POLITECNICO DI TORINO

Corso di Laurea in Ingegneria Dell'Autoveicolo

Presentazione della Tesi di Laurea Magistrale

Electro-Thermal Modelling of Lithium-Ion Battery

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Laureando:

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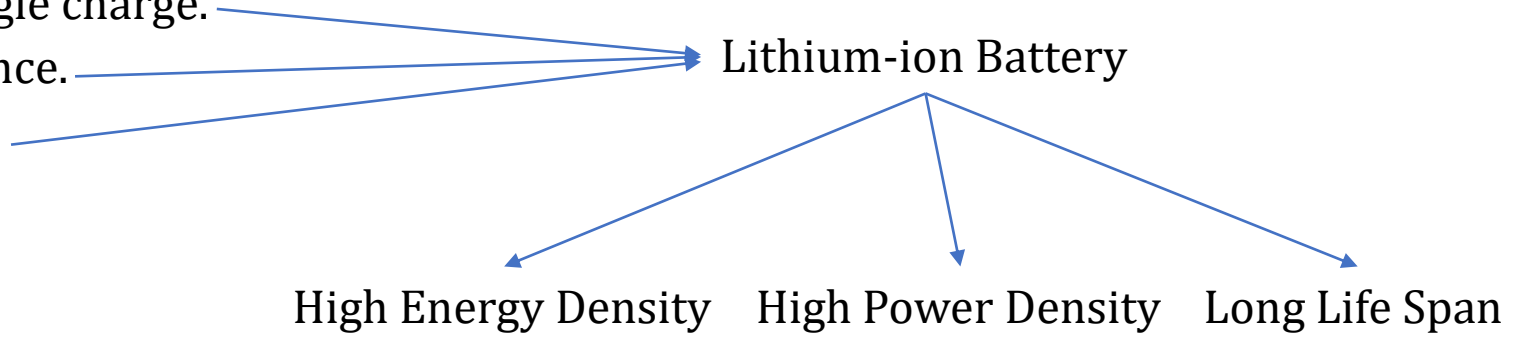
Outline

- Why Lithium-ion Batteries
- Battery Structure
- Battery Electrical Model
- Battery Thermal Model
- Battery Cooling-Heating System
- Battery Model Validation
- Panasonic 138.6 Ah Battery Pack Simulation
- Battery Pack Simulation under Different Drive Cycles.

Why Lithium-ion Battery

- Increased investments in EV's to:
  - Reduce gas emissions that affect climate change.
  - Account for fossil fuel degradation in the future.

- Automotive makers are looking to:
  - Increase travel distance in a single charge.
  - Improve acceleration performance.
  - Improve life time of the battery.



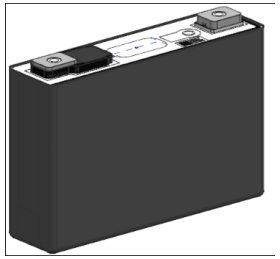
However, Li-ion battery is sensitive to temperature that greatly effects its performance and life time.

Thesis Objective: Create virtual electro-thermal model to study the thermal behavior of the battery under different charging/discharging tests.

Battery Structure

Battery Cell

Cylindrical



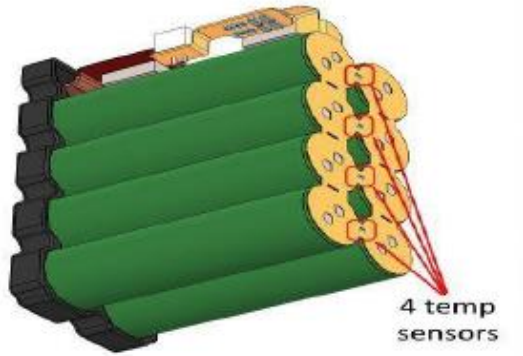
Prismatic

Grouped in Series/Parallel Config.

Battery Module

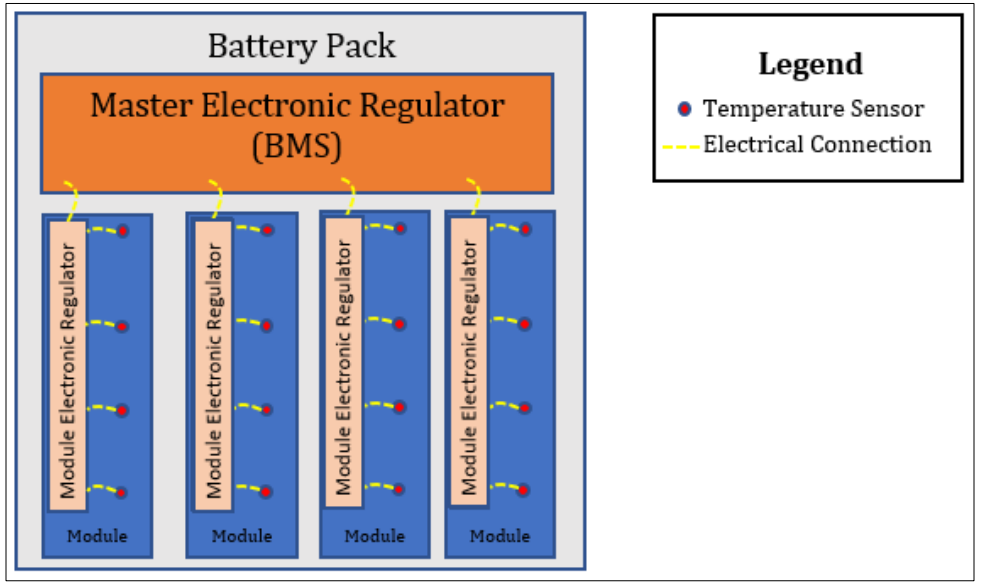
Electronic Regulator Monitors:

- Voltage
- Current
- Temperature



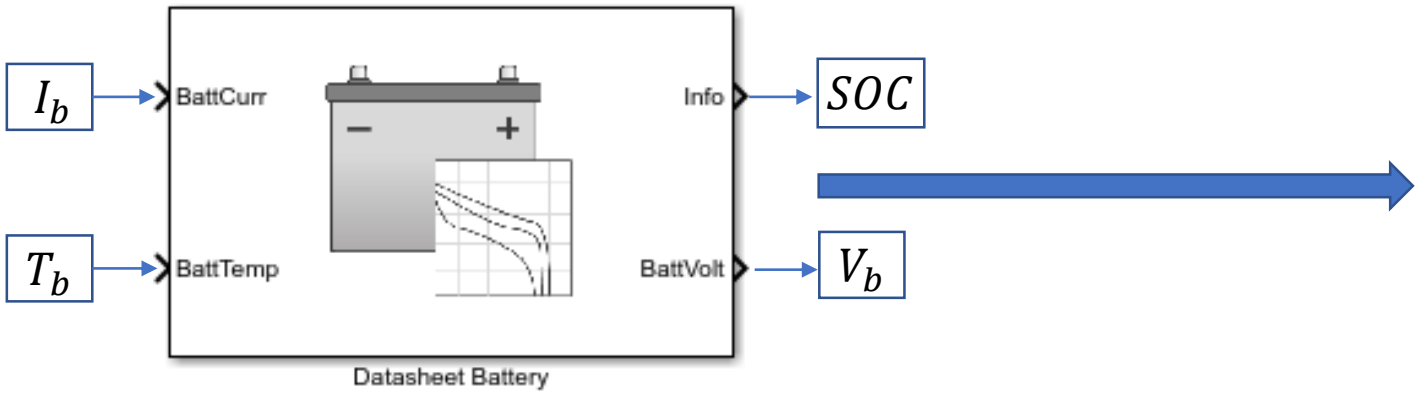
Grouped in Series/Parallel Config.

Battery Pack

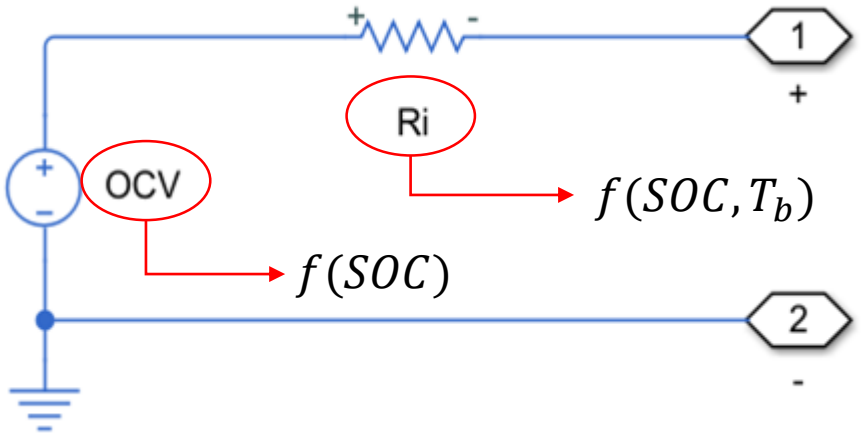


Battery Electrical Model

Datasheet Battery Block



Equivalent Circuit Model



Other Parameters:

- Number of Cells in series.
- Number of Cells in parallel.
- Initial and nominal battery capacity

Condensed model: from multiple temp. states to one temp. state

Available Data

Panasonic

Lithium Ion

NCR18650B

Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

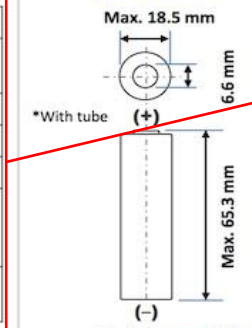
*At temperatures below 10°C, charge at a 0.25C rate.

Specifications

Rated capacity(1)	Min. 3200mAh
Capacity(2)	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

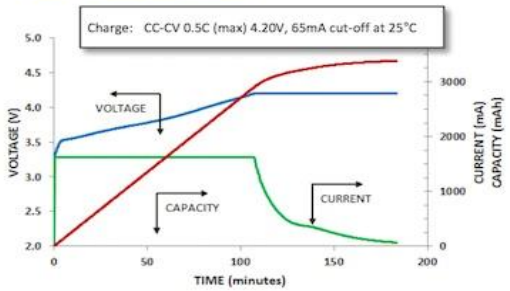
(1) At 20°C (2) At 25°C (3) Energy density based on bare cell dimensions

Dimensions

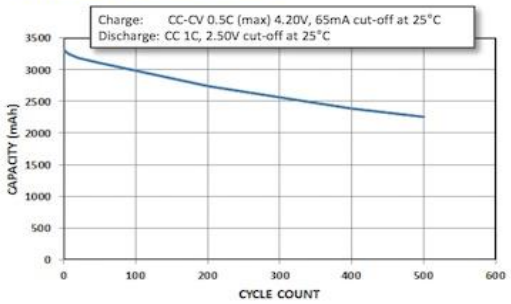


For Reference Only

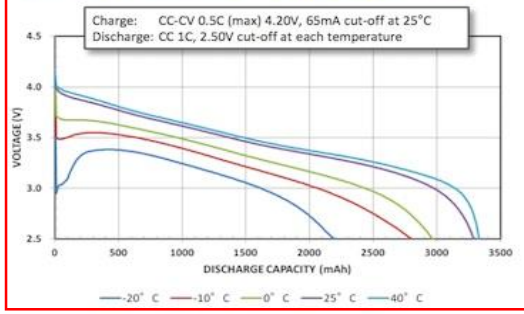
Charge Characteristics



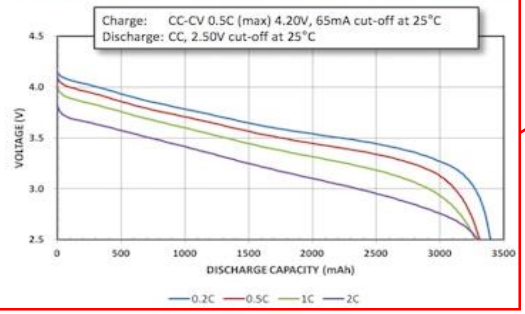
Cycle Life Characteristics



Discharge Characteristics (by temperature)

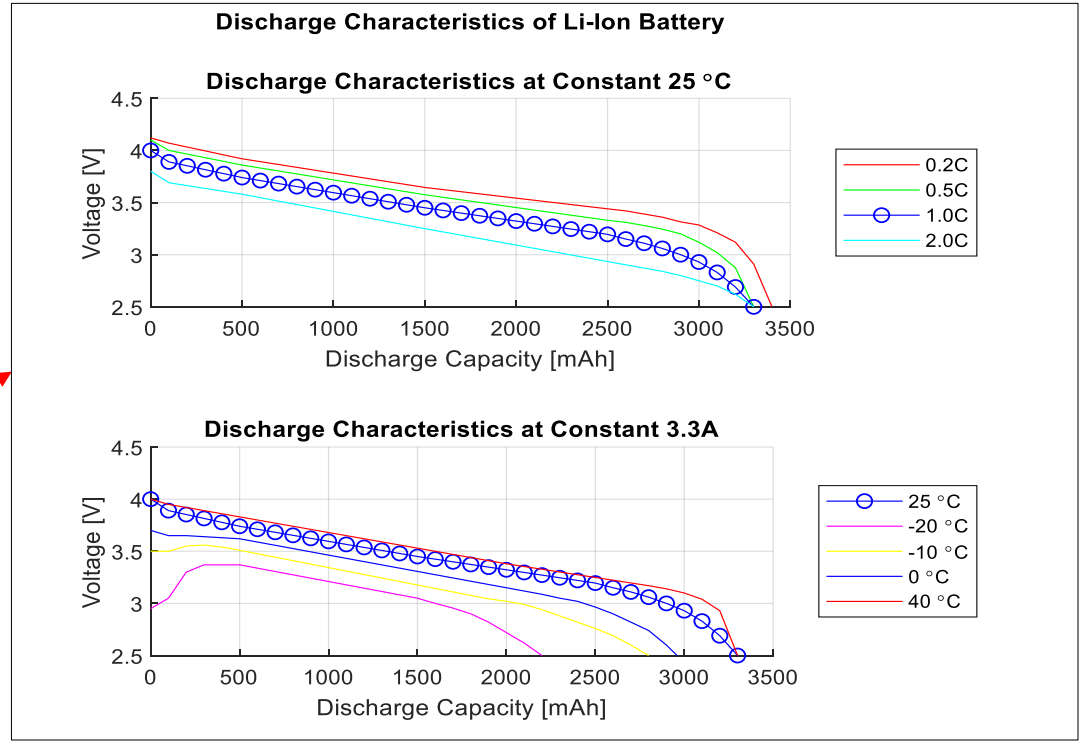


Discharge Characteristics (by rate of discharge)

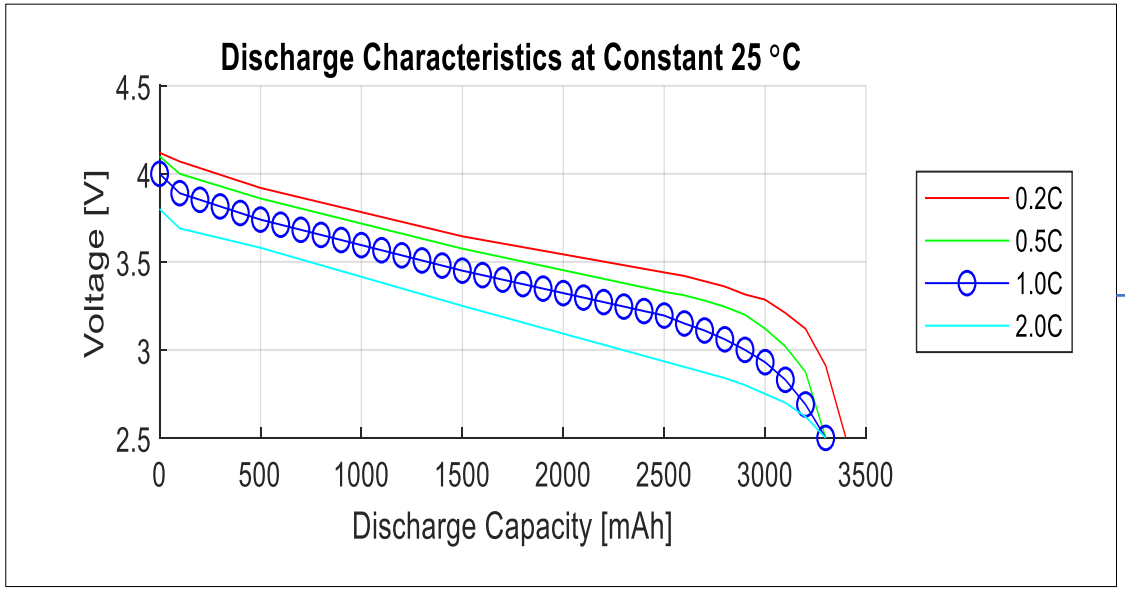


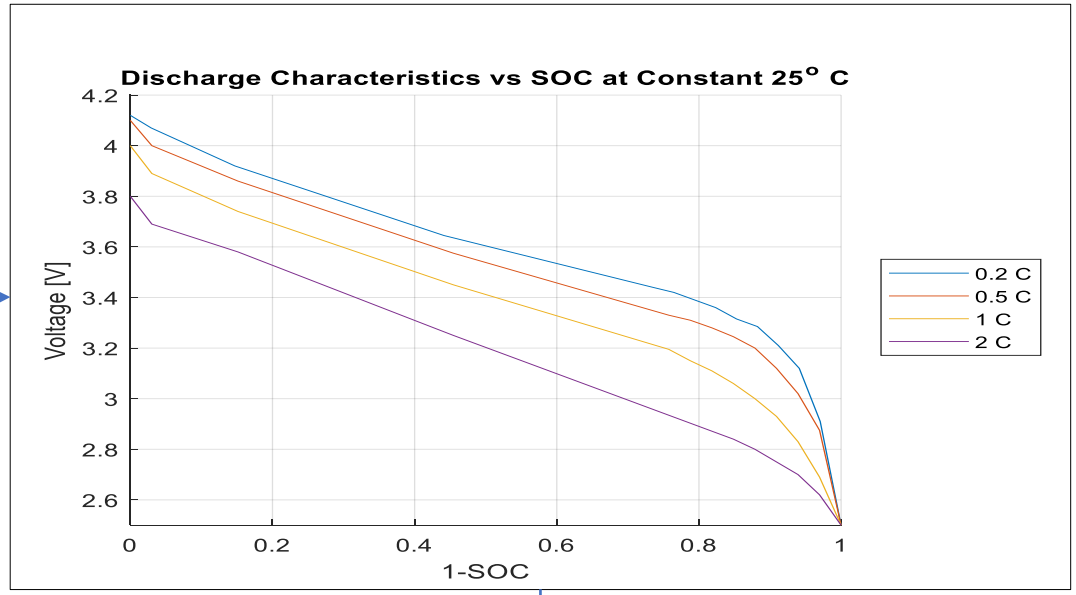
The data in this document is for descriptive purposes only and is not intended to make or imply any guarantee or warranty.

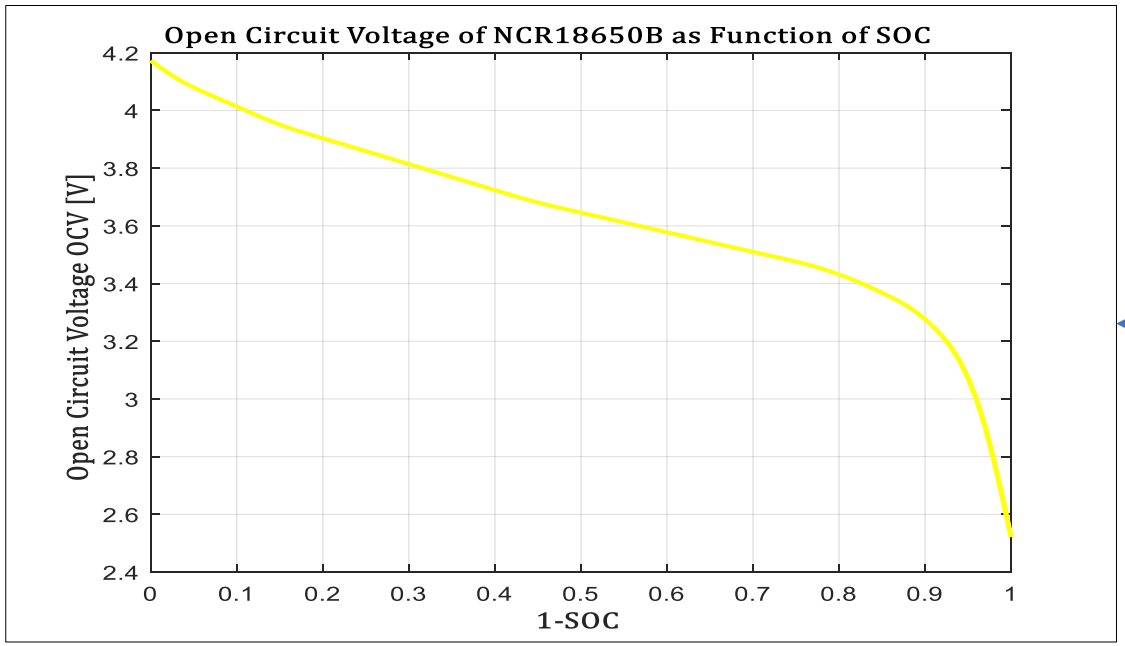
		Element	Module	Pack
Nominal voltage	*V*	**3.6**	**50.4**	**100.8**
Upper limit voltage	*V*	*4.2*	*58.8*	*117.6*
Lower limit voltage	*V*	*2.7*	*37.8*	*75.6*
Nominal capacity	*Ah*	**3.3**	**138.6**	**138.6**
Specific capacity	*Ah/kg*	68		
Nominal energy	*kWh*	**0.0119**	**6.99**	**13.97**
Specific energy (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
Life cycle	#			
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

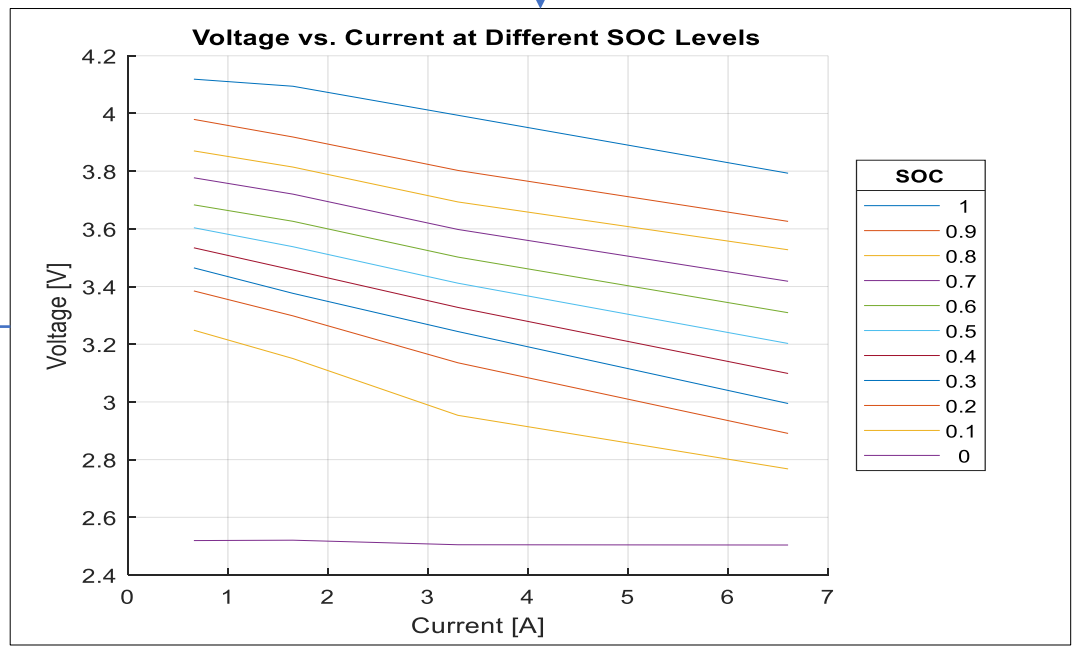


Open Circuit Voltage:



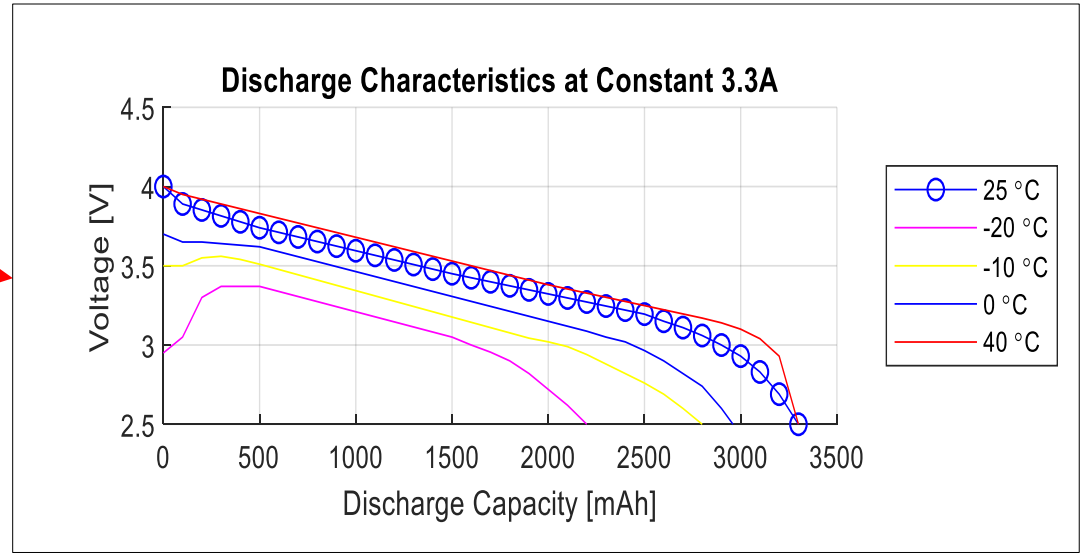


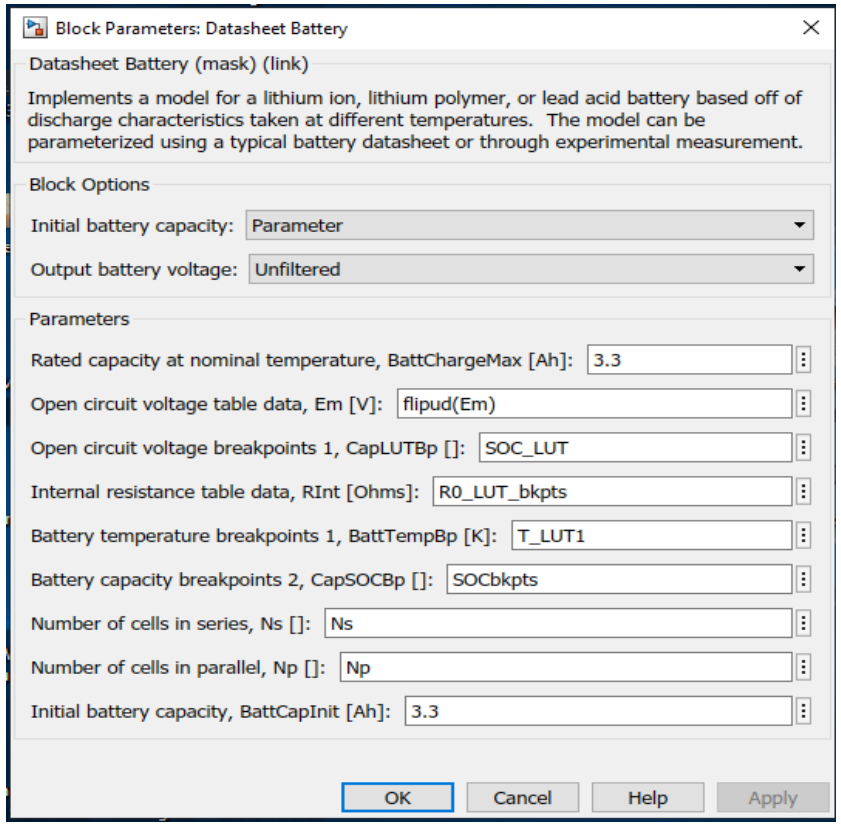


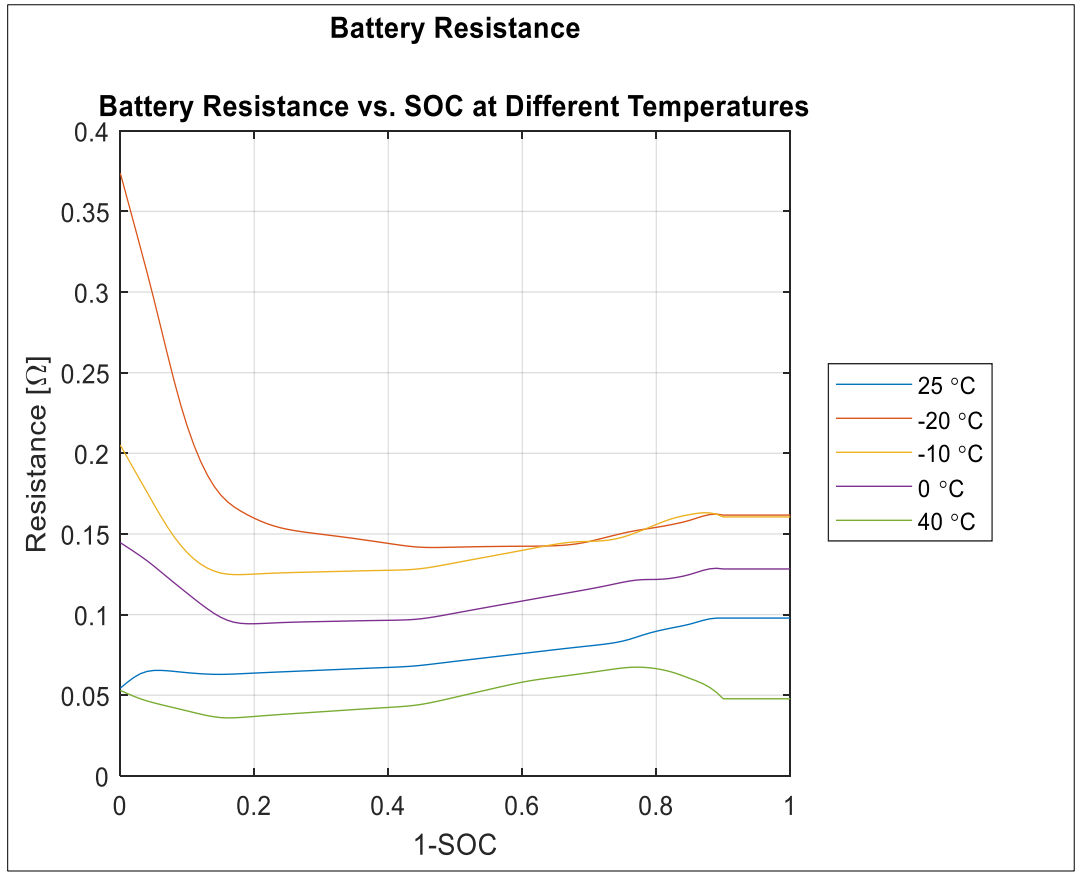


Battery Internal Resistance:

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





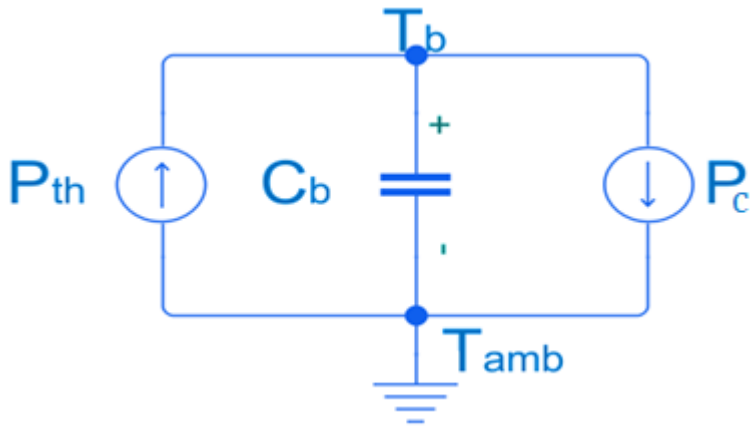


Battery Thermal Model

- Battery generates heat due to **joule's effect** when charging/discharging.

- Energy balance Equation:

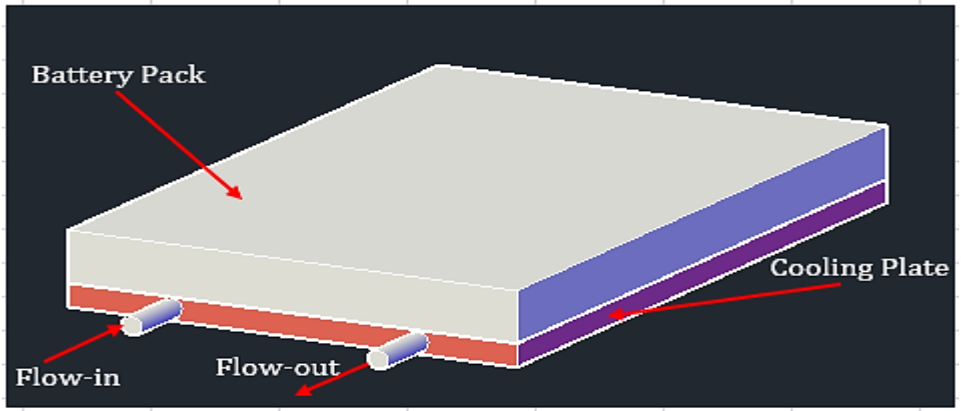
$$m_b C_{p,b} \frac{dT_b}{dt} = P_{th}(t) - P_c(t) = R_i(SOC, T_b) I_b^2(t) - P_c(t)$$

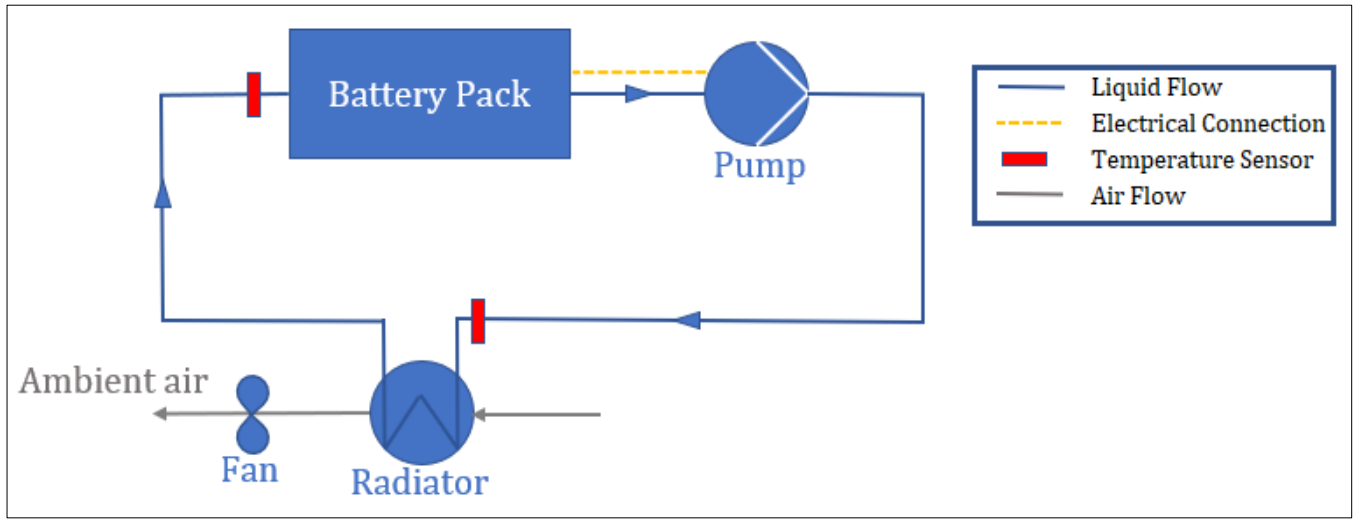


$$C_b = m_b C_{p,b}$$

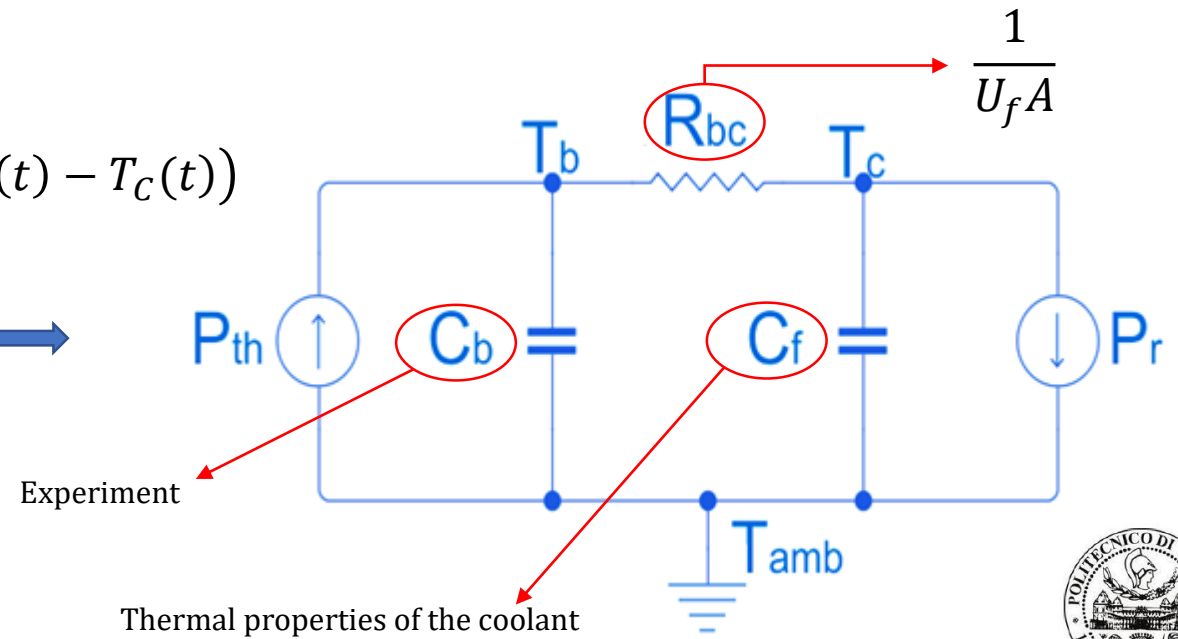
Battery Cooling System

- **Liquid Cooling Plate System**





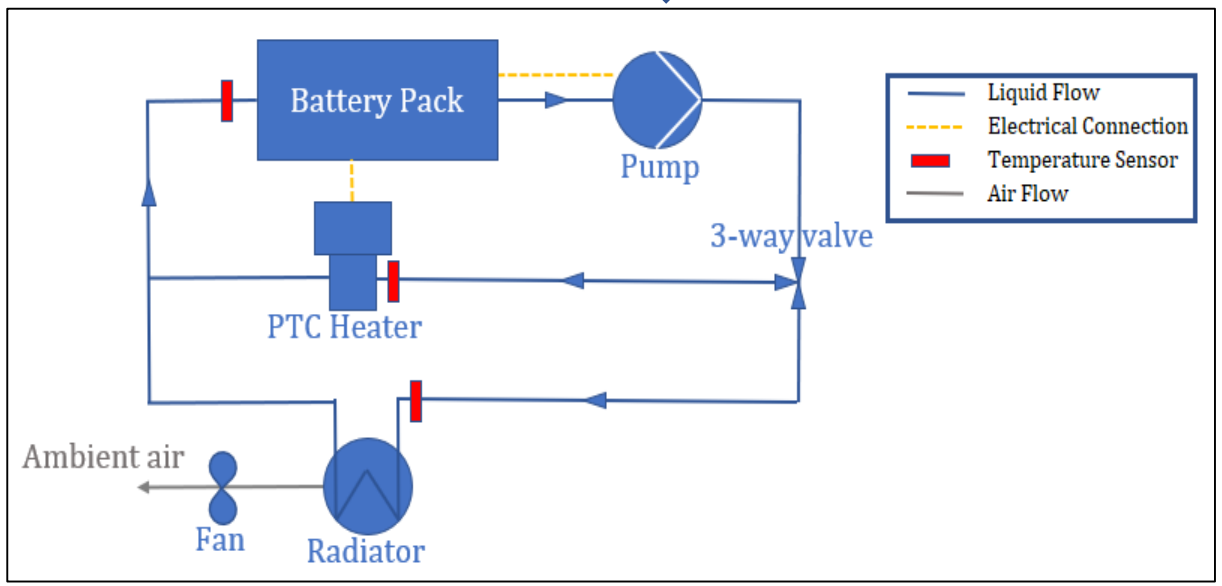
- $m_b C_{p,b} \frac{dT_b}{dt} = P_{th}(t) - P_C(t) = R_i(SOC, T_b) I_b^2(t) - U_f A\big(T_b(t) - T_C(t)\big)$
- $m_f C_{p,f} \frac{dT_C}{dt} = P_C(t) - P_r(t)$
- $P_r(t) = K_r A_r (T_C(t) - T_{amb})$



PTC Heating Element

- Battery Performance decreases at very low temperatures (in extreme weather conditions)

PTC Heater is added beside the Cooling Circuit



- $T_b \leq 0^o C$:

  $PTC\ is\ \boldsymbol{On}, Coolant\ circulate\ in\ the\ first\ loop.$

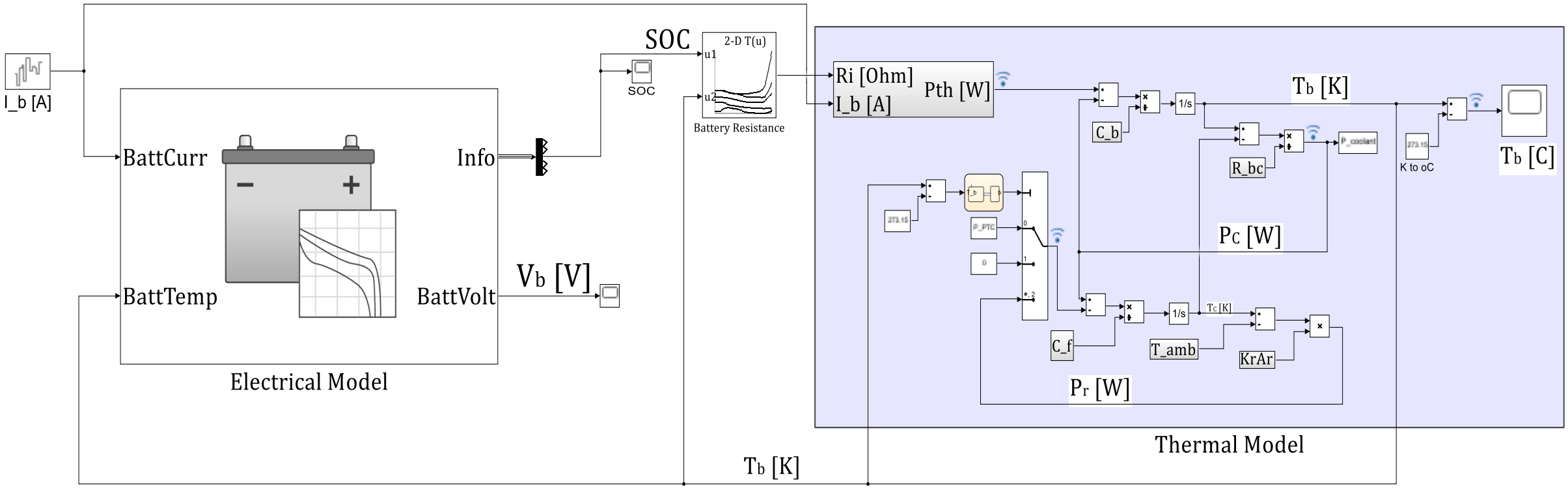
- $0^o C < T_b \leq 15^o C$:

  $PTC\ is\ \boldsymbol{Off}, Coolant\ circulate\ in\ the\ first\ loop.$

- $T_b > 15^o C$:

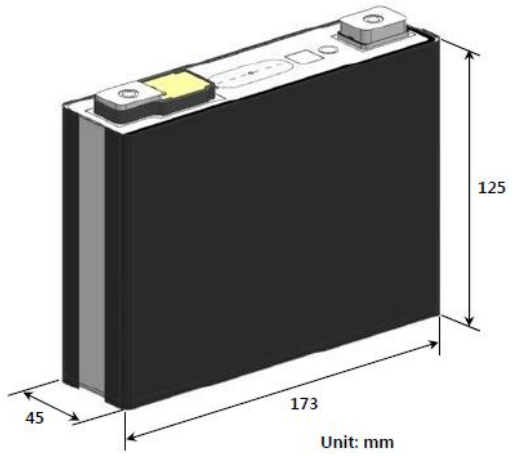
  $PTC\ is\ \boldsymbol{Off}, Coolant\ circulate\ in\ the\ second\ loop.$

Electro-Thermal Model



Battery Model Validation

- To ensure model reliability, the model is tested under same experimental tests done on Samsung 94 Ah prismatic battery module.



		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

- Module has 10 cells in series.
- Tests are done inside climatic chamber at $25^{o}C$ with natural convection as only cooling system.

Samsung 94Ah Electrical Model Parameters:

Technical Customer Information
94Ah cell

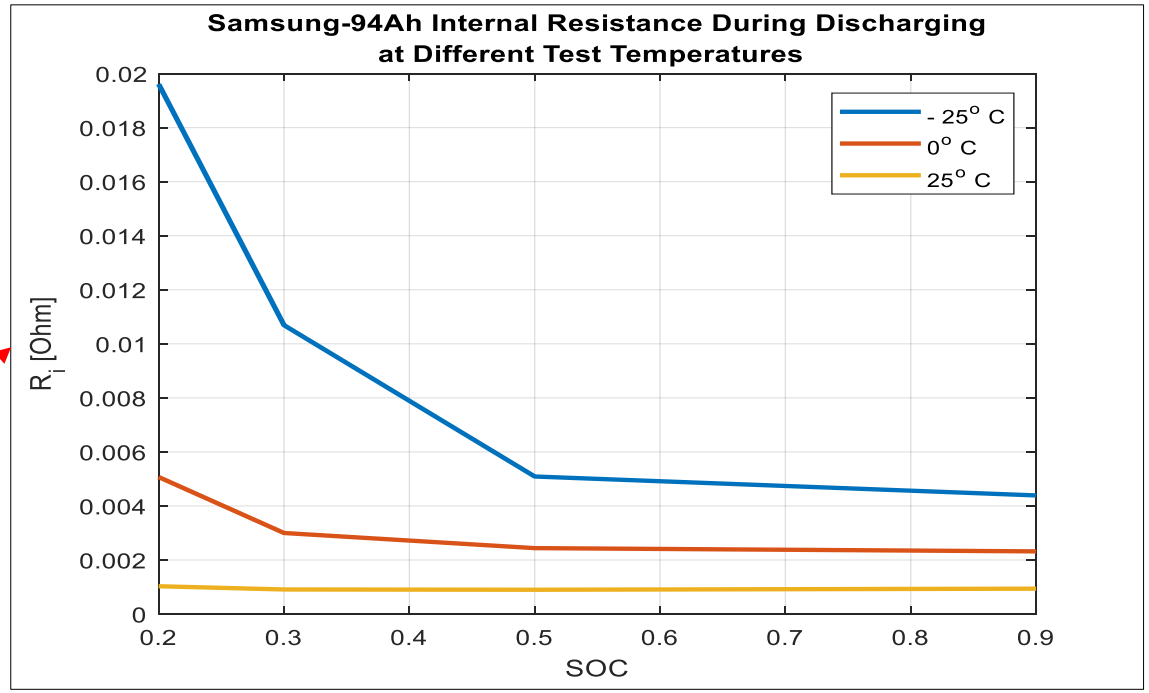
SAMSUNG SDI

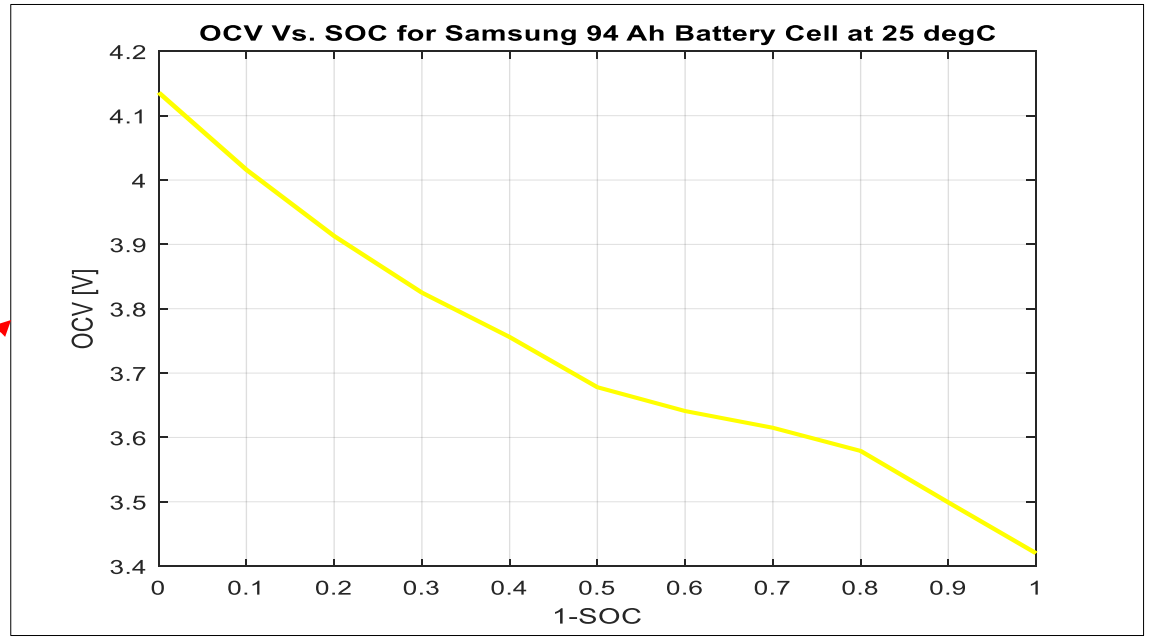
2.3.3. DC-IR

Temperature	-	DC-IR [mΩ]					
		Duration time	SOC90	SOC50	SOC30	SOC20	Max current
25℃	Discharge	5sec	0.68	0.68	0.68	0.74	413A
		30sec	0.94	0.90	0.91	1.03	294A
	Charge	5sec	0.65	0.65	0.65	0.67	413A
		30sec	0.92	0.90	0.81	0.88	294A
-5℃	Discharge	5sec	1.86	2.00	2.46	3.80	413A
		30sec	2.32	2.44	3.00	5.07	294A
	Charge	5sec	4.10	2.99	2.96	3.10	413A
		30sec	3.74	2.83	2.65	2.77	294A
-25℃	Discharge	5sec	3.87	4.32	8.71	18.01	413A
		30sec	4.39	5.09	10.69	19.61	294A
	Charge	5sec	26.02	13.47	13.30	13.17	413A
		30sec	28.34	16.73	15.97	16.66	294A

2.3.4. OCV (Average value)

Temp.	OCV (V)											
	SOC%	100	90	80	70	60	50	40	30	20	10	0
25℃	Discharge	4.136	4.016	3.913	3.825	3.756	3.678	3.641	3.615	3.579	3.499	3.420
	Charge	4.133	4.022	3.921	3.833	3.765	3.690	3.653	3.627	3.598	3.517	3.433

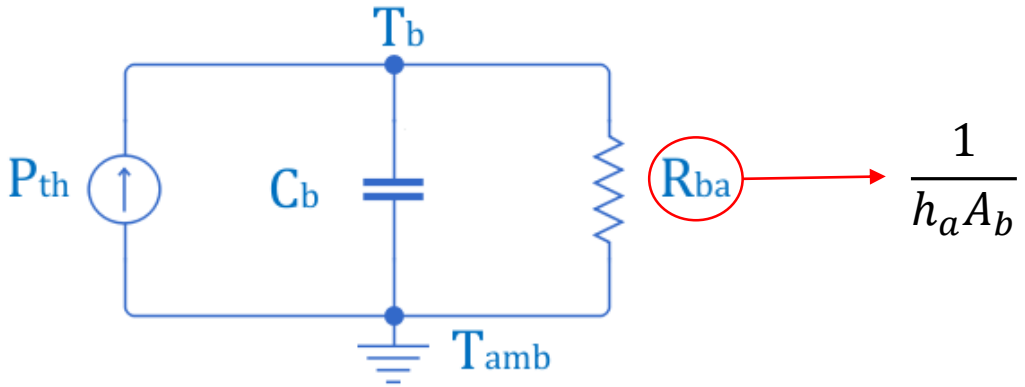




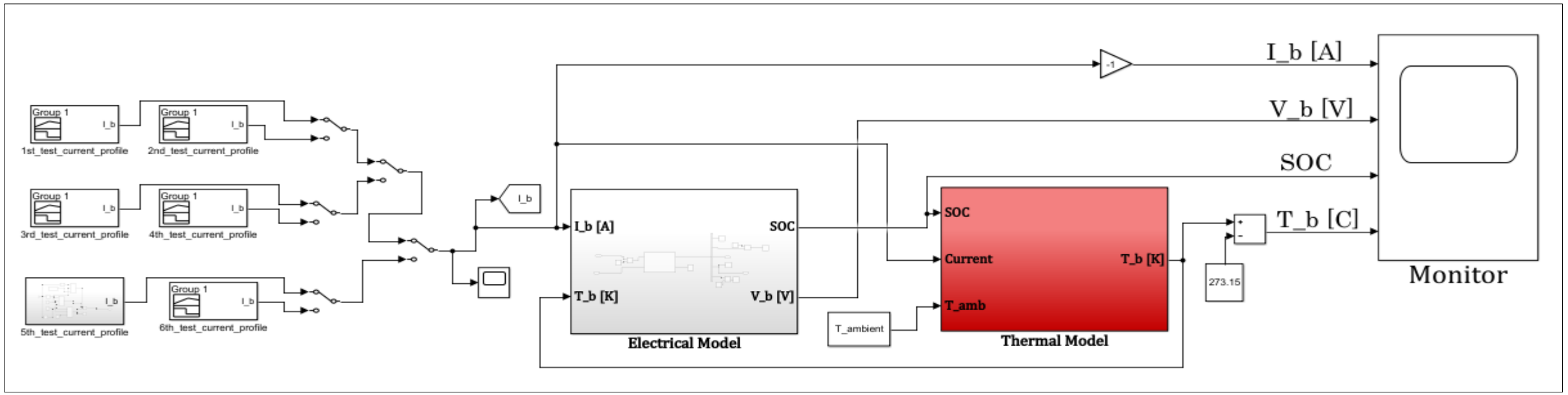
Samsung 94Ah Thermal Model:

- Cooling of battery through natural convection.
- Energy balance equation:

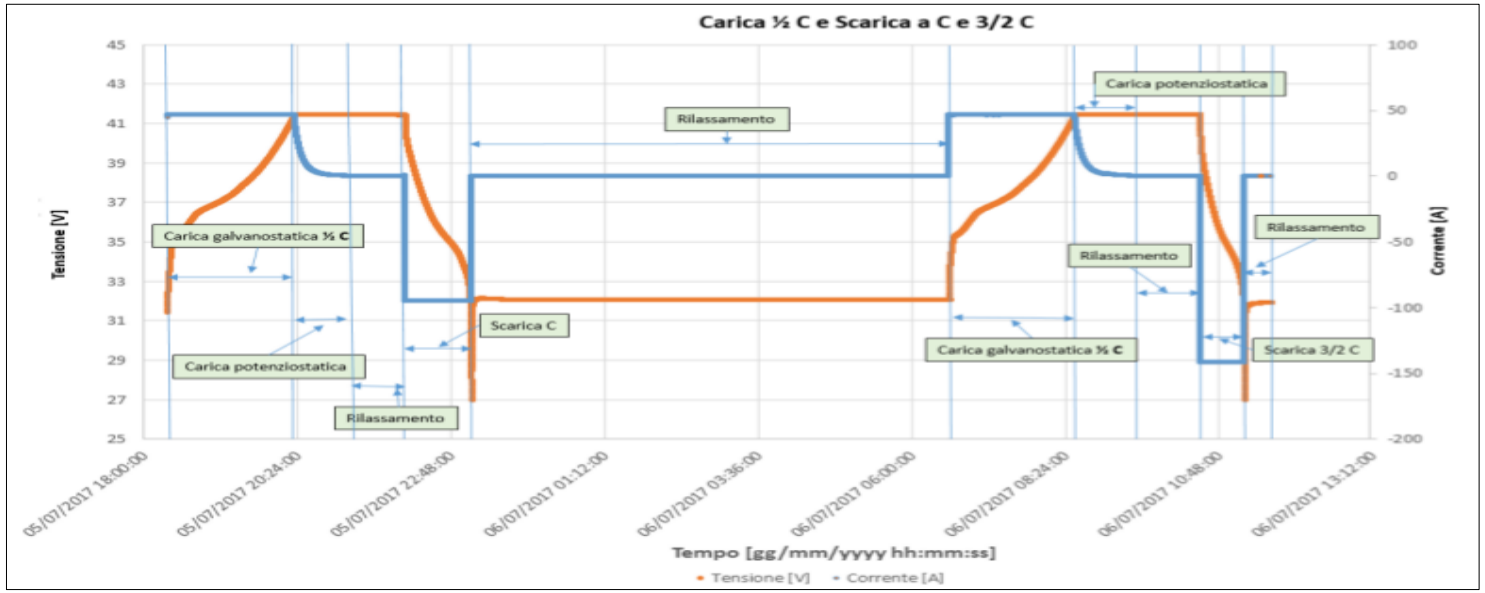
$$m_b C_{p,b} \frac{dT_b}{dt} = P_{th}(t) - P_a(t) = R_i(SOC, T_b) I_b^2(t) - h_a A_b (T_b(t) - T_{amb})$$

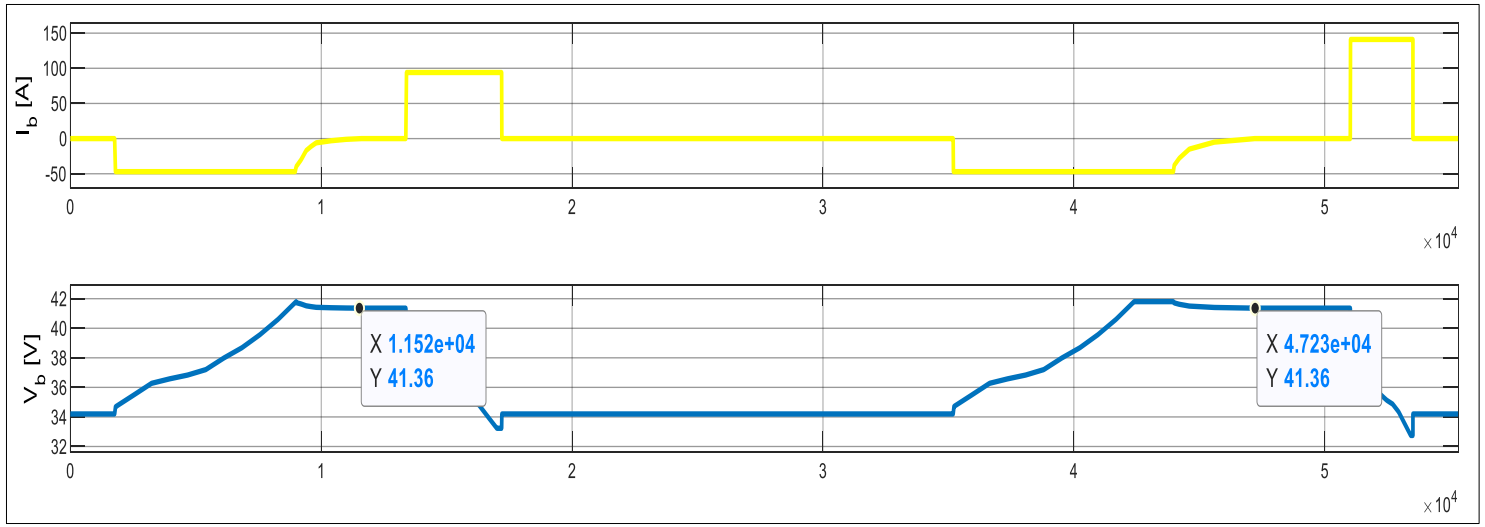


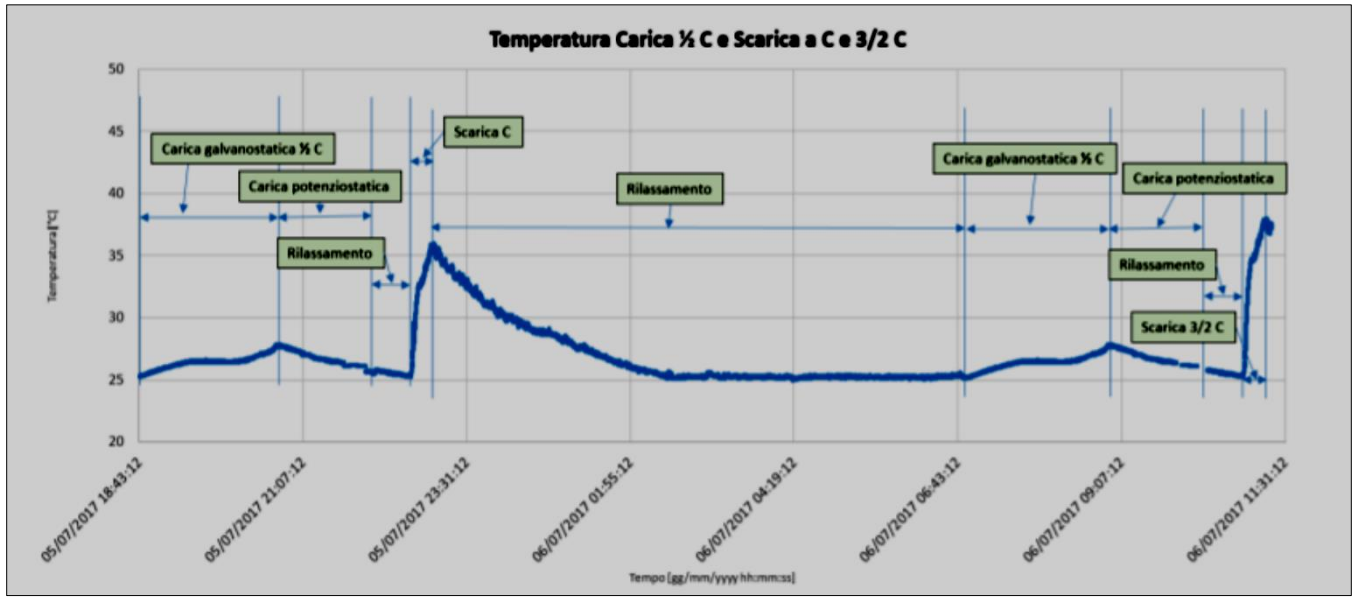
$$\frac{1}{h_a A_b}$$

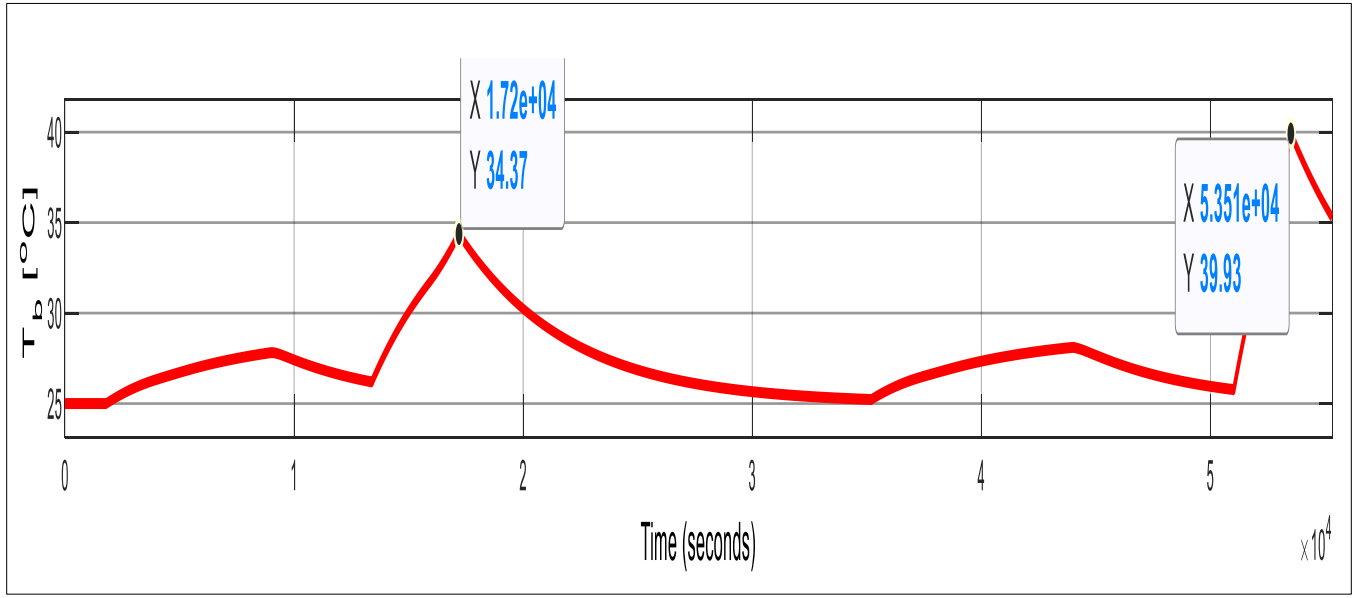


Full "rated" 1/2 C Charge and 1 C & 3/2 C Discharge

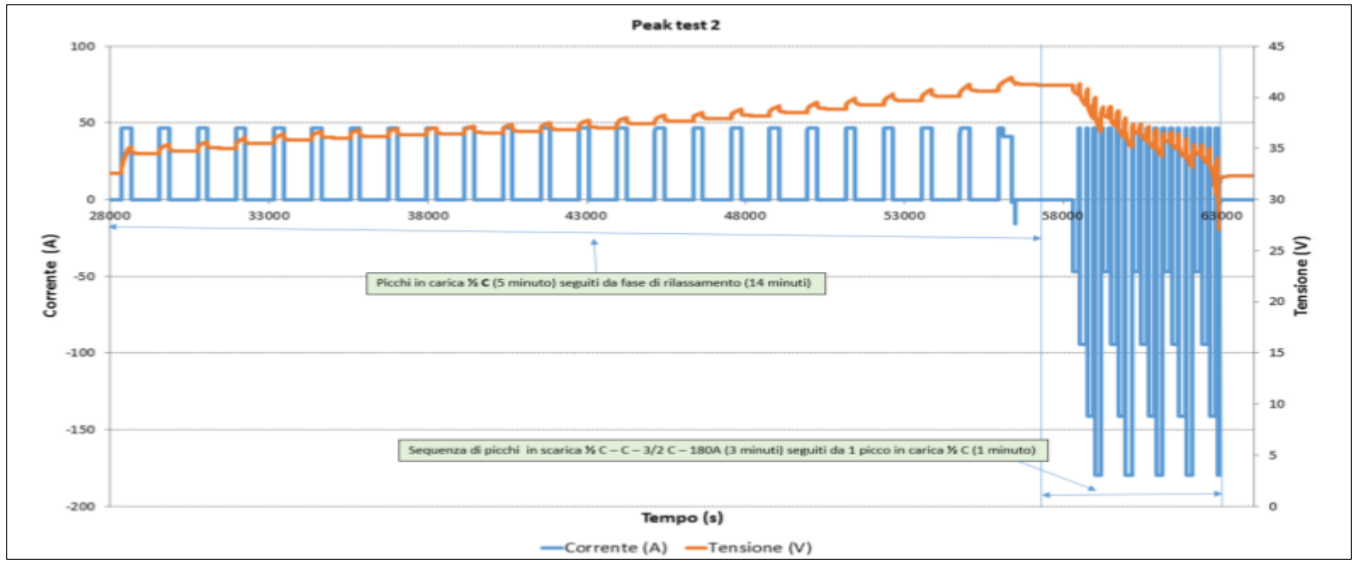


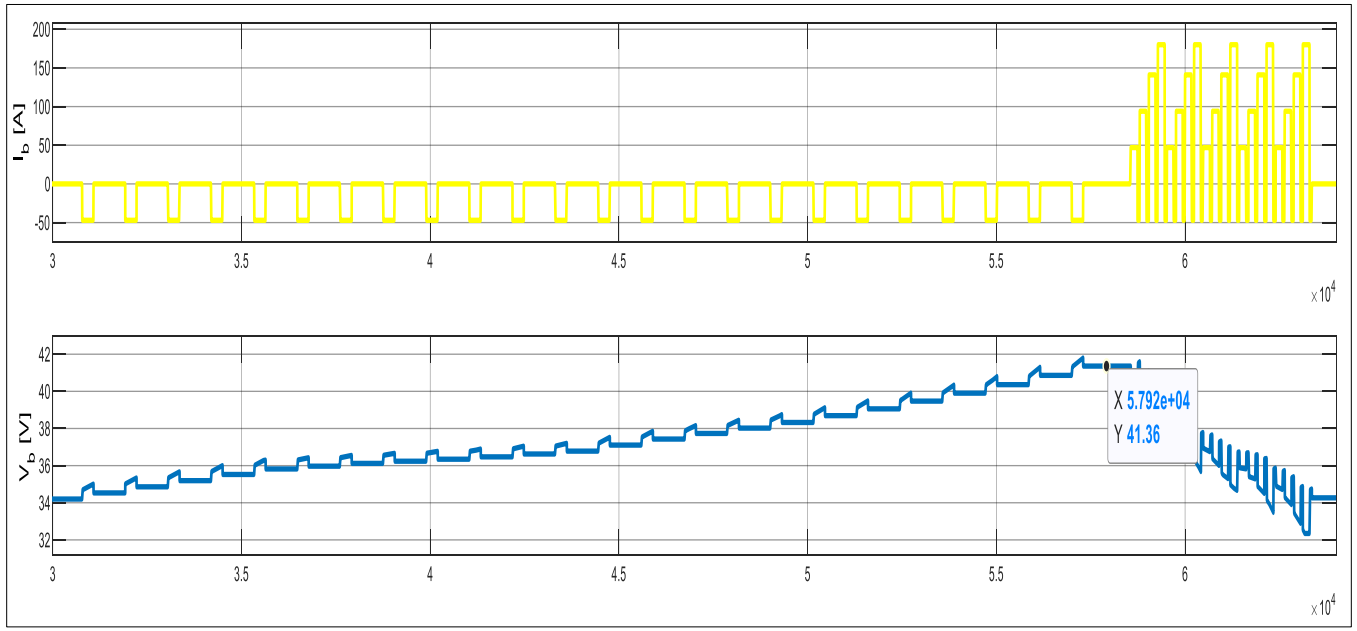


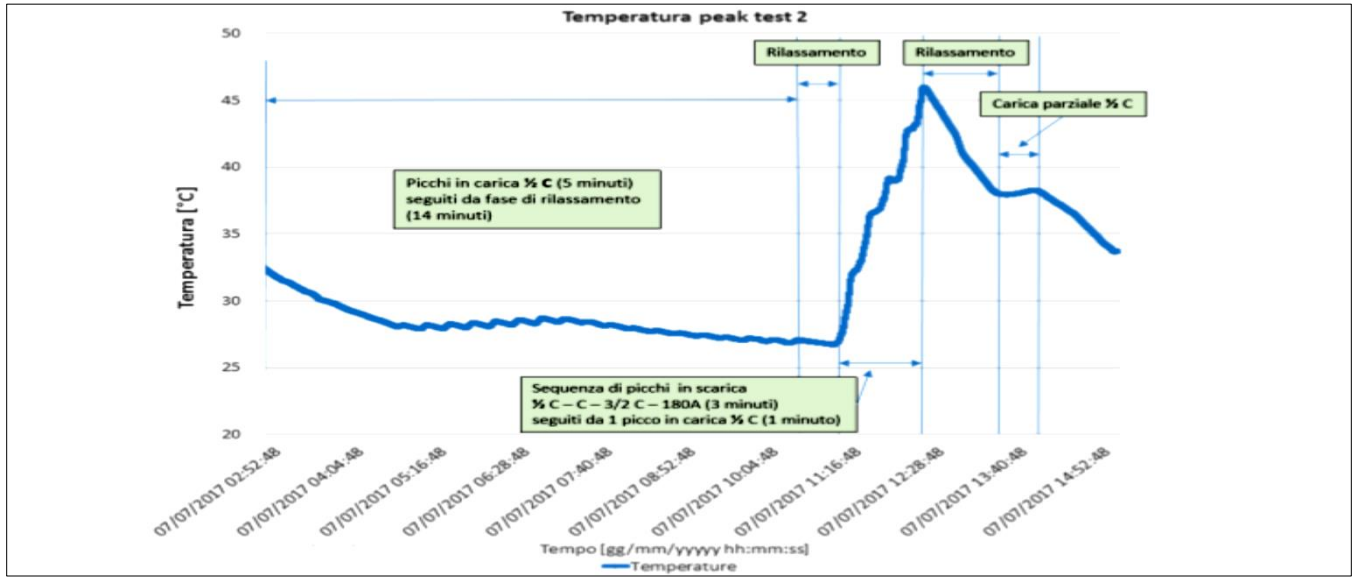

Temperatura Carica ½ C e Scarica a C e 3/2 C
Carica galvanostatica ½ C
Carica potenziostatica
Rilassamento
Scarica C
Rilassamento
Carica galvanostatica ½ C
Carica potenziostatica
Rilassamento
Scarica 3/2 C
Temperatura [°C]
Tempo [gg/mm/yyyy hh:mm:ss]

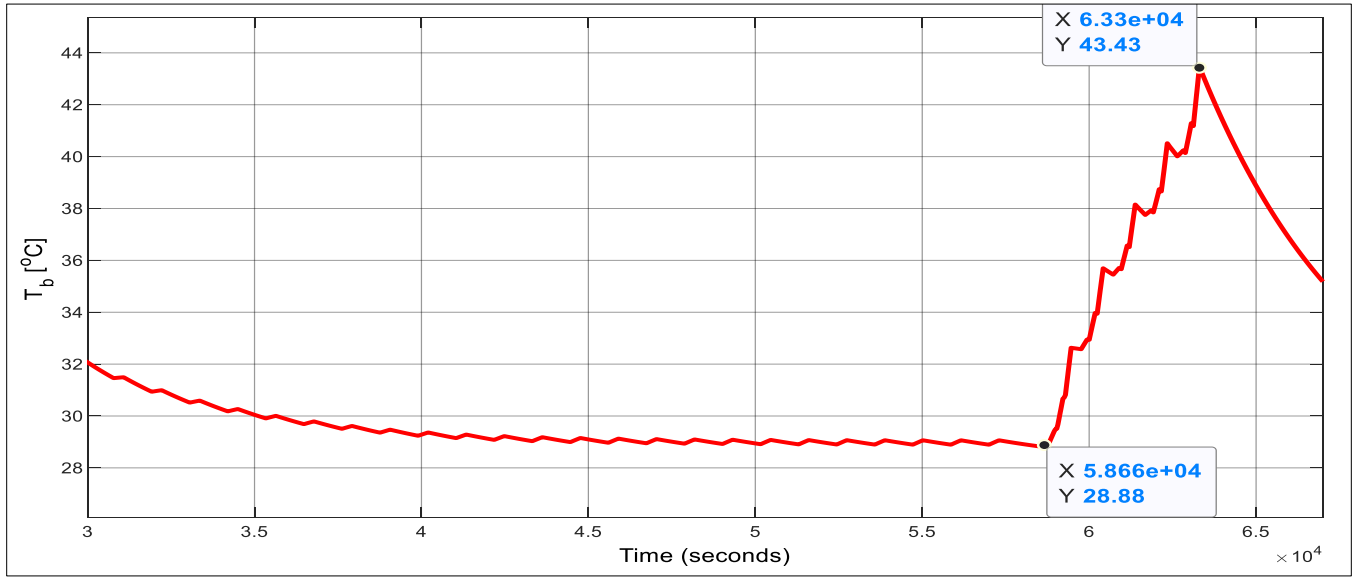

X 1.72e+04
Y 34.37
X 5.351e+04
Y 39.93
T [°C]
Time (seconds)
x10^4

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





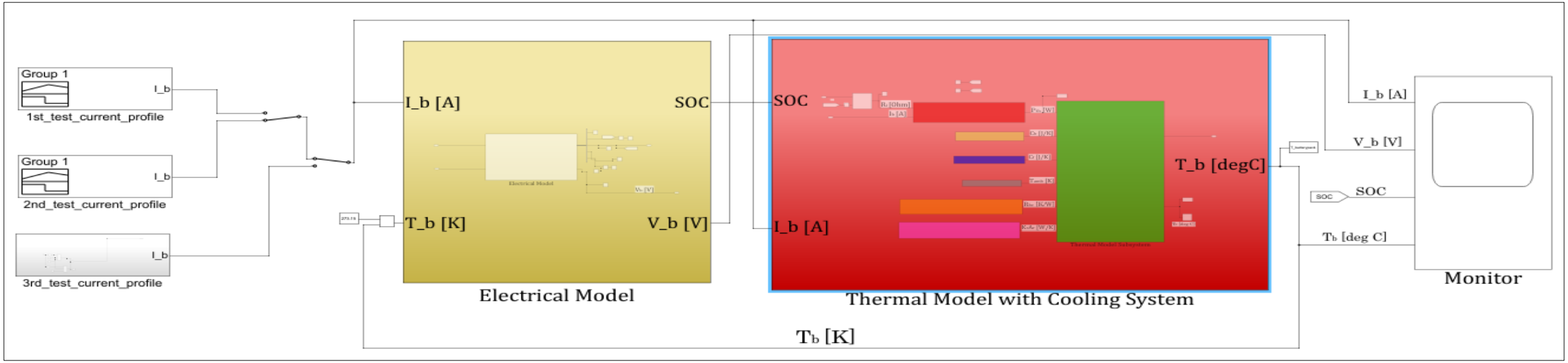




The results show that the virtual model was able to provide similar results as real model with around $\pm 2\ V$ difference on battery voltage and $\pm$ 4°C difference on battery temperature.

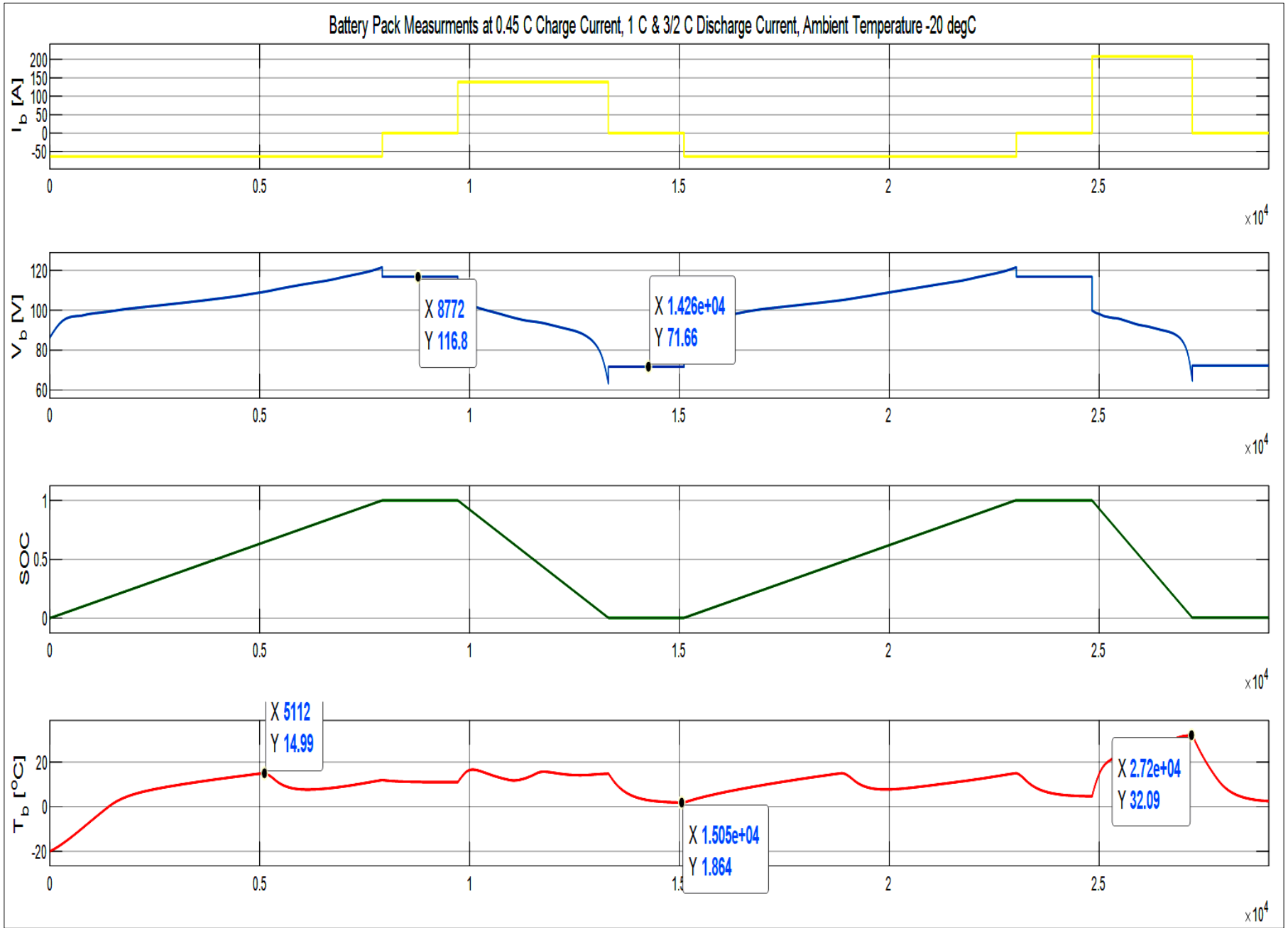
Panasonic 138.6Ah Battery Pack Simulation

- 138.6 Ah Battery pack is tested at different ambient temperatures under:
  - Constant charging/discharging cycles.
  - Impulse charging/discharging cycles.
- Tests Common Conditions:
  - Initial Battery Temp. is stabilized with ambient temperature.
  - Charging current of the battery is 63 A (0.45 C).
  - Initial SOC is 0.
  - Ambient Temperatures: -20, -10, 0, 25, 40 ^{o}C



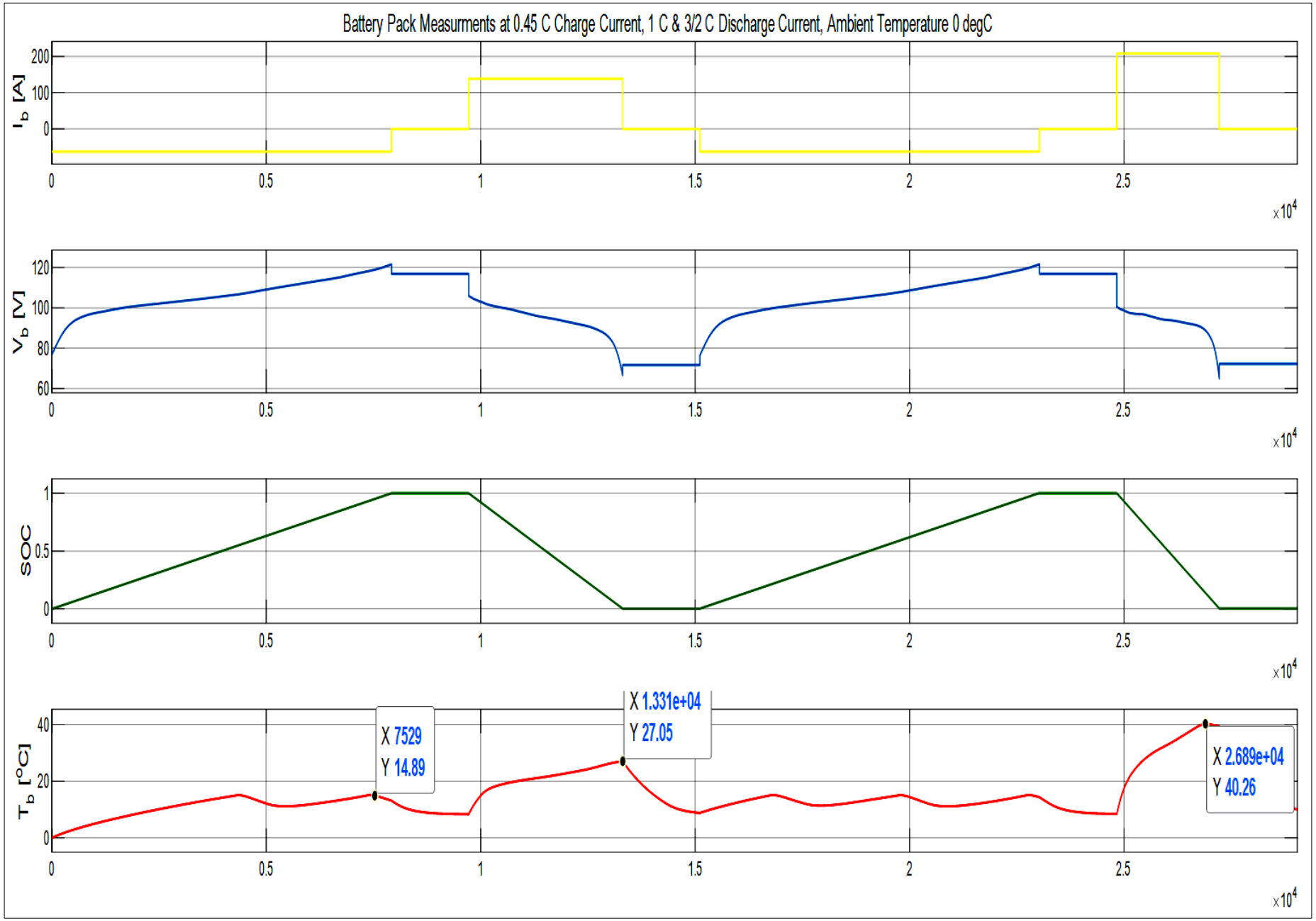
Full 0.45 C Charge and 1 C & 3/2 C Discharge Test

$T_{amb} : -20^{o}C$



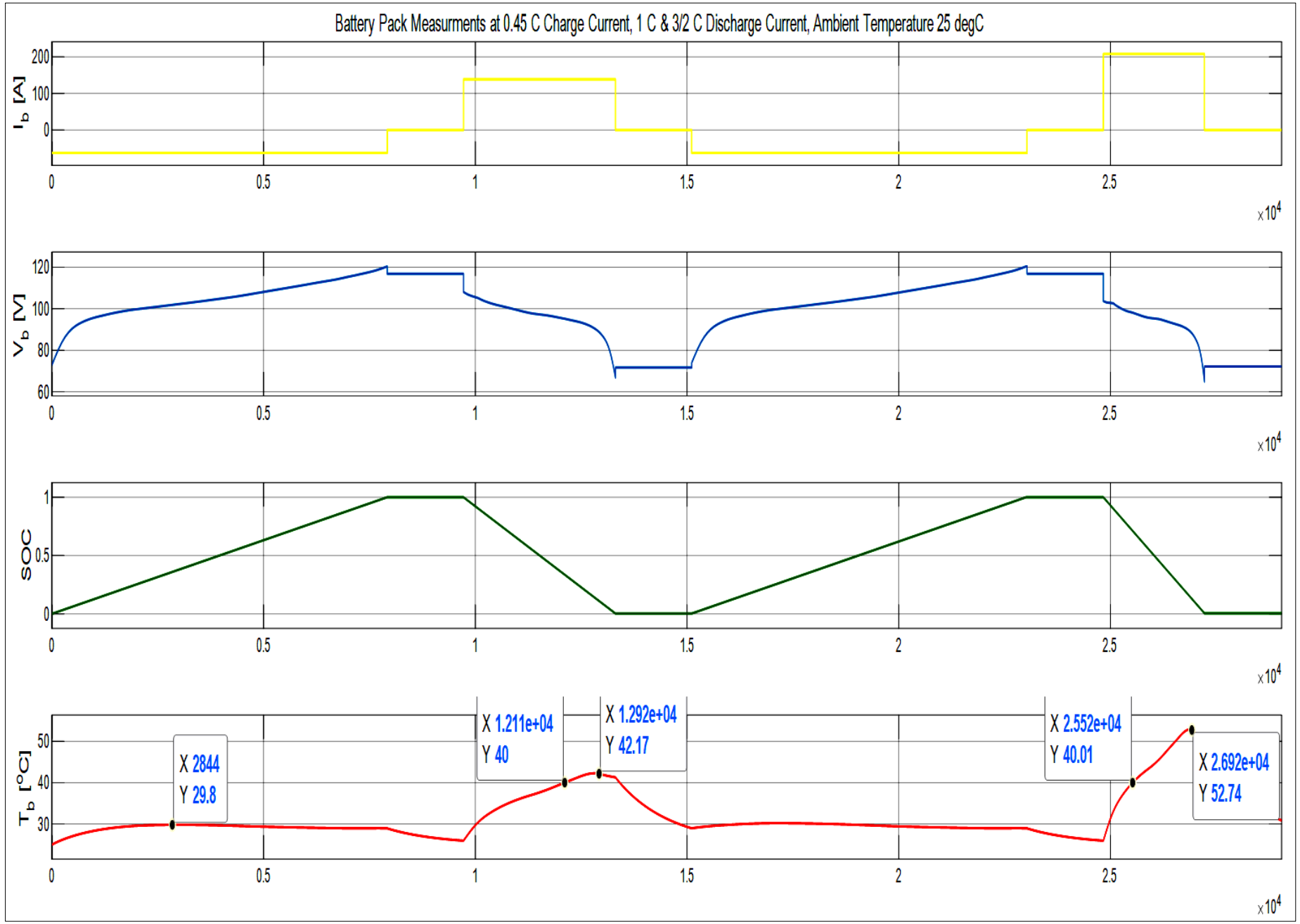
Full 0.45 C Charge and 1 C & 3/2 C Discharge Test

$T_{amb} : 0^{o}C$



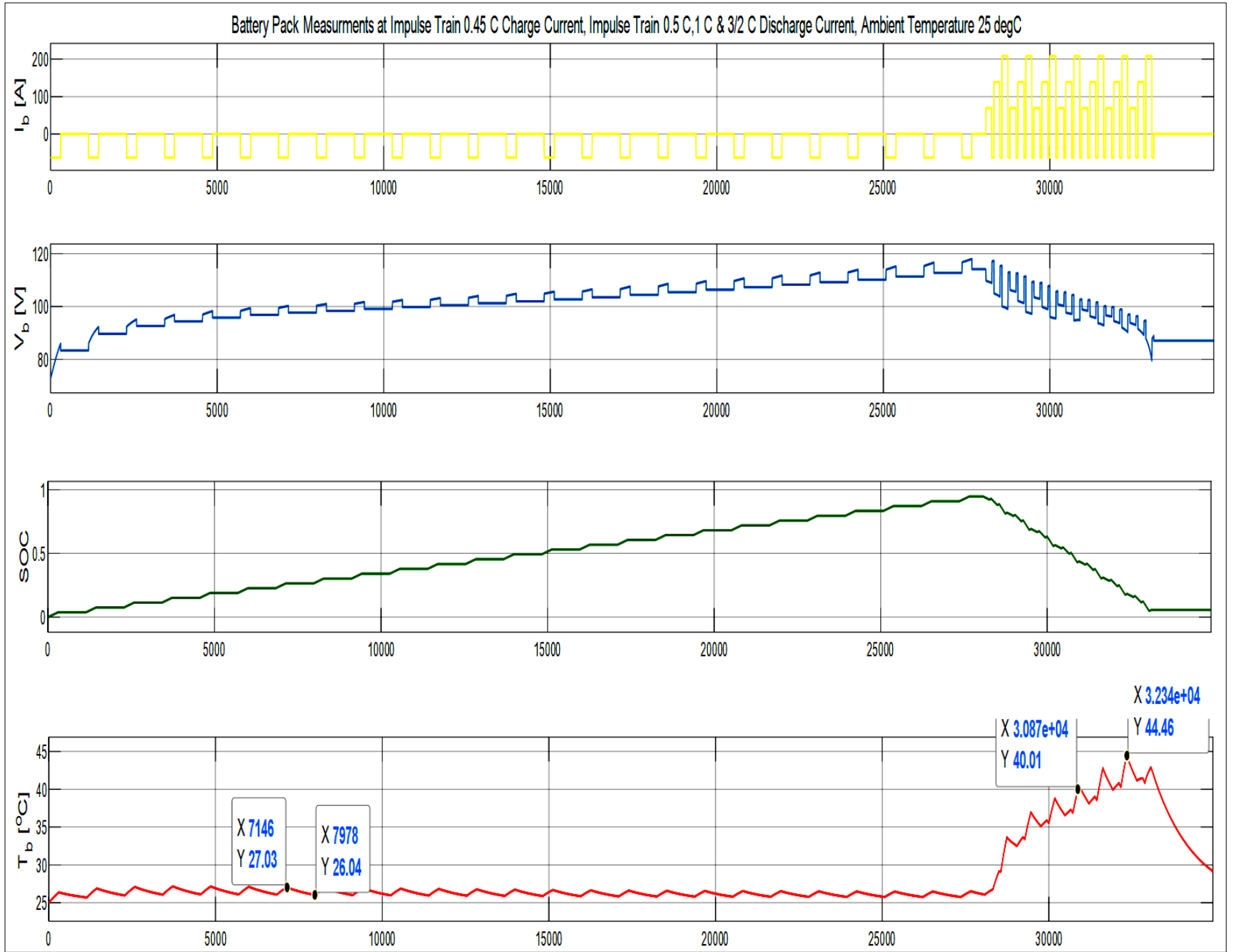
Full 0.45 C Charge and 1 C & 3/2 C Discharge Test

$T_{amb} : 25^{o}C$



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

$T_{amb} : 25^{o}C$

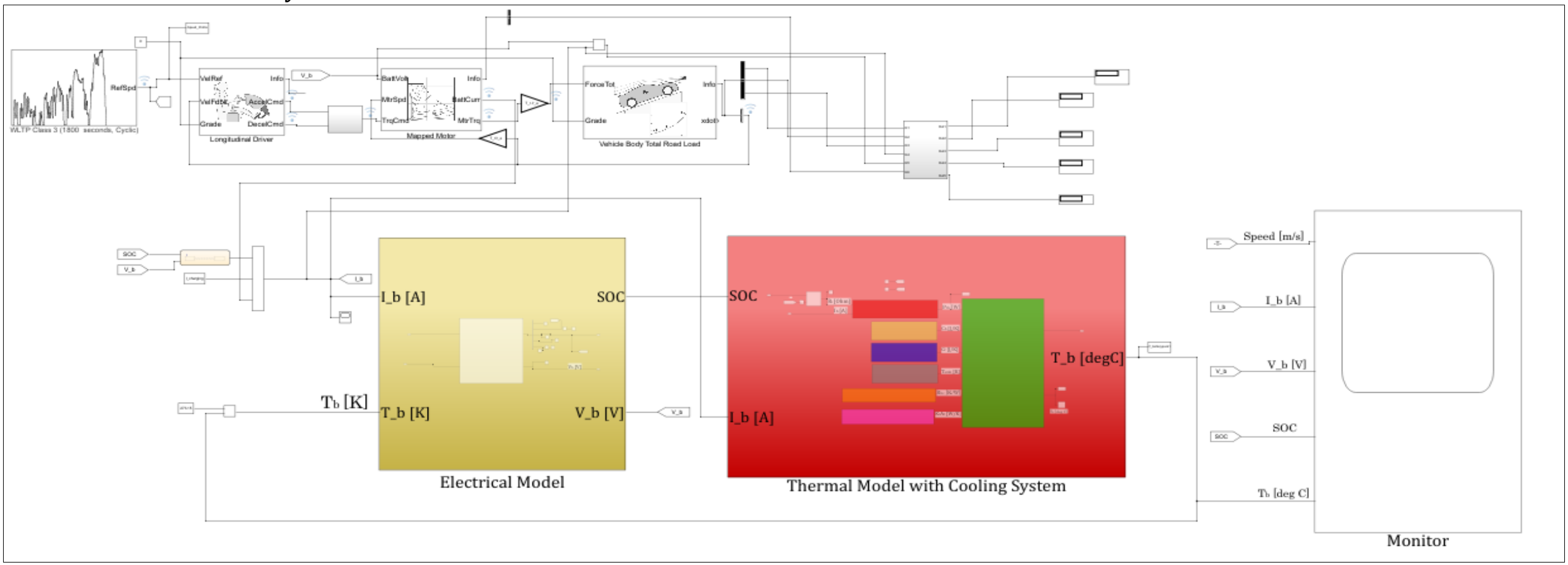


Conclusions from Test Results:

- As ambient Temp. increases, the ability of passive cooling system to extract heat from battery decreases.
- Limitations on the duration and amplitude of delivered current should be taken into consideration by BMS as battery temperature starts approaching its upper limits.
- At high ambient temperatures, an active cooling system could be installed that uses A/C evaporator to remove heat from battery instead of air-cooled radiator.

Battery Pack Simulation under Different Drive Cycles

- Panasonic 138.6 Ah battery pack is coupled with the vehicle dynamics of Fiat Panda first series.
- Test Cycles are:
  - NEDC cycle
  - WLTP cycle

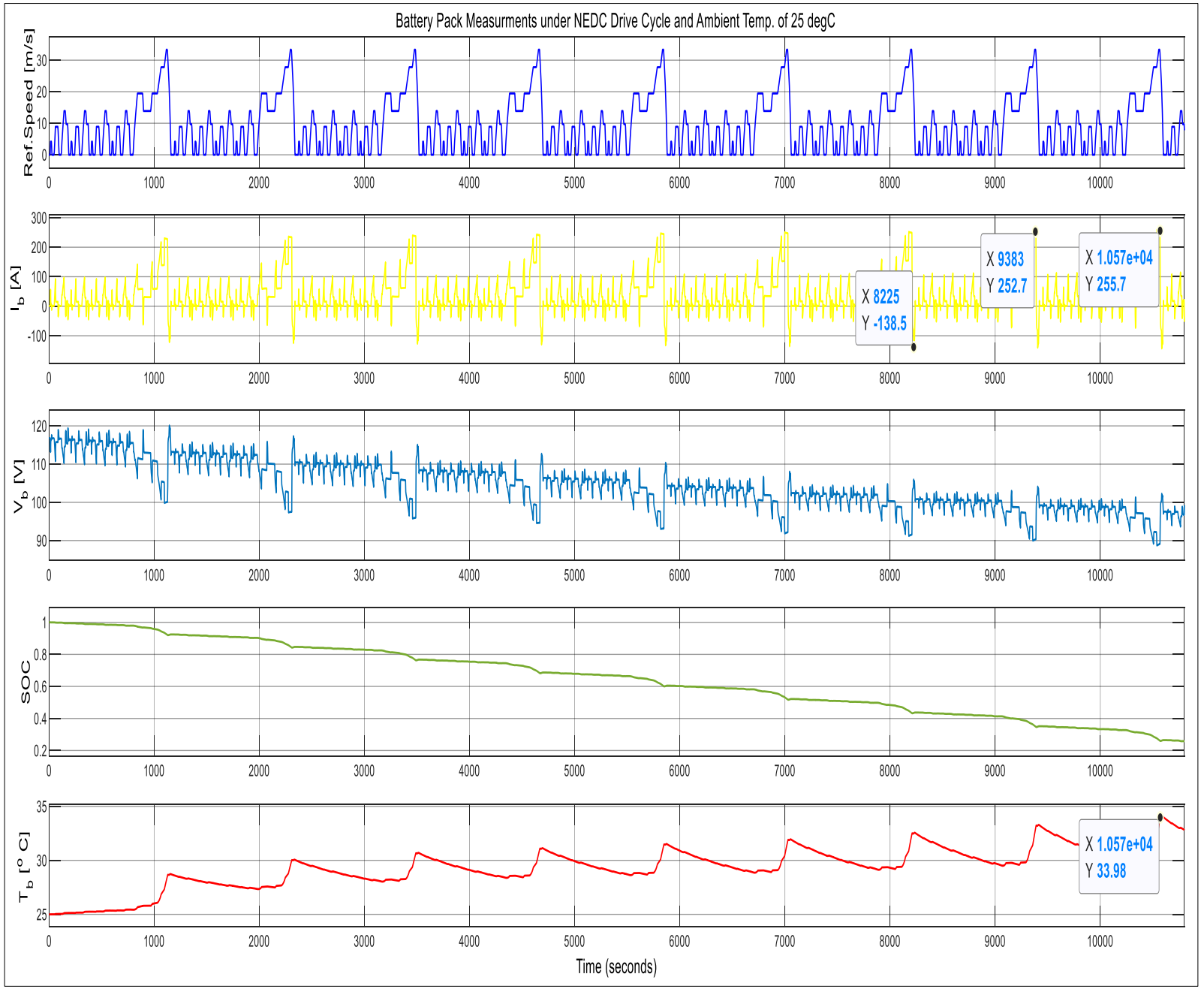


A) Testing Under NEDC Drive Cycle:

Ambient Temperature: **25°C**

Initial SOC: 100%

Test Time: 3hrs

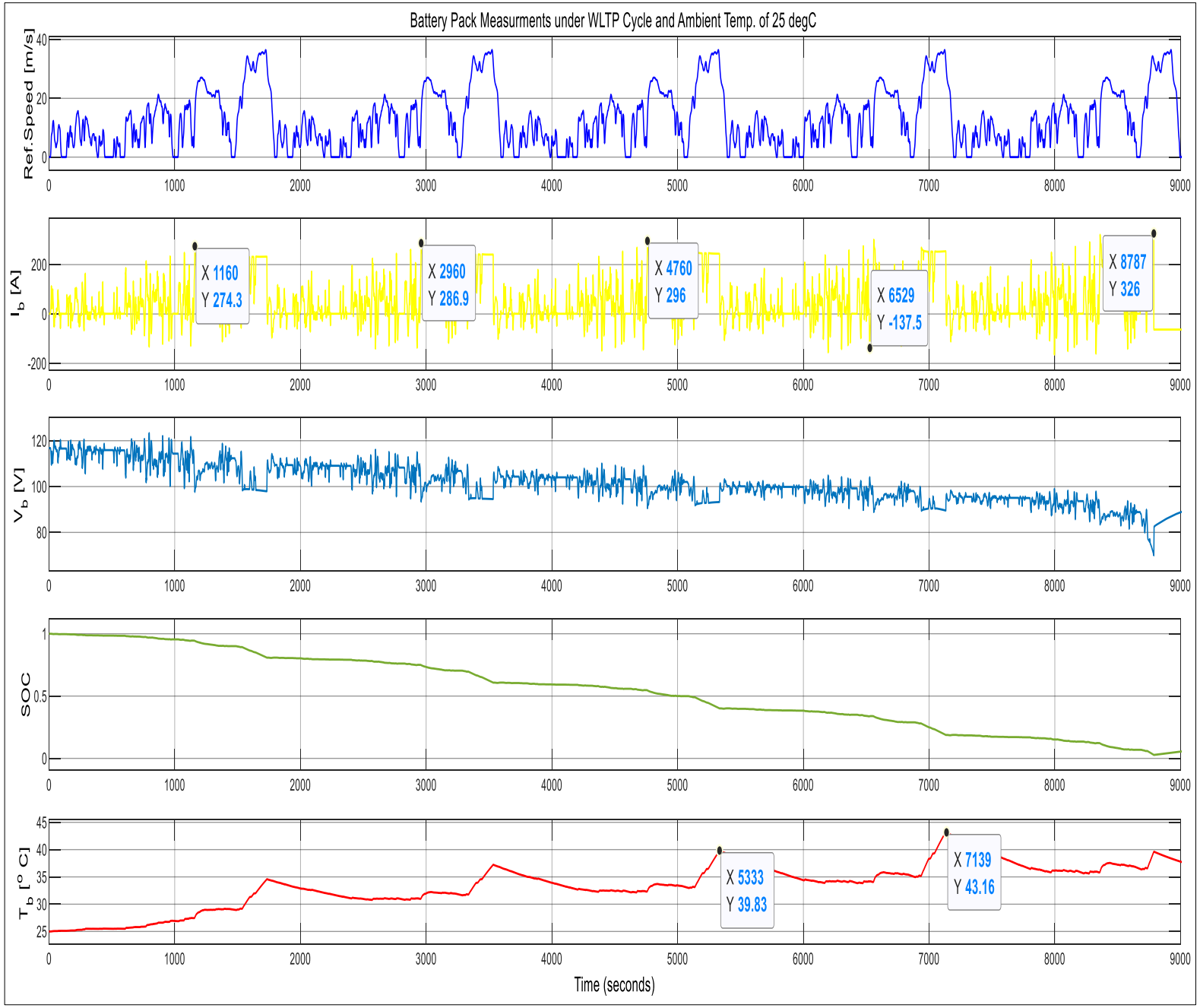


B) Testing Under WLTP Drive Cycle:

Ambient Temperature: **25°C**

Initial SOC: 100%

Test Time: 3hrs



Possible future perspective:

Design and integration of predictive control model with battery model to:

- Predict battery temperature.
- Approve current amplitude.
- Approve current duration.

Thank You