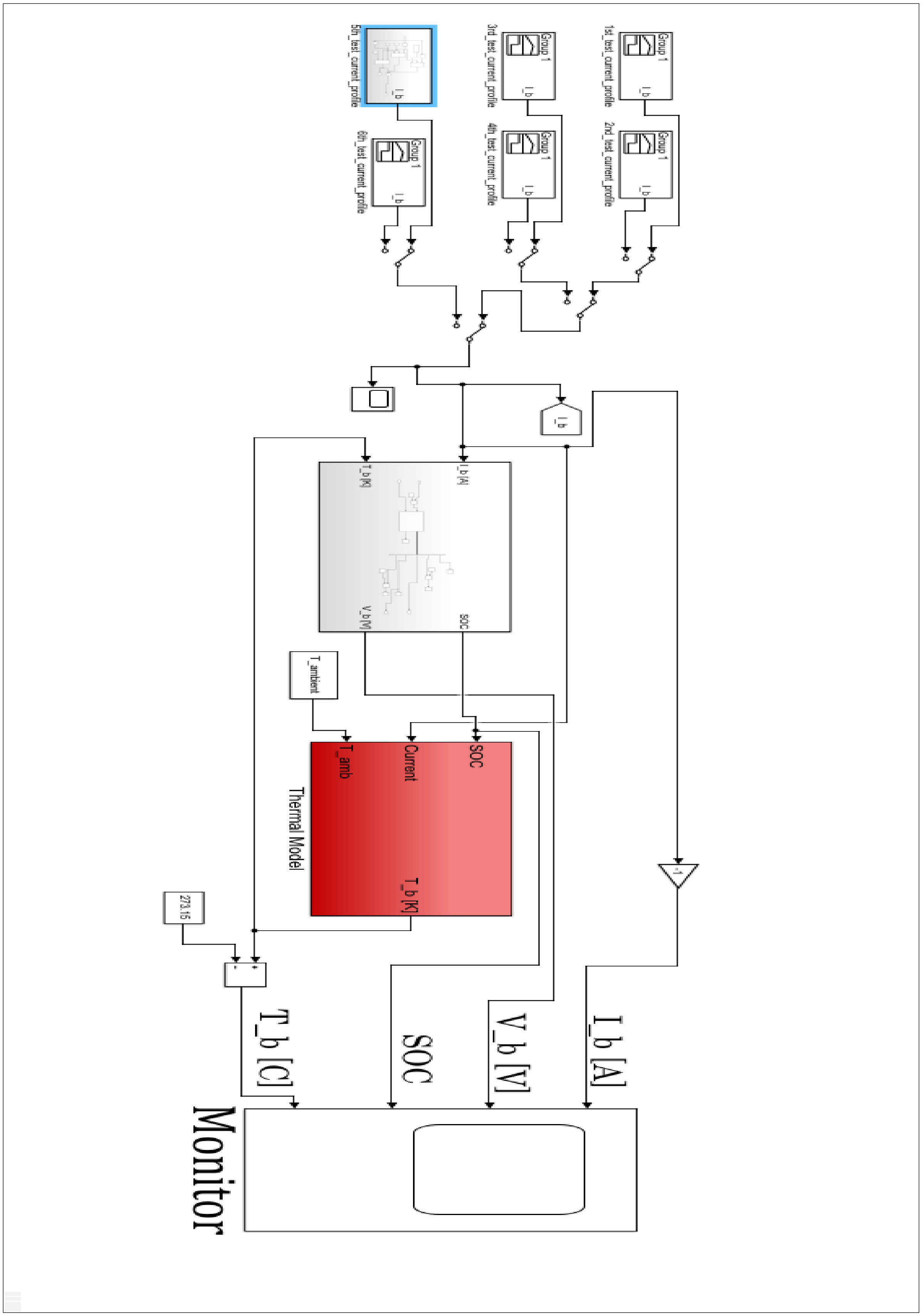
Appendix B: Simulink Model – Panasonic 138.6Ah Battery Pack Model



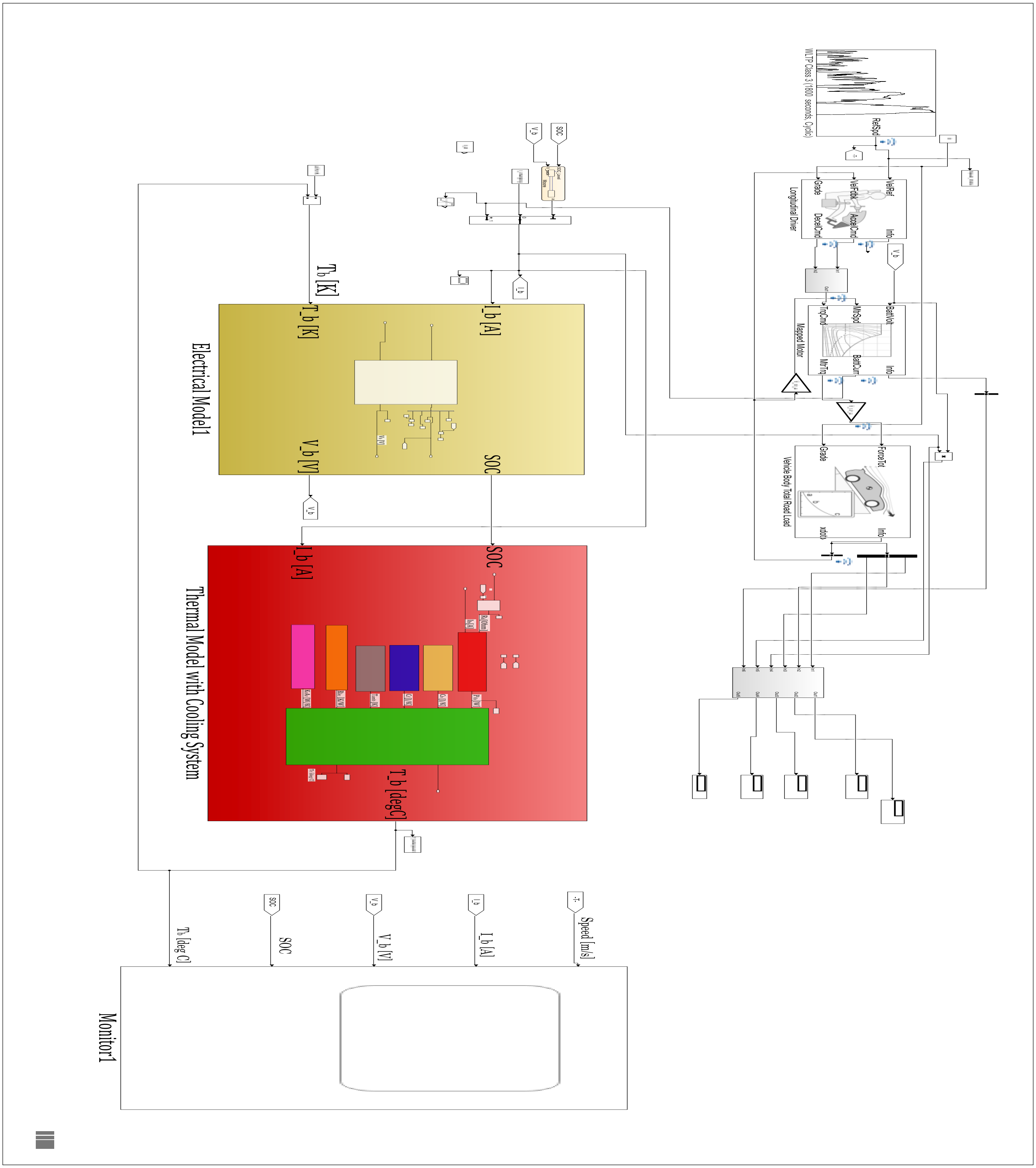
Appendix C: Matlab Code – Parameters Generation of 94Ah Samsung Battery

```
% Samsung Battery 94 Ah Datasheet Block Parameters
Em=[4.136 4.016 3.913 3.825 3.756 3.678 3.641 3.615 3.579 3.499 3.420]';
SOC_Brkpoints=0:0.1:1;
figure (1)
plot(SOC_Brkpoints,Em)
T_LUT=[248.15 273.15 298.15];
SOC_Resistance_Brkpoints= [0.2 0.3 0.5 0.9];
R_battery_Discharging=[19.61 10.69 5.09 4.39;5.07 3 2.44 2.32;1.03 0.91 0.9
0.94]*10^-3; %in Ohm
R_battery_Charging=[16.66 15.97 16.73 28.34;2.77 2.65 2.83 3.74;0.88 0.81 0.9
0.92]*10^-3; %in Ohm
figure (2)
for i=1:1:size(R_battery_Discharging,1)
    plot (SOC_Resistance_Brkpoints,R_battery_Discharging(i,:))
    hold on
end
hold off

% Cell dimensions and sizes
cell_thickness = 45*10^-3; %m
cell_width = 125*10^-3; %m
cell_length = 173*10^-3; %m

% Cell surface area
cell_area =
2*(2*(cell_thickness+cell_width)+2*(cell_thickness+cell_length)+2*(cell_width+cell_
length)); %m^2
% Cell volume
cell_volume = cell_thickness*cell_width*cell_length; %m^3
% Cell mass
Battery.cell_mass = 2.06; %kg
% Volumetric heat capacity
% assumes uniform heat capacity throughout the cell
% ref: J. Electrochemical Society 158 (8) A955-A969 (2011) pA962
cell_rho_Cp = 2.04E6; %J/m3/K
%Specific Heat
Battery.cell_Cp_heat = (cell_rho_Cp * cell_volume)/Battery.cell_mass; %J/kg/K
% Module Mass
module_mass= 27.5; %Kg
% Module Dimensions
Module_Height= 176*10^-3; %m
Module_Width= 206*10^-3; %m
Module_Thickness= 476*10^-3; %m
% Module Surface Area
Module_Surface_Area=
2*(2*(Module_Height+Module_Width)+2*(Module_Height+Module_Thickness)+(Module_Thickn
ess+Module_Width));
%% Initial Conditions
% Charge deficit
Battery.Qe_init = 0; %Ampere*hours
% Initial Temperatures
Battery.T_init = 35 + 273.15; %K
T_ambient= 32 + 273.15; %K
% Cells in series
Ns=10;
% Cells in parallel
Np=1;
```

Appendix D: Simulink Model – Samsung 94Ah Battery Model



Appendix E: Simulink Model – Panasonic 138.6Ah Battery with Fiat Vehicle Dynamics



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