# State-of-Charge (SOC) governed fast charging method for lithium based batteries

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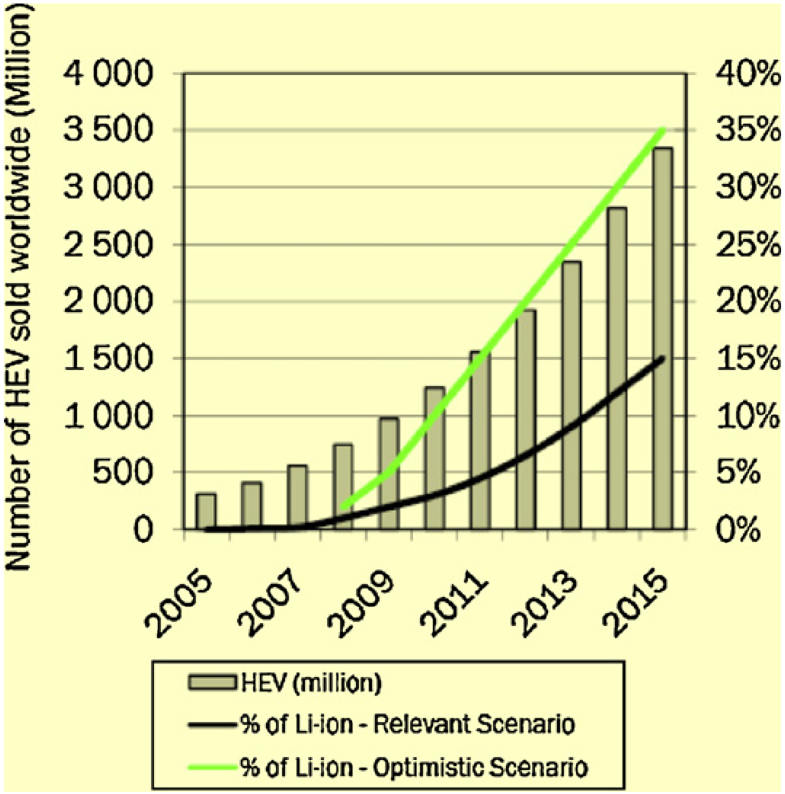
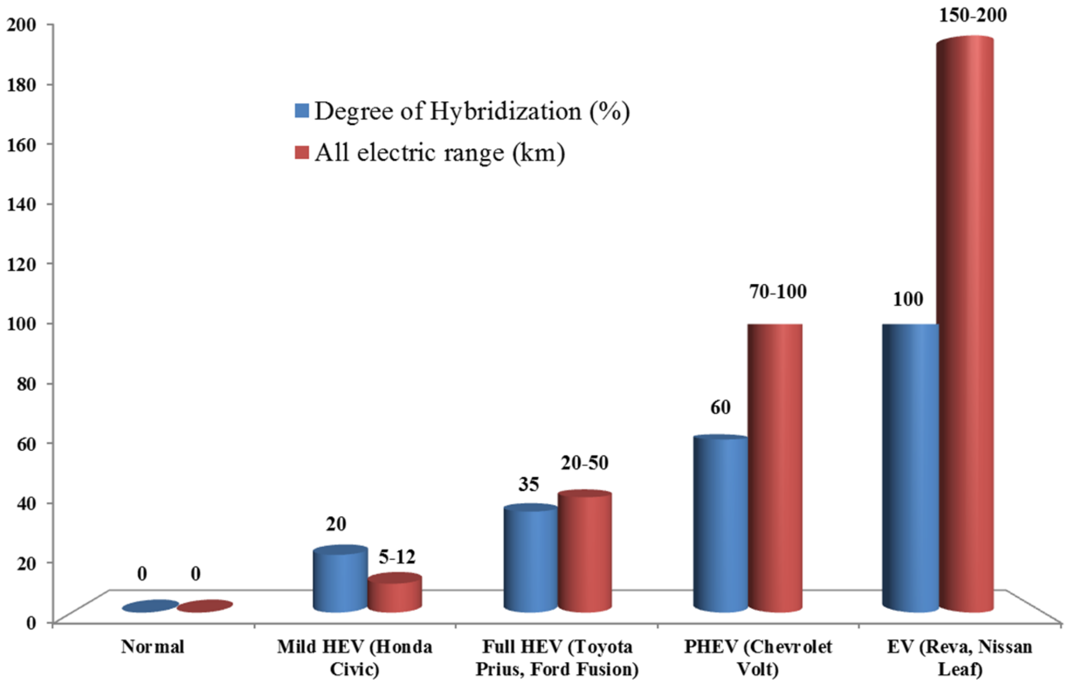
# Hybrid technology & battery requirement





**References:**

1. Battery Market Development: Materials Requirements and Trends 2012-2025; Christophe Pillot, Director, Avicenne Energy; Advanced Automotive Battery Technology, Application and Market Symposium 2013
2. Plug-in Hybrid and Battery-Electric Vehicles: State of the research & development and comparative analysis of energy & cost efficiency; Nemry F. et.al.; JRC ITPS technical notes

# Need of fast charging

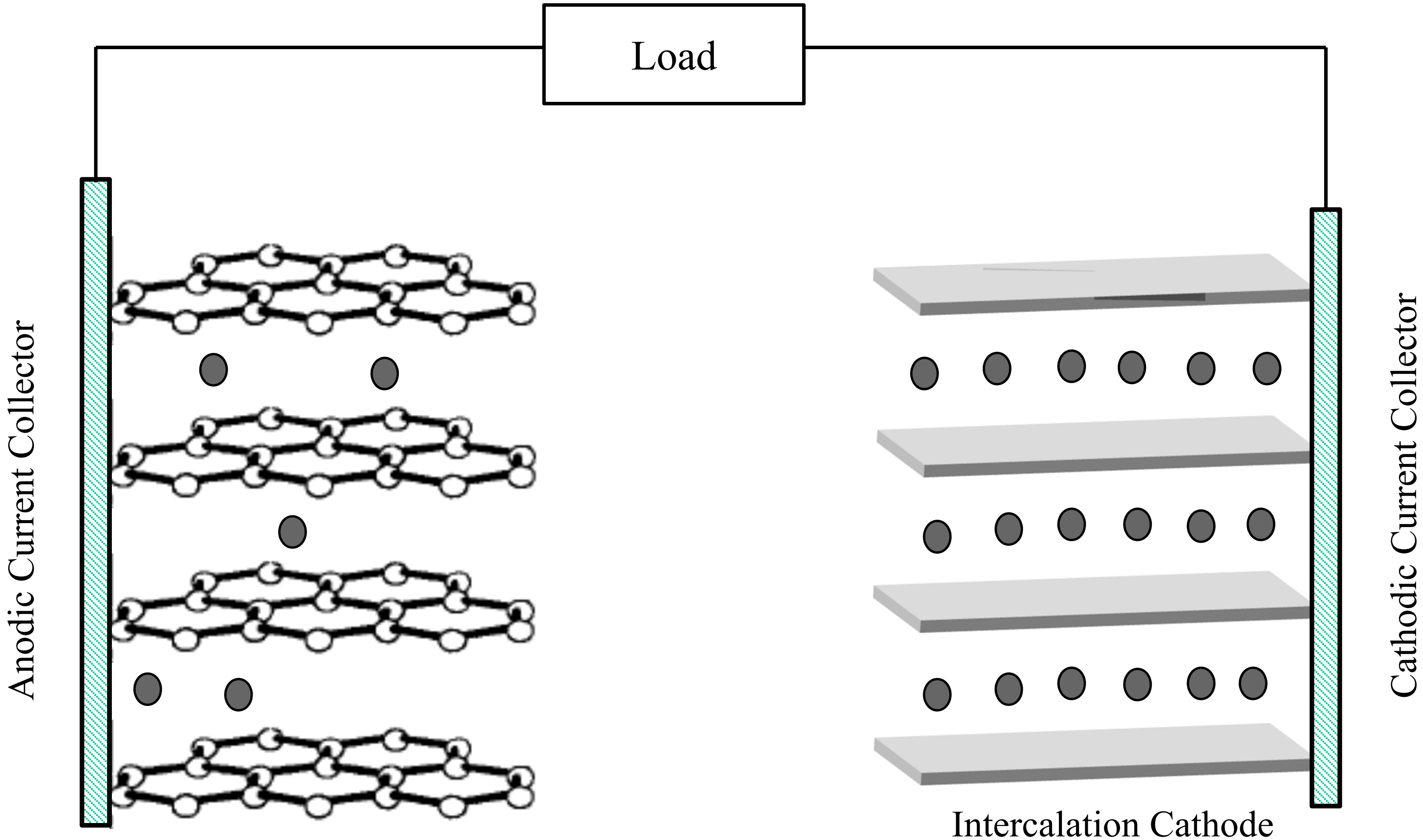
## Comparison of energy sources: Gasoline powered vs. battery powered

| Energy Source | Energy Density [1] (Wh/kg) | Charging Time [2] | No. of Cycles |
|---|---|---|---|
| Gasoline | ~ 4,000 | ~ 5-10 min [3] | N/A |
| Lead Acid Battery | 80 - 100 | 4 – 6 hrs. | 800-1000 |
| Lithium Battery | 400 - 500 | 2 – 3 hrs. | ~ 2000 |
| Fuel-cell | ~ 19,000 | ~ 15-30 min [3] | N/A |
| Ultra-capacitor | 5 - 10 | 0.3 – 30 s | ~ 500,000 |

[1]: practical energy density based on system efficiency
[2]: based on widely used conventional methods
[3]: re-fueling time

- Conventional CC-CV algorithm takes ~2-3 hrs. to completely charge a battery

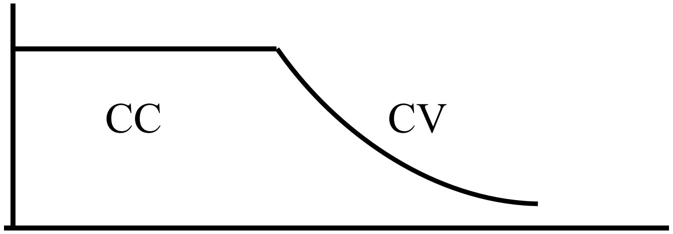
# Working of a Lithium-ion battery

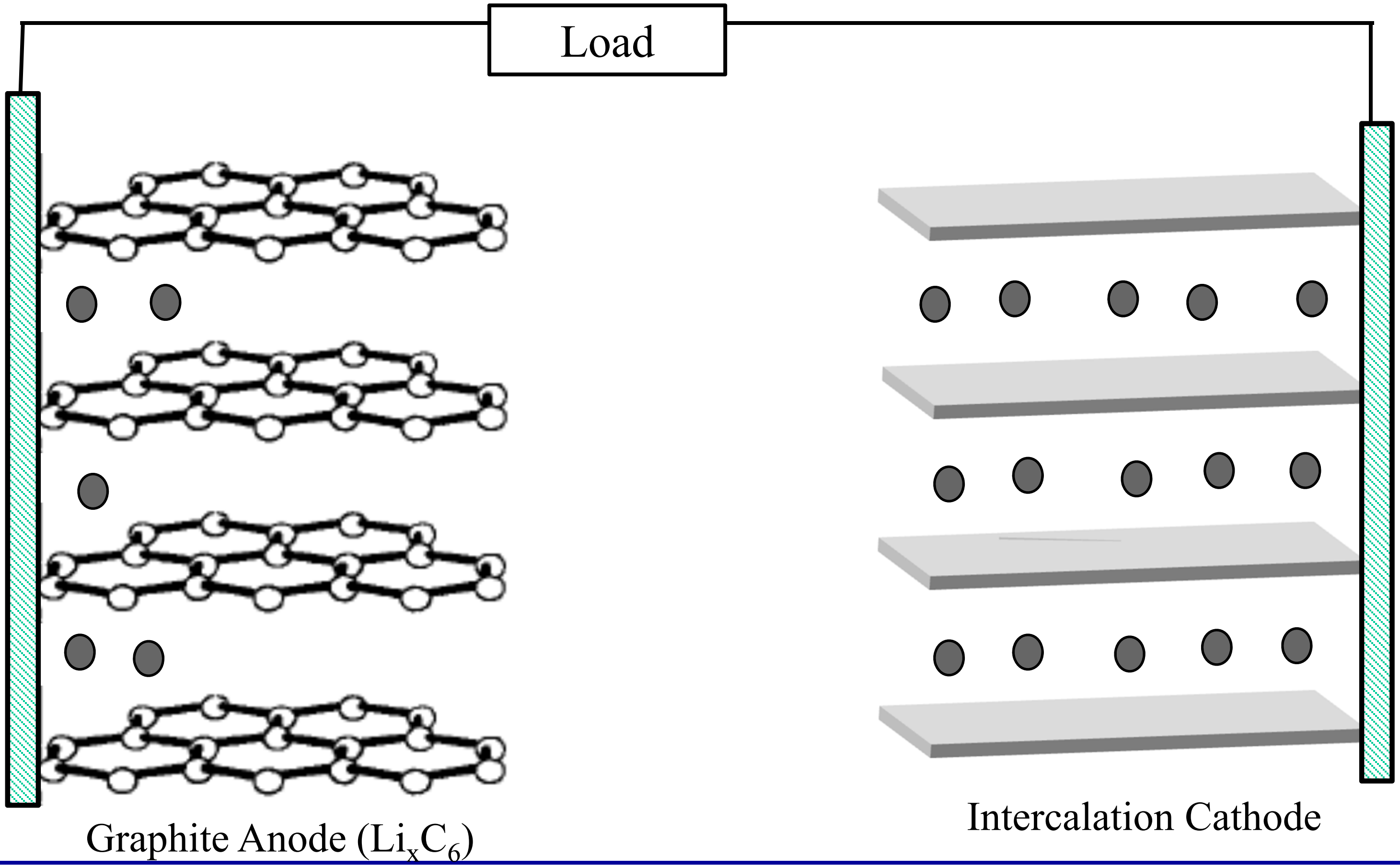


Graphite Anode ($Li_xC_6$)

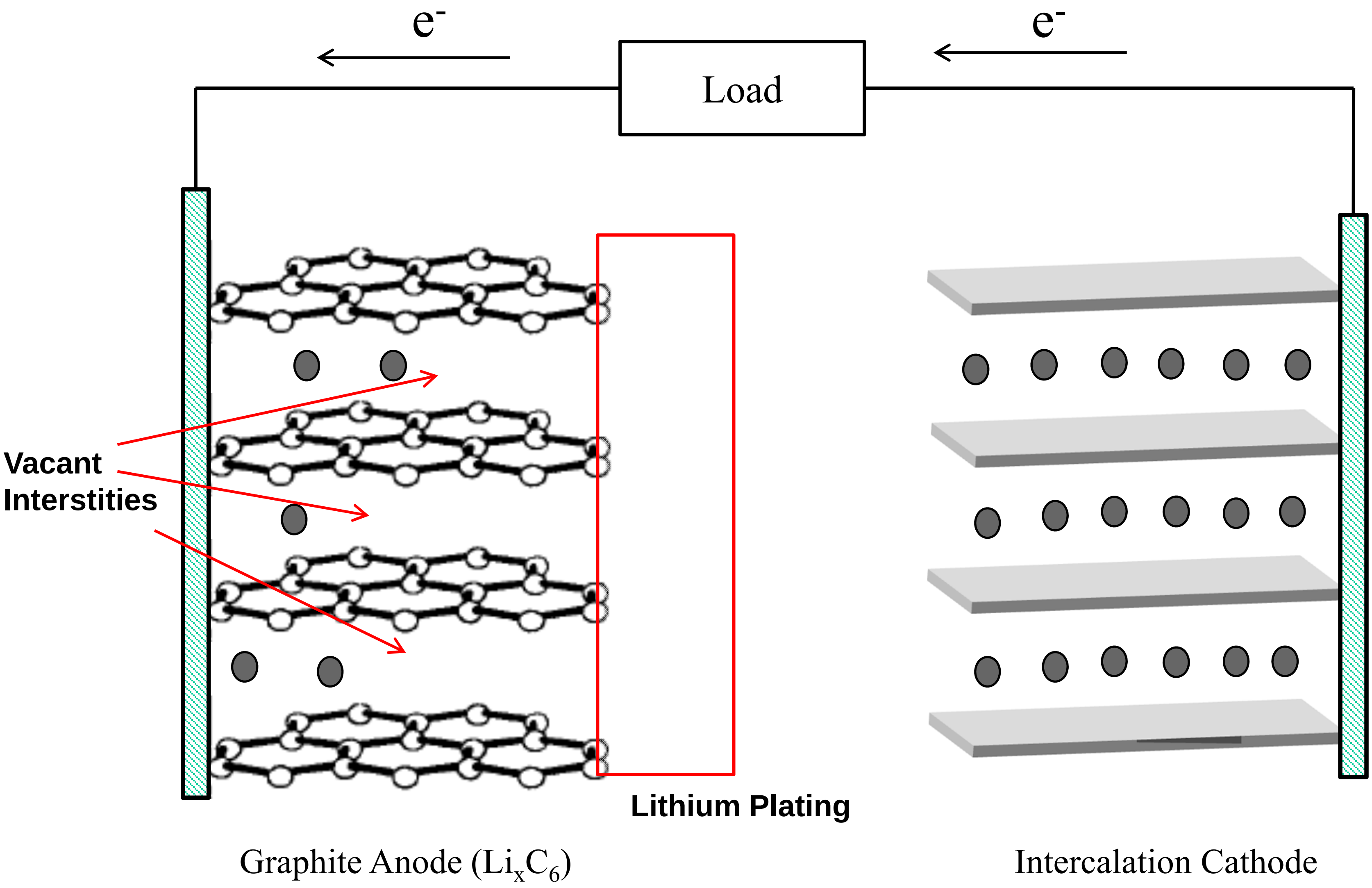
Intercalation Cathode
($Li_{1-x}CoO_2$; $Li_{1-x}FePO_4$;
$Li_{1-x}Mn_2O_4$ etc.)

# Charging using conventional CC-CV algorithm





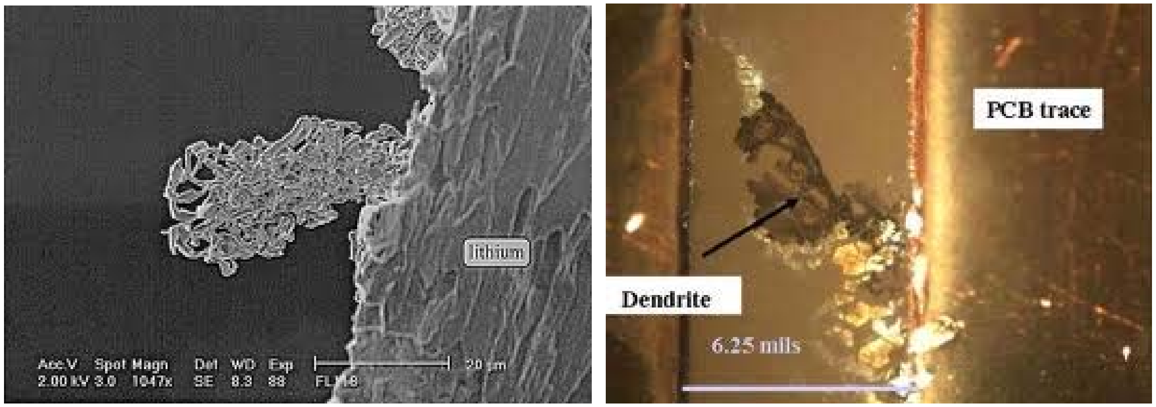
# Fast Charging



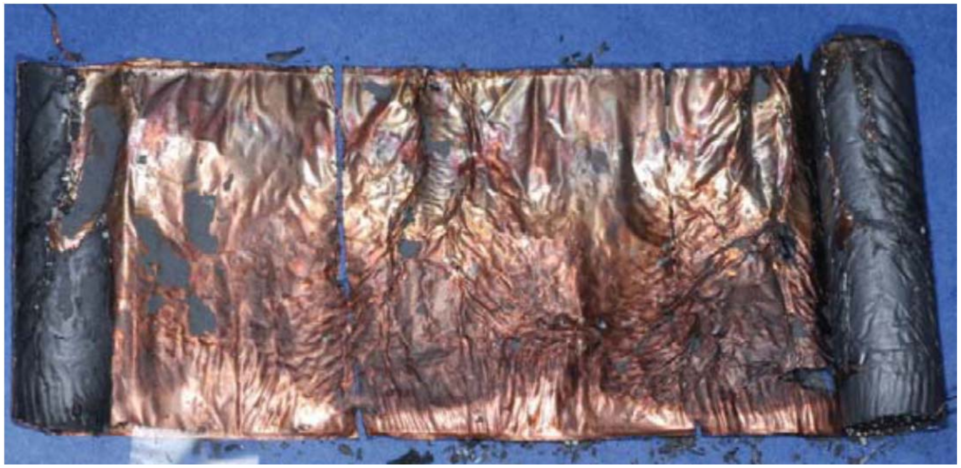
# Effects of fast charging

- Most fast charging methods have detrimental effect on battery life

Lithium plating on graphite Anode



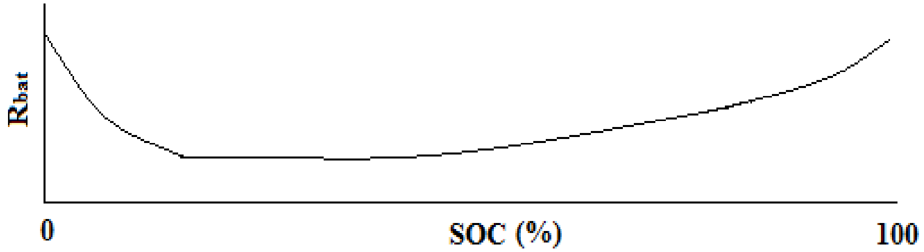
Dendrite growth

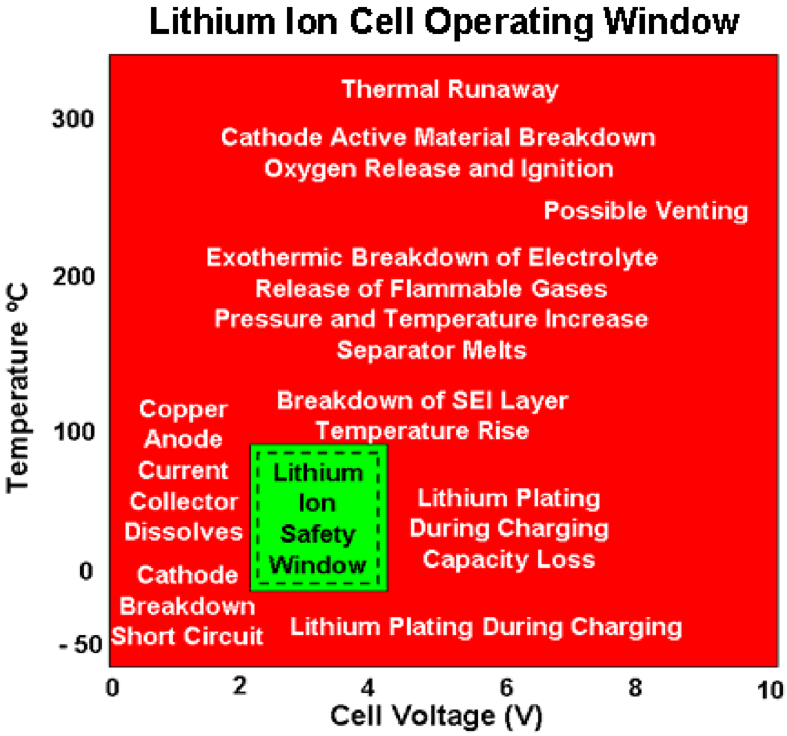


Separator puncture & Internal short-circuit due to dendrite growth

# Development of the charging method

- ✓ SOC governed fast charging algorithm
- ✓ Different charging stages to account for the varying internal impedance
- ✓ More setting time to smoothen out conc. gradients on anode surface
- ✓ Controlled charging for better safety



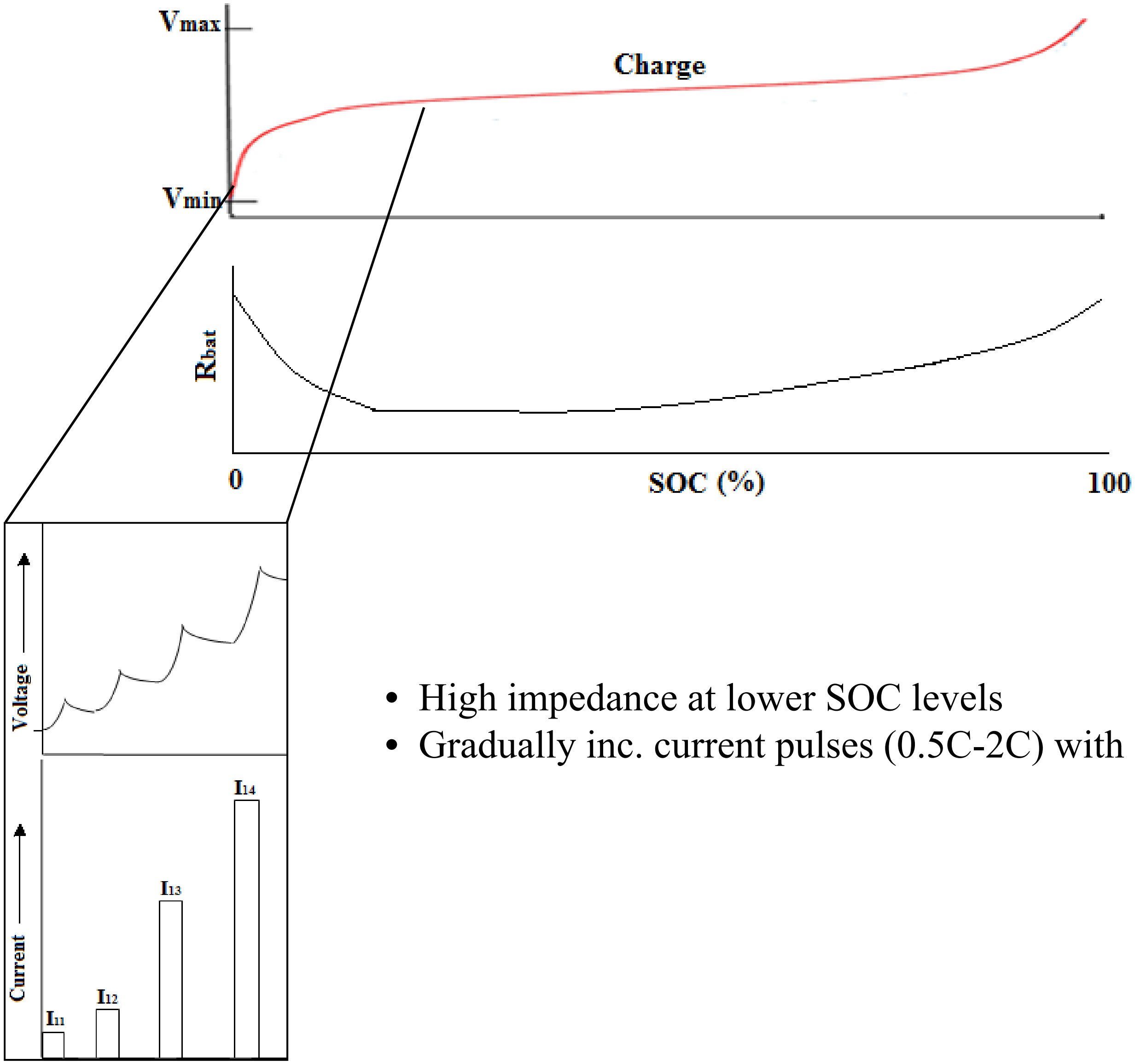


**References:**

1. Paryani et.al.; Fast charging of battery using adjustable voltage control; *US 2011/0012563 A1*; Tesla Motors Inc. (US), 2011
2. *www.electropaedia.com*

# Development of the charging method (contd.)

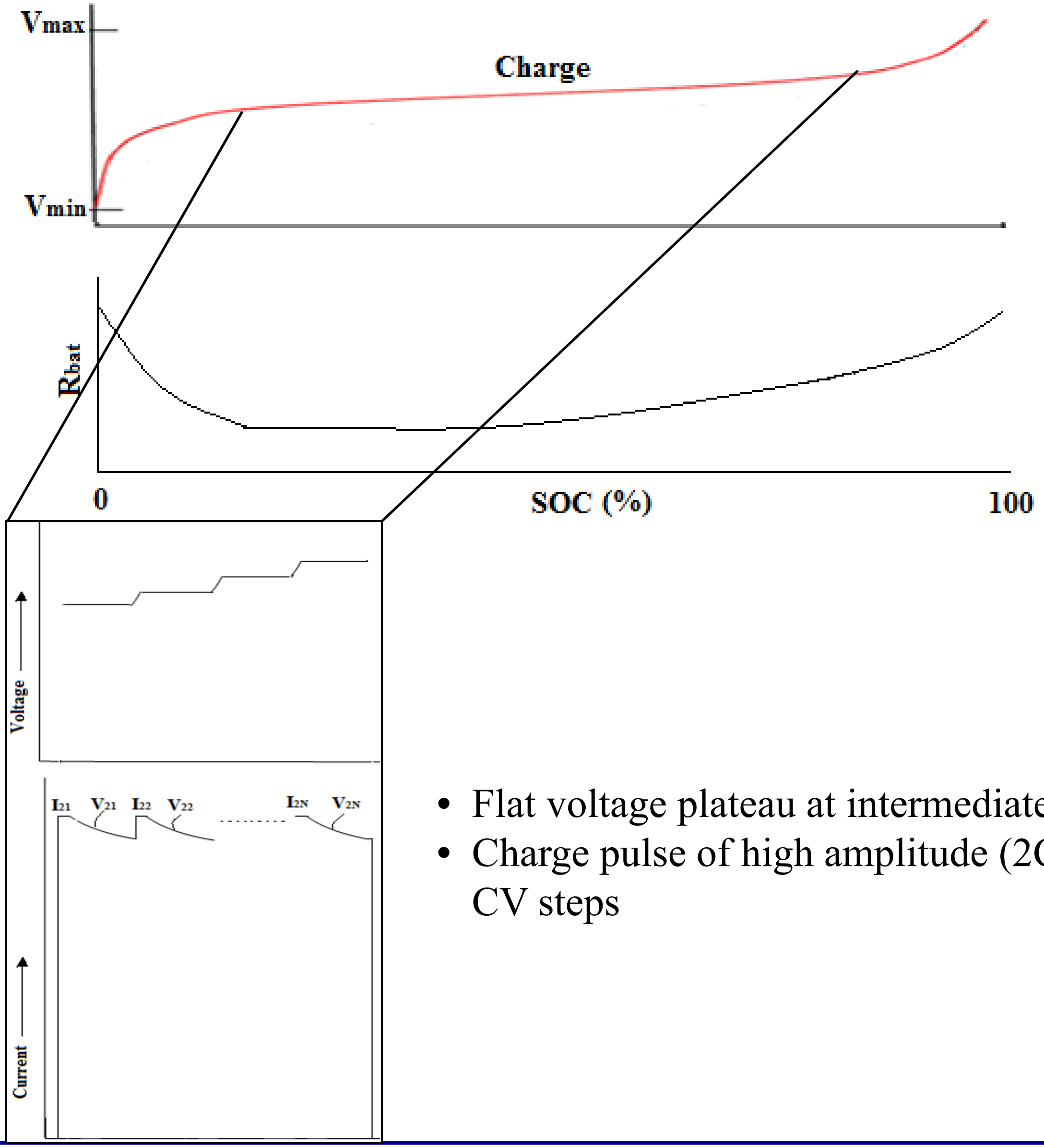
## Stage 1: Multiple CC charging ( 0 = SOC ≤ 50)



- High impedance at lower SOC levels
- Gradually inc. current pulses (0.5C-2C) with alternate rest periods

# Development of the charging method (contd.)

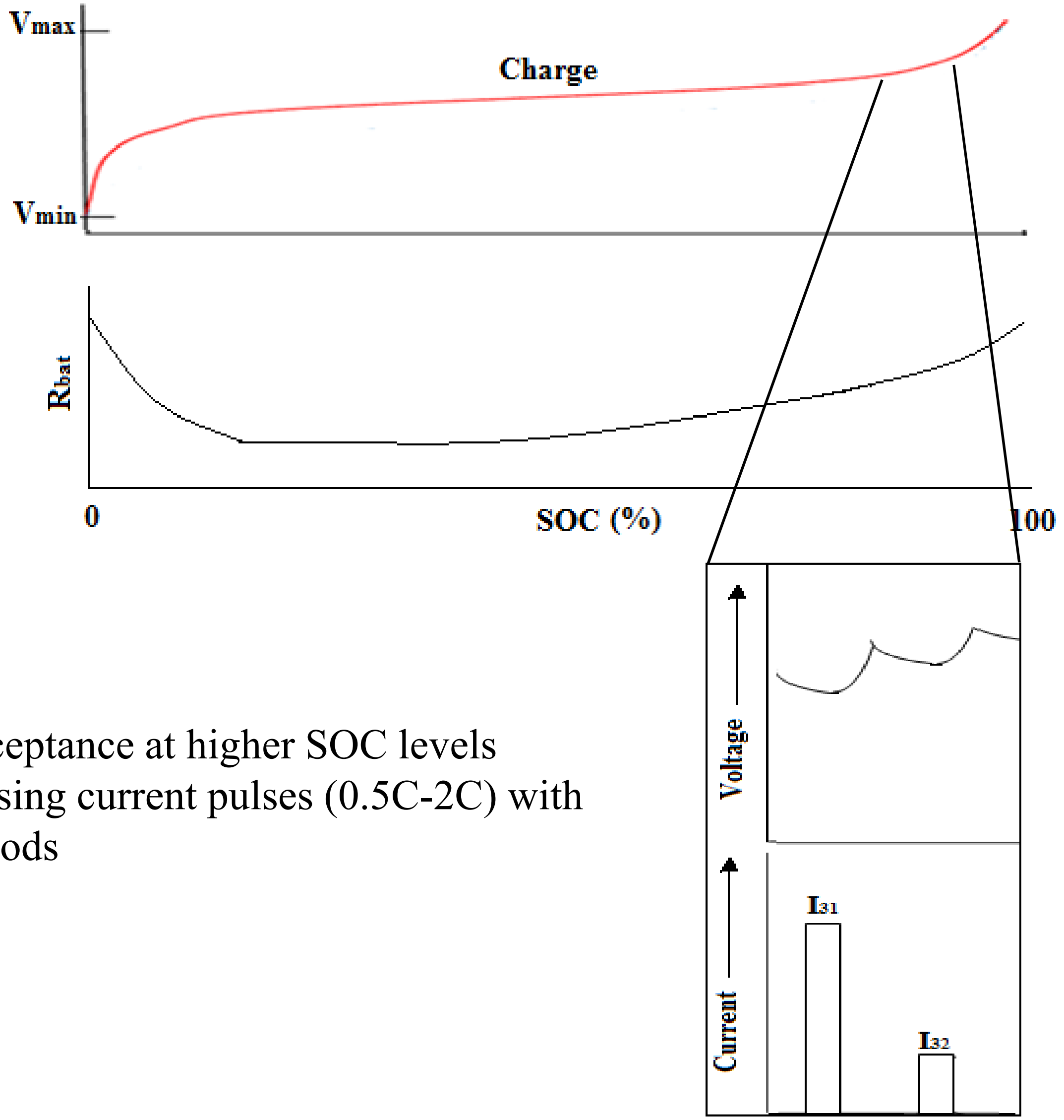
## Stage 2: Multiple CC-CV charging ( $50 \leq SOC \leq 80$)



- Flat voltage plateau at intermediate SOC levels
- Charge pulse of high amplitude (2C-8C) with alternate CV steps

# Development of the charging method (contd.)

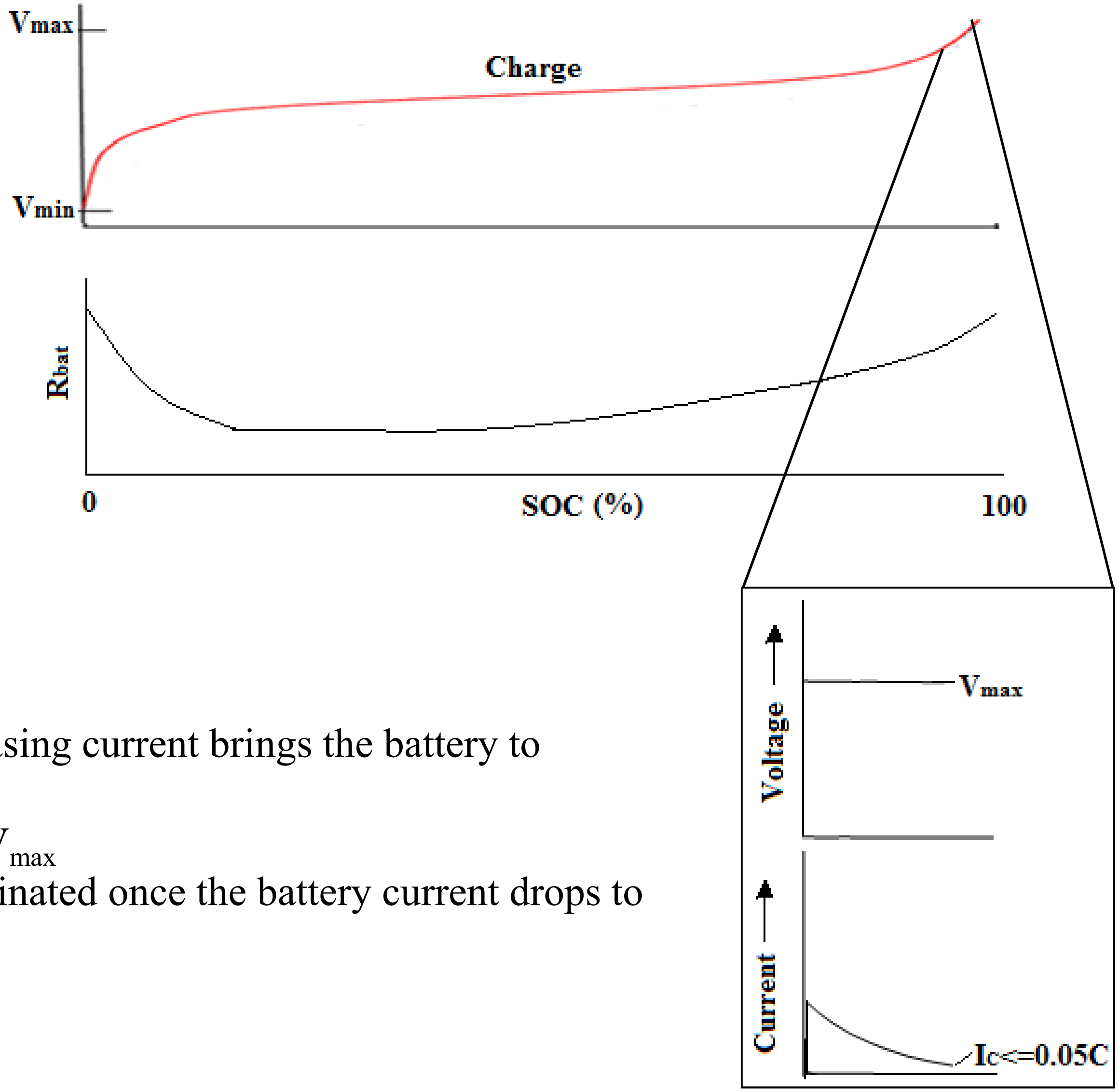
## Stage 3: Multiple CC charging ( 80 ≤ SOC ≤ 95)



- Lower charge acceptance at higher SOC levels
- Gradually decreasing current pulses (0.5C-2C) with alternate rest periods

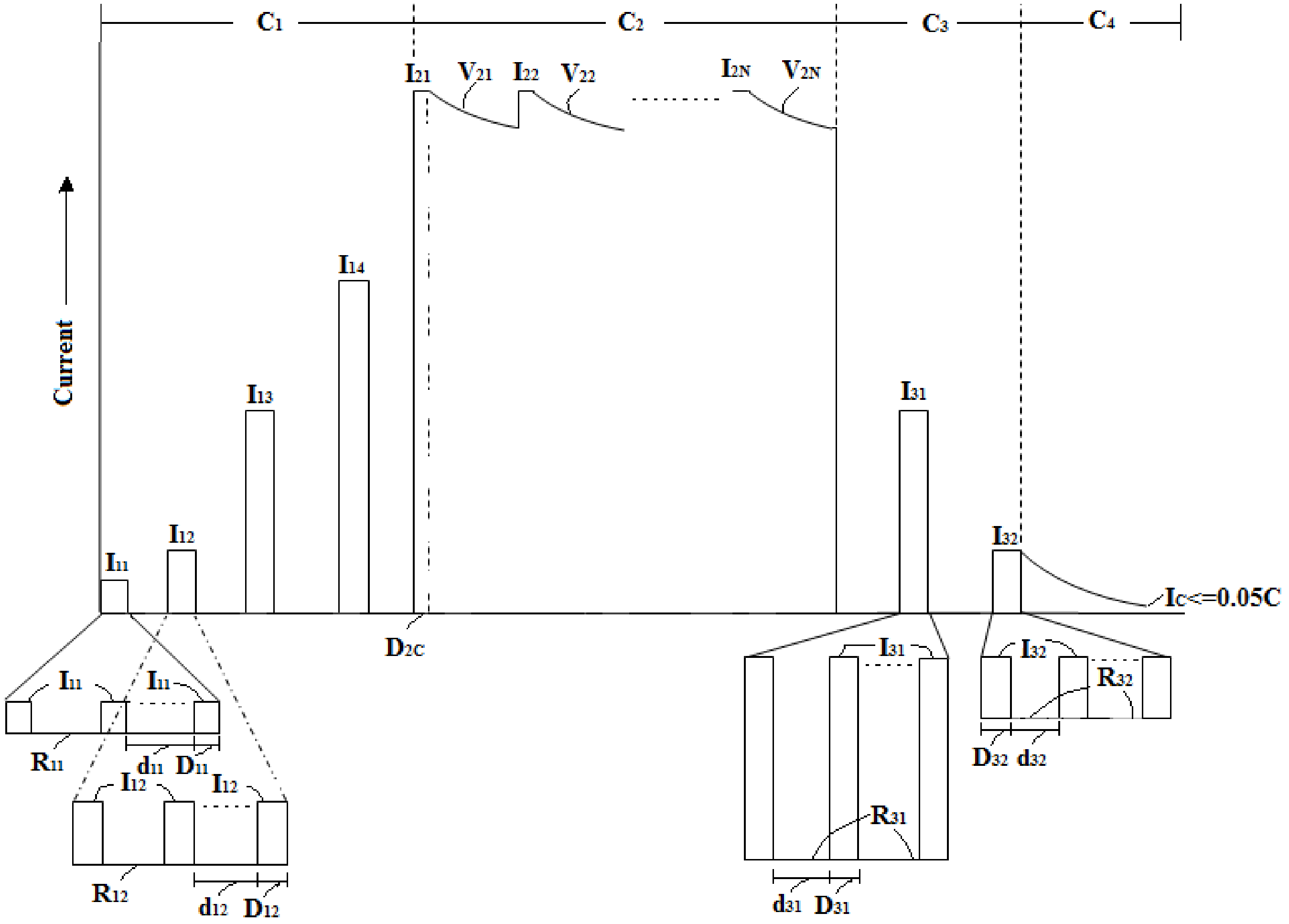
# Development of the charging method (contd.)

## Stage 4: CV charging ( 95 ≤ SOC = 100)



- Gradually decreasing current brings the battery to equilibrium
- CV charging at $V_{max}$
- Charging is terminated once the battery current drops to 0.1-0.05C

# Proposed  charging method



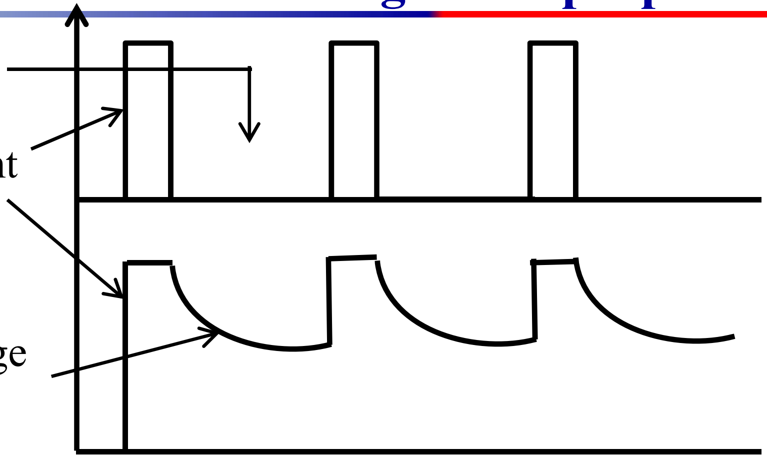
$C_1$:  m-$CC_i$ ;  $0 = SOC < 0.5$

$C_2$:  m-(CC-CV);  $0.5 \leq SOC < 0.80$

$C_3$:  m-$CC_r$;  $0.80 \leq SOC < 0.95$

$C_4$:  CV;  $0.95 \leq SOC = 1$

# Working of the proposed charging method



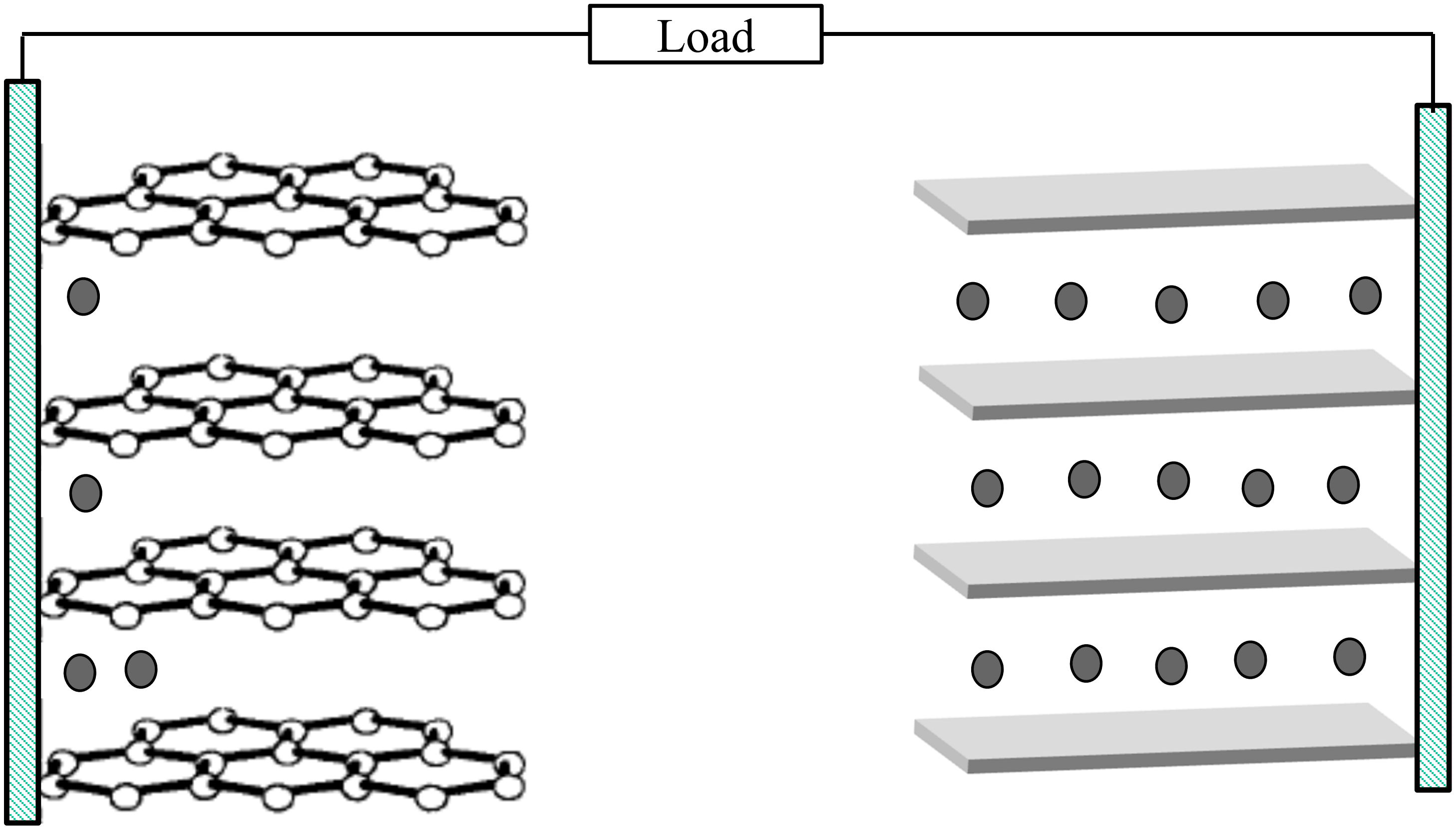
Rest period

Const. Current
Pulse

Const. Voltage
Step

Pulse Charging
(Stage 1 & Stage 3)

CC-CV Charging
(Stage 2)



# Model development with Comsol Multiphysics 4.3b

- Cell characteristics

| | |
|---|---|
| Cell chemistry | $LiC_6/LiMn_2O_4$ |
| Cell capacity, C | 10Ah |
| Charge cut-off voltage, $V_{max}$ | 4.2V |
| Discharge cut-off voltage, $V_{min}$ | 3.0V |
| Charge cut-off current, $I_{min}$ | 0.05C (5A) |

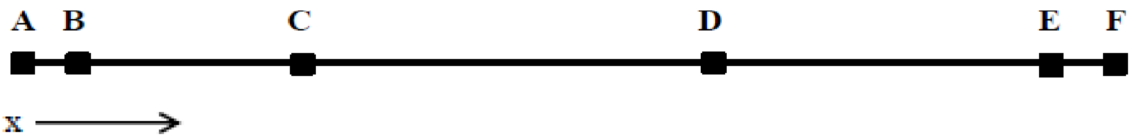
- Dependent variables

Solid phase potential, $\phi_s$
Electrolyte potential, $\phi_l$
Electrolyte salt concentration, $c_l$

- Material properties of the domain materials have been derived from that **Material Library**

# 1D lithium-ion battery model using **“Batteries and Fuel cells module”**

- Consists of 5 domains:
  -ve current collector (Copper) of length L_neg_cc
  -ve electrode ($Li_xC_6$) of length L_neg
  Separator with electrolyte (1:1 EC:DEC in $LiPF_6$ salt) of length L_sep
  +ve electrode ($Li_{1-x}Mn_2O_4$) of length L_pos
  +ve current collector (Aluminum) of length L_pos_cc



Where,

A; x=0
B; x=L_neg_cc
C; x=L_neg_cc+L_neg
D; x=L_neg_cc+L_neg+L_sep
E; x= L_neg_cc+L_neg+L_sep+L_pos
F; x= L_neg_cc+L_neg+L_sep+L_pos+L_pos_cc

# Governing equations

| Governing equation | Physics | Applied to | Expression |
|---|---|---|---|
| Butler-Volmer | Electrode kinetics | +ve & -ve electrodes | $J_n = \frac{i_0}{F}\left[\exp\left(\frac{\alpha_a F\eta}{RT}\right) - exp\left(\frac{-\alpha_c F\eta}{RT}\right)\right]$ |
| Ohm's law (liquid phase) | Charge balance of Li$^+$ in electrolyte | Electrolyte region in separator, +ve & -ve electrodes | $i_l = -\sigma_{l,eff}\nabla\emptyset_l + \frac{2RT\sigma_{l,eff}}{F}\left(1+\frac{\partial lnf}{\partial lnc_l}\right)(1 - t_+^0)\nabla lnc_l$ |
| Ohm's law (solid phase) | Charge balance of Li$^+$ in the solid matrix | +ve & -ve electrodes | $i_s = -\sigma_{s,eff}\nabla\emptyset_s$ |
| Fick's second law (liquid phase) | Diffusion in electrolyte | Electrolyte region in separator, +ve & -ve region | $\epsilon_l\frac{\partial c_l}{\partial t} = \frac{\partial}{\partial x}\left(D_{l,eff}\frac{\partial c_l}{\partial x}\right) + (1 - t_+^0)a_s J_n$ |
| Fick's second law (solid phase) | Intercalation / diffusion of Li$^+$ into the active materials | +ve & -ve electrodes | $\frac{\partial c_s}{\partial t} = D_s\left[\frac{\partial^2 c_s}{\partial r^2} + \frac{2}{r}\left(\frac{\partial c_s}{\partial r}\right)\right]$ |
| Double layer capacitance | Film formation on electrode surface | +ve & -ve electrodes | $i_{dl} = \left(\frac{\partial\emptyset_s}{\partial t} - \frac{\partial\emptyset_l}{\partial t}\right)a_{dl}C_{dl}$ |

# Boundary conditions

| Physics | Applied at | Expression |
|---|---|---|
| No flux condition | -ve electrode \| -ve current-collector interface | $\frac{\partial c_{s,n}}{\partial x}_{x=L\_neg\_cc} = 0$ |
| No flux condition | +ve electrode \| +ve current-collector interface | $\frac{\partial c_{s,n}}{\partial x}_{x=L\_neg\_cc+L\_neg+L\_sep+L\_pos} = 0$ |
| No flux condition | Center of active material particles in +ve & -ve electrodes | $\frac{\partial c_s}{\partial r}_{r=0} = 0$ |
| Flux is equal to the rate of generation / consumption of $Li^+$ at particle surface | Surface of active material particles in +ve & -ve electrodes | $\frac{\partial c_s}{\partial r}_{r=r_p} = J_n$ |
| Electric ground | -ve electrode | $\emptyset_s \vert_{x=0} = 0$ |
| Applied current density | +ve electrode | $\emptyset_s \vert_{x=L\_neg\_cc+L\_neg+L\_sep+L\_pos+L\_pos\_cc} = -i\_app$ |

# Modeling charging methods using **"Events interface"**

- **Explicit Event**: Occurs at predetermined times
  Can be repeatedly invoked until the desired condition is fulfilled
  $C_1$ and $C_3$ stages modeled using explicit events

- **Implicit Event**: Occurs when a condition involving an indicator state is fulfilled
  $C_2$ and $C_4$ stages modeled using implicit events

- **Discrete states**: Describes the individual steps in a load profile
  Needs to be used for both implicit and explicit events
  e.g. OCV, C1_CC_CH1, C1_CC_CH2, C2_CC_CH1, C2_CV_CH1, etc.

- **Indicator states**: Indicates the conditions that needs to be fulfilled to switch from one step to another
  To be used only for implicit events
  e.g.

| Step change | Condition |
|---|---|
| c2_cc_ch1_to_c2_cv_ch1 | C2_CC_CH1*(t-(t+20)) |
| c2_cv_ch1_to_c2_cc_ch2 | C2_CV_CH1*(SOC-(SOC+0.5)) |
| c2_cc_ch2_to_c2_cv_ch2 | C2_CC_CH2*(t-(t+50)) |

# Modeling charging methods using **"Events interface"** (contd.)

- Applied current is defined using a global ODEs and DAEs interface

  e.g. i_C1_1 = C1_CC_CH1*(i_ch11-i_C1_1) + !C1_CC_CH1*i_C1_1
  i_C1_2 = C1_CC_CH2*(i_ch12-i_C1_2) + !C1_CC_CH2*i_C1_2
  i_C2 = C2_CC_CH1*(i_ch2-i_C2) + C2_CV_CH1*(E_cell-E_max1) + ……….. +
  !C2_CC_CH1*!C2_CV_CH1*…………*i_C2

- Shift from one stage to another depends on the SOC of the cell, given by

$$SOC = \frac{\int c_s \, dS}{c_{s,max} L}$$

  e.g. i_C11 = i_C1_1*(SOC<0.3)
  i_C12 = i_C1_2*(SOC>0.3)*(SOC<0.5)
  i_C20 = i_C2*(SOC>0.5)*(SOC<0.8)

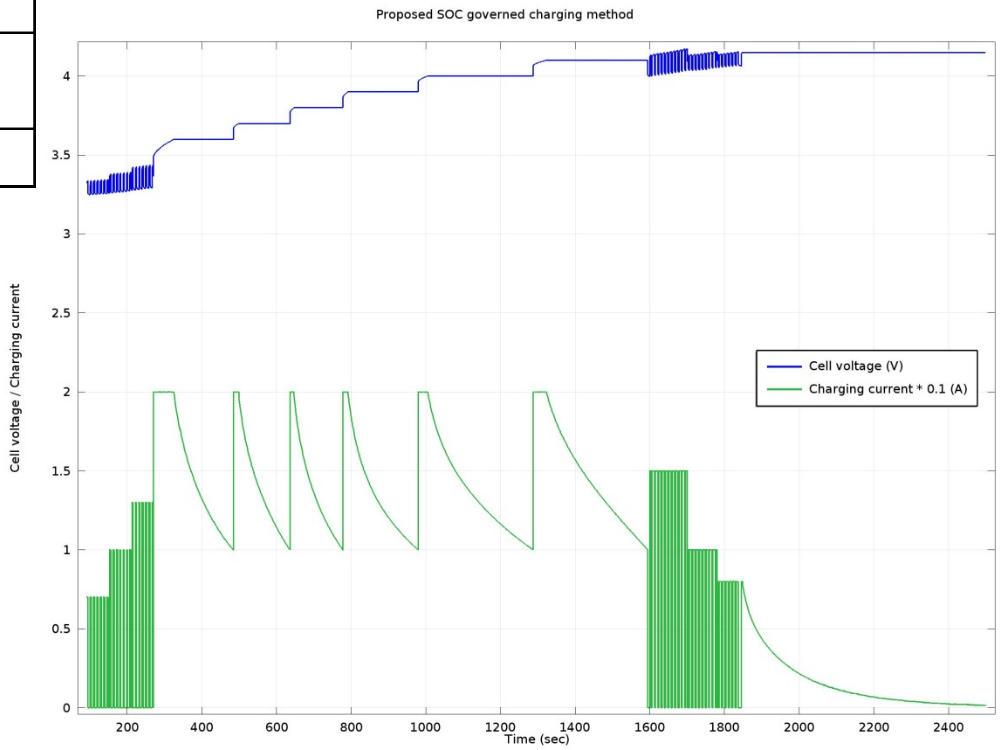
- Applied current is defined as

  i_app = i_C11 + i_C12 + ……… + i_C20 + i_C31 + i_C32 + ………. + i_C40

# Charging profile modeled using Comsol Multiphysics 4.3b

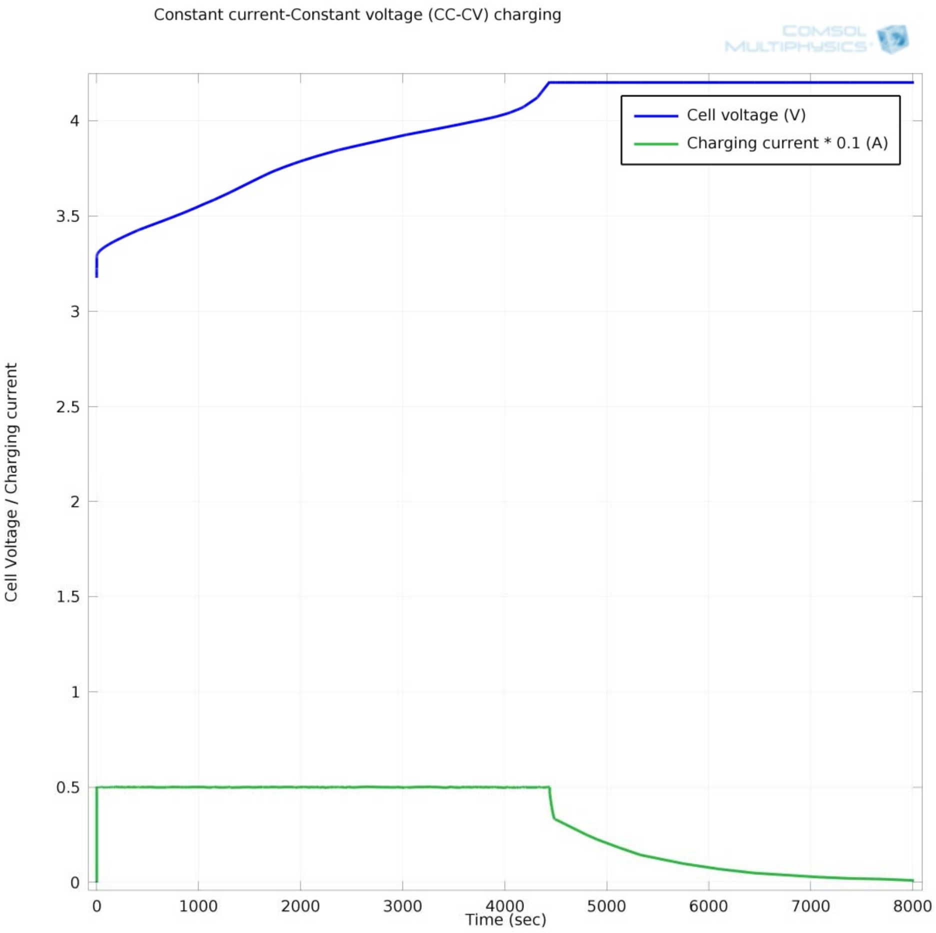
| Charging stage ($C_x$) | Sub step ($C_{xy}$) | Charging current ($i\_C_{xy}$) | SOC range | Charging time (s) |
|---|---|---|---|---|
| $C_1$ | $C_{11}$ | 0.7C (7A) | 0.2-0.3 | 280 |
| | $C_{12}$ | 1C (10A) | 0.3-0.4 | |
| | $C_{13}$ | 1.3C (13A) | 0.4-0.5 | |
| $C_2$ | $C_{20}$ | 2C (20A) | 0.5-0.8 | 1300 |
| $C_3$ | $C_{31}$ | 1.5C (15A) | 0.8-0.85 | 280 |
| | $C_{32}$ | 1C (10A) | 0.85-0.9 | |
| | $C_{33}$ | 0.8C (8A) | 0.9-0.95 | |
| $C_4$ | $C_{40}$ | 0.8C (8A) to 0.05C (0.5A) | 0.95-1.0 | 640 |
| Total charging time | | | | 2500 |

**Proposed charging method**



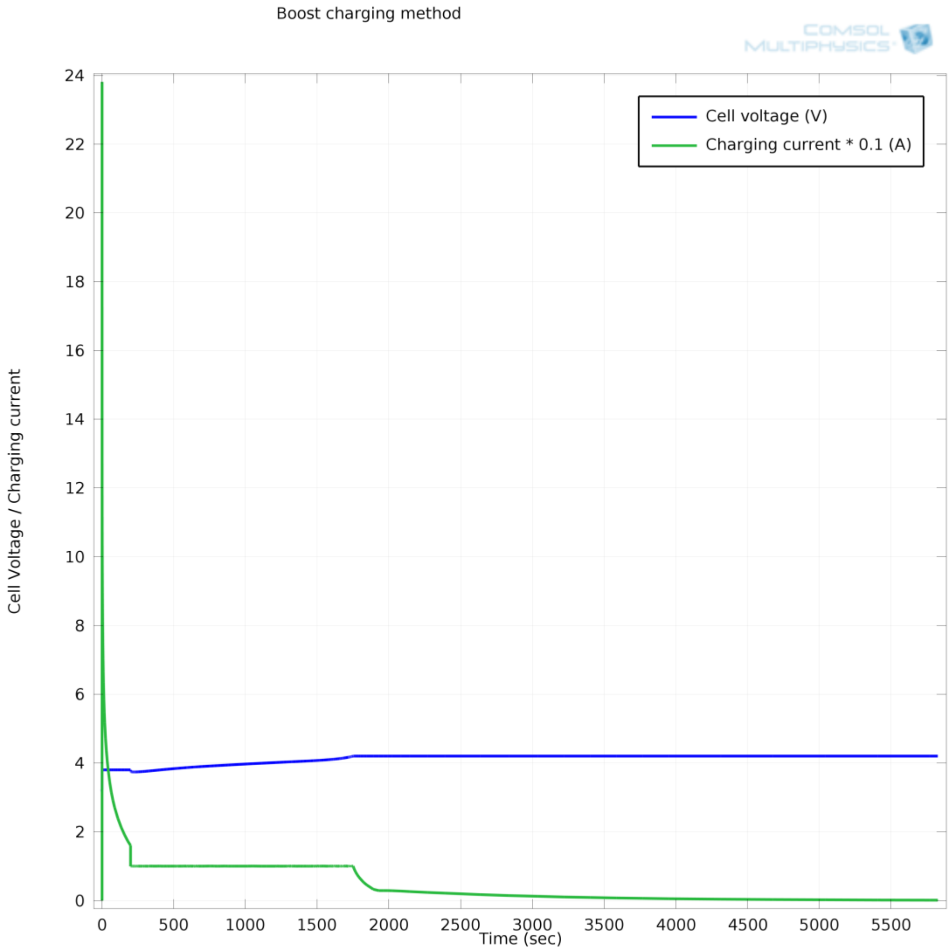
# Constant-current constant-voltage (CC-CV) charging

| Charging stage | Charging current | Step limit | Charging time (s) |
|---|---|---|---|
| Constant current | 0.5C (5A) | till the cell reaches $V_{max}$ | 4460 |
| Constant voltage | 0.5C (5A) to 0.05C (0.5A) | @ $V_{max}$ till the charging current drops to $I_{min}$ | 3540 |
| Total charging time | | | 8000 |



# Boost charging

| Charging stage | Charging current | Step limit | Charging time (s) |
|---|---|---|---|
| Boost charging | 20C-50C (max.) | 3.5 mins | 210 |
| Constant current | 1C (10A) | till the cell reaches $V_{max}$ | 1540 |
| Constant voltage | 1C (10A) to 0.05C (0.5A) | @ $V_{max}$ till the charging current drops to $I_{min}$ | 3250 |
| | | Total charging time | 5000 |

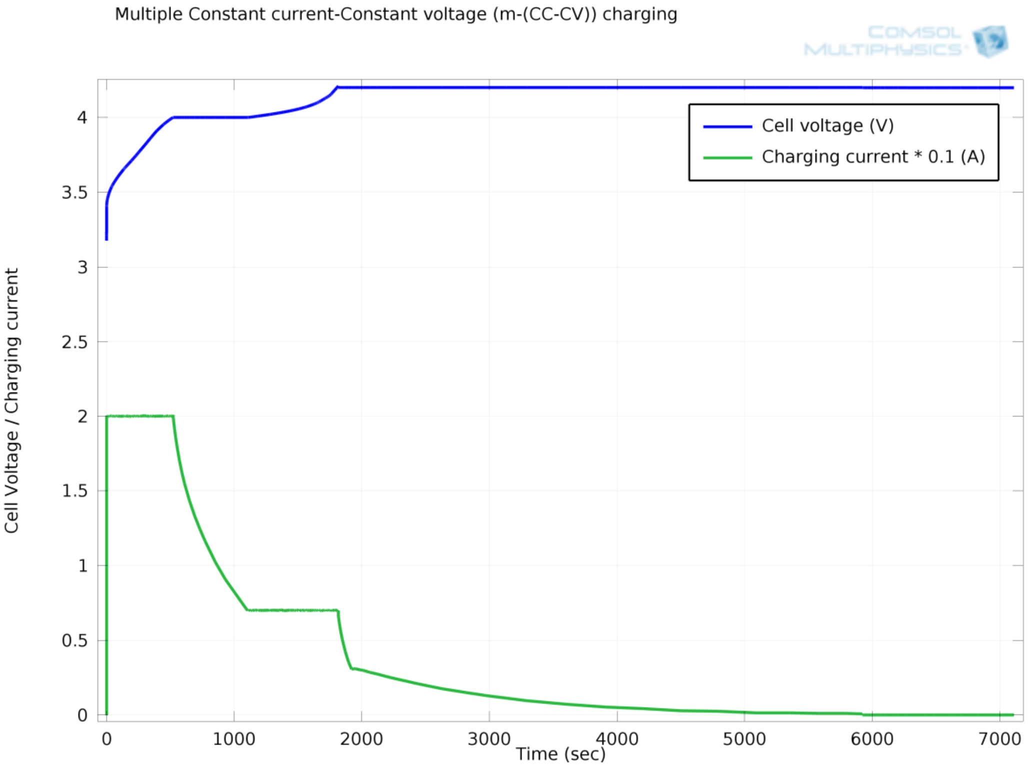


**References:**

1. Notten et.al, Method and charger for boost charging a rechargeable battery on the basis of a physical model, US2010/0148731 A1, 2010
2. Notten P.H.L. et.al, Boost-charging Li-ion batteries: A challenging new charging concept, Journal of Power Sources, 145, 89-94 (2005)

# Multistage constant-current constant-voltage, m(CC-CV) charging

| Charging stage | Charging current | Step limit | Charging time (s) |
|---|---|---|---|
| Constant current | 2C (20A) | till the cell reaches $V_{0.8}$ | 550 |
| Constant voltage | 2C (10A) to 0.7C (7A) | @ $V_{0.8}$ till the charging current drops to 0.7C (7A) | 550 |
| Constant current | 0.7C (7A) | till the cell reaches $V_{max}$ | 750 |
| Constant voltage | 0.7C (7A) to 0.05C (0.5A) | @ $V_{max}$ till the charging current drops to $I_{min}$ | 3600 |
| | | Total charging time | 5400 |



**References:**

1. Paryani et.al, Fast charging of battery using adjustable voltage control, US2011/0012563 A1, 2011
2. Tomohisa Hagino, Pulse charging method for rechargeable batteries, US5808447, 1998

# Comparison of charging methods

- ✓ Simulation has been carried for 500 cycles
- ✓ Capacity fade as a result of cycling
- ✓ Initial capacity: 10Ah

| **Charging method** | **Charging time (s)** | **Cell capacity after 500 cycles (Ah)** | **Capacity fade (%)** |
|---|---|---|---|
| CC-CV | 8000 | 9.06 | 9.4% |
| m(CC-CV) | 5400 | 8.63 | 13.7% |
| Boost | 5000 | 8.42 | 15.8% |
| Proposed SOC based | 2500 | 8.96 | 10.4% |

## Advantages of the present method

- ✓ Faster charging
- ✓ Lower capacity fade
- ✓ Lower safety risks due to controlled charging

## Future work

- ✓ Inclusion of side reaction (e.g. SEI formation)
- ✓ Temperature performance
- ✓ 3D modeling to visualize current density distribution on electrode surface

# Queries