MathWorks
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Developing Battery Management Systems

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MathWorks

Introduction to ONE and myself

Headquartered in Novi, Michigan, ONE is on a mission to overcoming the barriers to electrification and transforming the energy storage industry with offices in Michigan and California. Product offerings include the lithium-phosphate iron (LFP) batteries, Aries I and Aries II, and the recently announced Aries Grid, utility-scale battery system that can serve as long-duration energy storage. Voted #3 Startup among 11,000 companies by Forbes magazine.

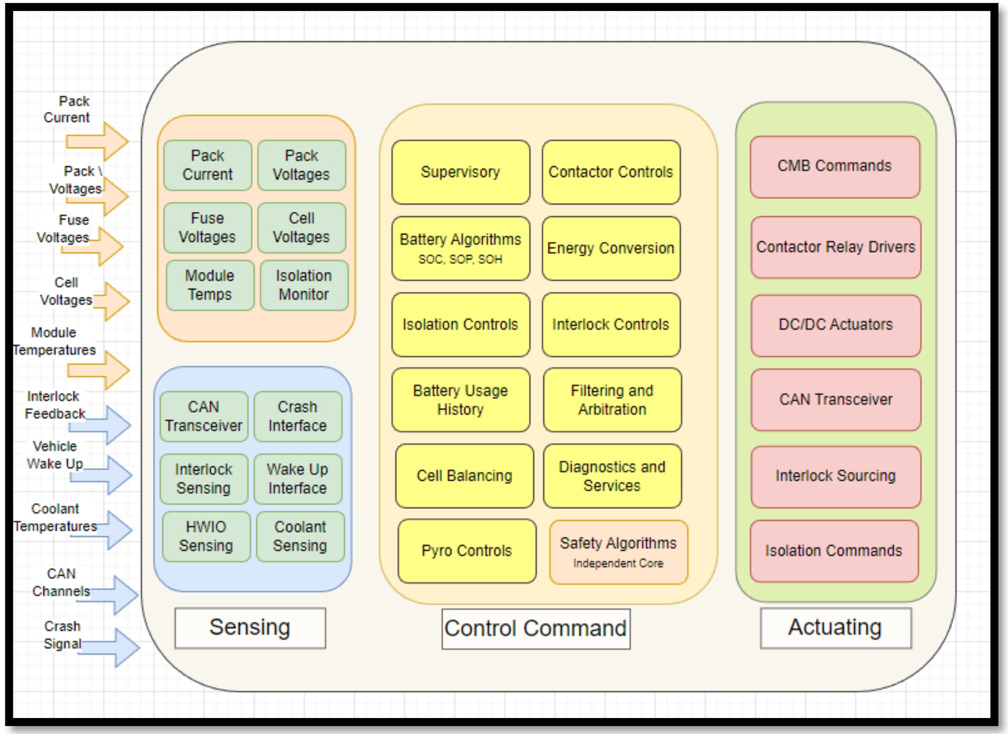
Awad Syed Ali, director of systems engineering at Our Next Energy (ONE), is working on developing best-in-class controls algorithms and systems engineering. Awad has worked on energy storage solutions for over a decade; starting in 2011 when he was part of the controls team at Bosch that developed the BMS system for the Chrysler F500e. Awad has a Master of Science in electrical engineering from The Ohio State University, majoring in power electronics and controls systems.

Presentation Overview

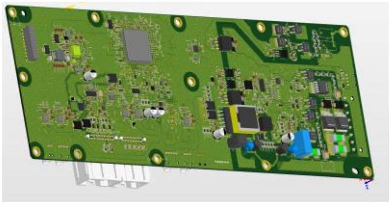
- Overview of Battery Management Systems (BMS)
- Battery Management Systems Core Functions
- Main Challenges in Battery Controls Development
- Algorithm Development
  - SOC, SOP, SOH
- Validation Methods
- Summary

Overview of Battery Management Systems

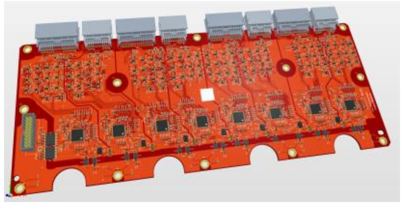
The Battery Management System (BMS) is responsible for monitoring the state of the battery pack cells and ensuring that the proper charging, discharging and diagnosing operations are performed to maintain the maximum health of the battery pack.



Battery Monitoring Controller (BMC): The electronic controller that has the required sense, actuation circuits, microprocessor(s) and embedded software.



Cell Monitoring Boards (CMBs): Sensing circuits mounted on/adjacent cell modules that are tasked with measuring cell voltages, temperatures & actuate cell balancing.



BMS Core Functions

Cell Module Management

- Acquire cell voltages and module temperatures and communicate with the BMC.
- Actuate cell balancing.
- Diagnose faults within the cell monitoring IC

Battery Pack Controls

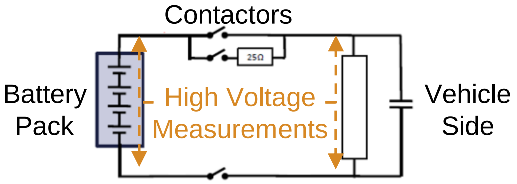
- Battery pack supervisory controls
- Calculate/estimate the state of the battery (SOC, SOP and SOH)
- Actuate valves/pumps for system thermal management.
- High voltage data acquisition (voltages, currents)
- Record battery usage history for service
- Open and close contactors, perform precharge
- Manage vehicle communication (CAN/Ethernet)

System Safety

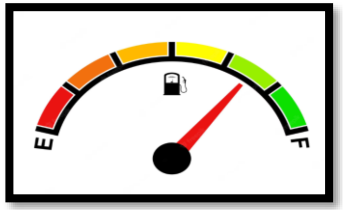
- React to safety events (thermal/loss of propulsion) perform a controlled shutdown and inform driver.
- Check battery isolation with chassis.
- Sense and prevent battery shock hazards.

Key Battery Algorithms

- Contactor Controls: Controlling actuators that connect the battery to the powertrain.



- State of Charge (SOC): Estimation of percentage available charge



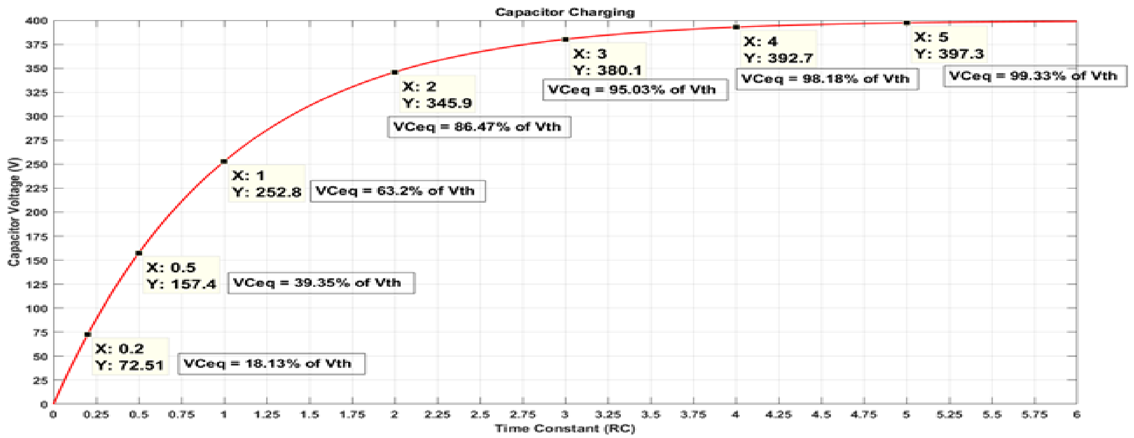
- State of Power (SOP): Estimation of available power

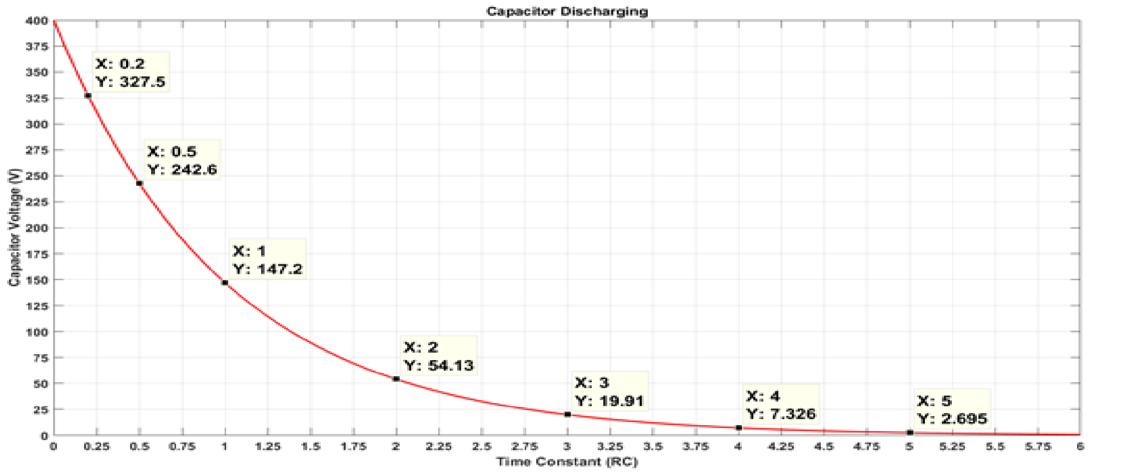
- State of Health (SOH): Tracking aging and capacity loss

Contactor Controls

Modeling precharge timing

- Precharge is a battery operation of using a resistive path via a small contactor during initial connection. This prevents a large inrush current and protects against arcing.
- Modeling battery pack allows creating energizing and de-energizing curves for precharge operation.
- Accurate circuit simulations helps in choosing components that can withstand system stress and operate for desired lifetime.
- Simulations enable calibrating diagnostics for successful and failed precharge.
- Simscape Electrical toolbox has come in very handy in modeling battery packs and components.





SOC Estimation Methodology
Coulomb Counting

From EEPROM SOC value written at shutdown

High-Accuracy Current Sensor with independent secondary current sensor and current rationality check in place to avoid large current accumulation error in single charge-discharge cycle

$$SOCc(t) = SOC_{init} - \frac{\int I(t)dt}{Cap}$$

Cycle Life from SOH based on calculated throughput compared with cell cycle life.

SOC Correction: Reset applied at top of charge and bottom of charge.

Cons:

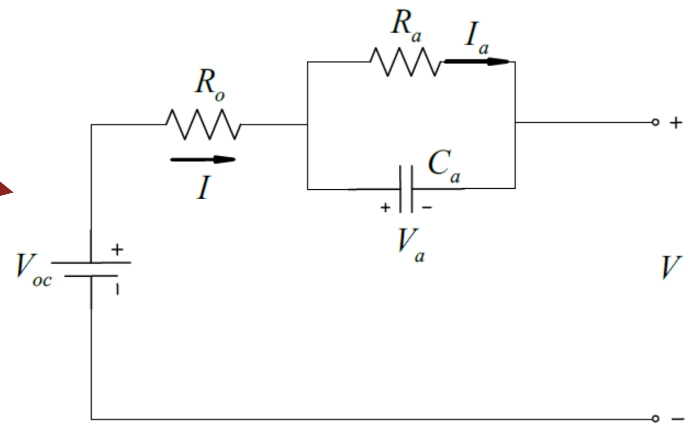
Error accumulates over cycles
No correction outside of top and bottom

SOC Estimation Methodology

Kalman Filter

- Model governing equations

$$\mathbf{x}_k = \mathbf{A}_{k-1}\mathbf{x}_{k-1} + \mathbf{B}_{k-1}\mathbf{u}_{k-1} + w_{k-1}$$
$$\mathbf{y}_k = \mathbf{C}_k\mathbf{x}_k + \mathbf{D}_k\mathbf{u}_k + v_k$$



Cell model

$$\mathbf{x}_k = \begin{bmatrix} V_{oc} \\ V_a \end{bmatrix}, \mathbf{y}_k = V_k, \mathbf{u}_k = I_k$$

$$\mathbf{A}_k = \begin{bmatrix} 1 & 0 \\ 0 & \theta \end{bmatrix}, \mathbf{B}_k = \begin{bmatrix} 0 \\ R_a(1-\theta) \end{bmatrix}$$

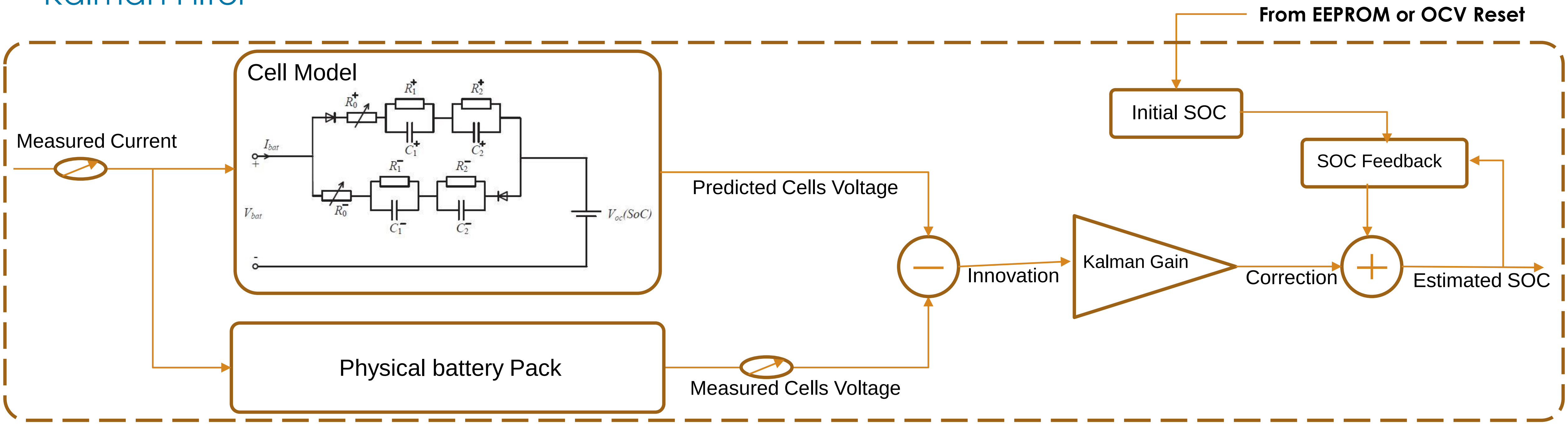
$$\mathbf{C}_k = [1 \quad -1], \boldsymbol{D}_k = [-R_o]$$

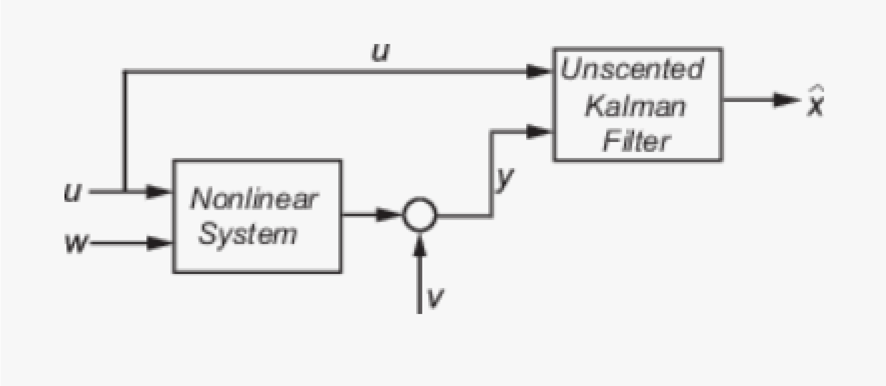
KF theory can be applied by viewing each cell in the battery pack as a dynamic system whose inputs include the current and temperature of the cell and whose output is the terminal voltage.

$$\dot{V}_a = -\frac{V_a}{R_a C_a} + \frac{I}{C_a}$$
$$V = V_{oc} - V_a - I R_o$$

SOC Estimation Methodology

Kalman Filter

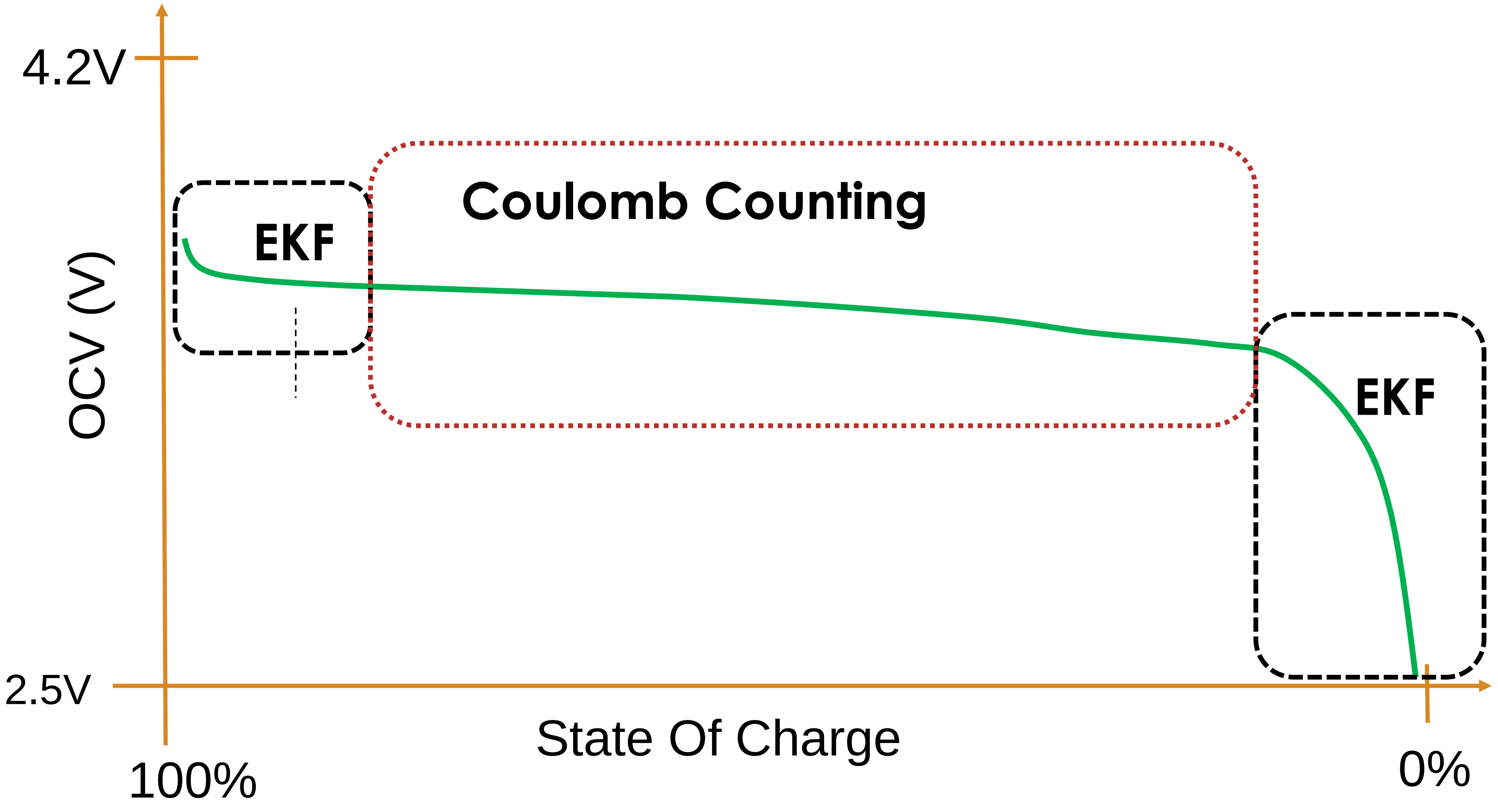




- Simulink provides library blocks for Kalman filters that are a good starting point.

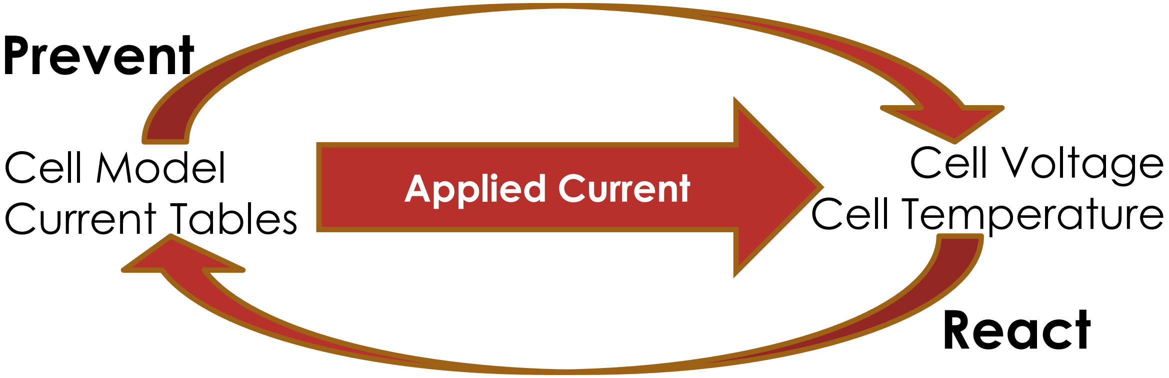
SOC Estimation Methodology

Hybrid Approach



SOP Calculation Methodology

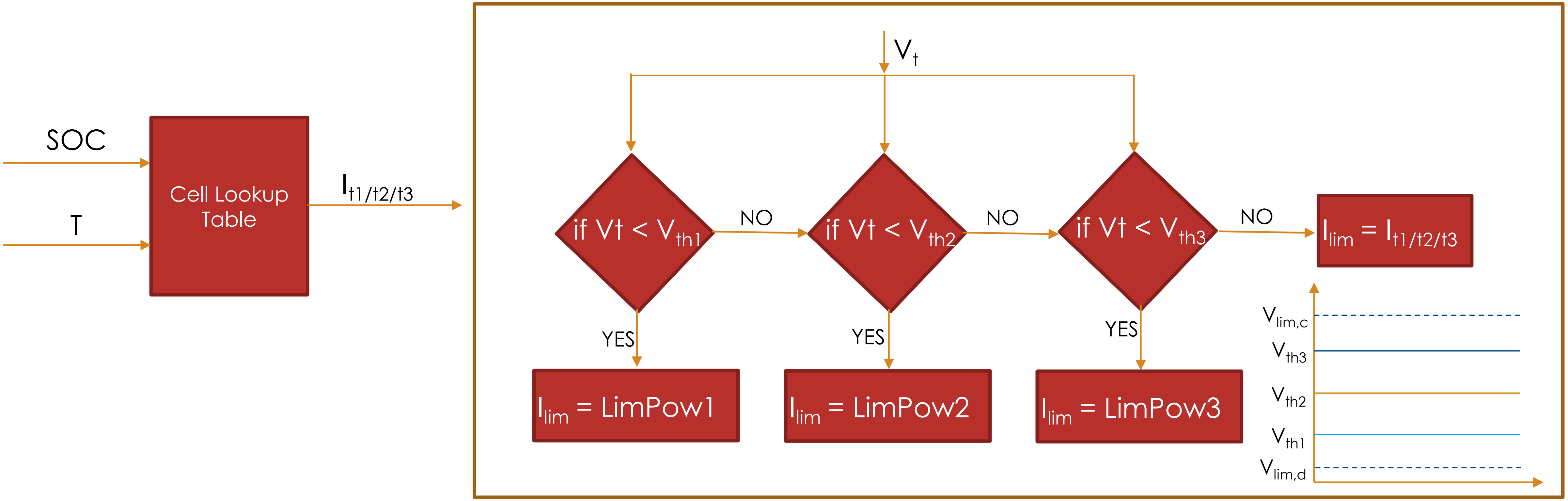
- Understanding what limits power
- Cell Current Limits
- Cell Voltage Limits
- Peak Power limits
- Cell State-Of-Charge
- Fault mode limits



SOP Methodology

Static Look Up

Determining the highest stepwise current that can be applied to the battery, while still maintaining its voltage within the manufacturer specified range, for a given pulse period.



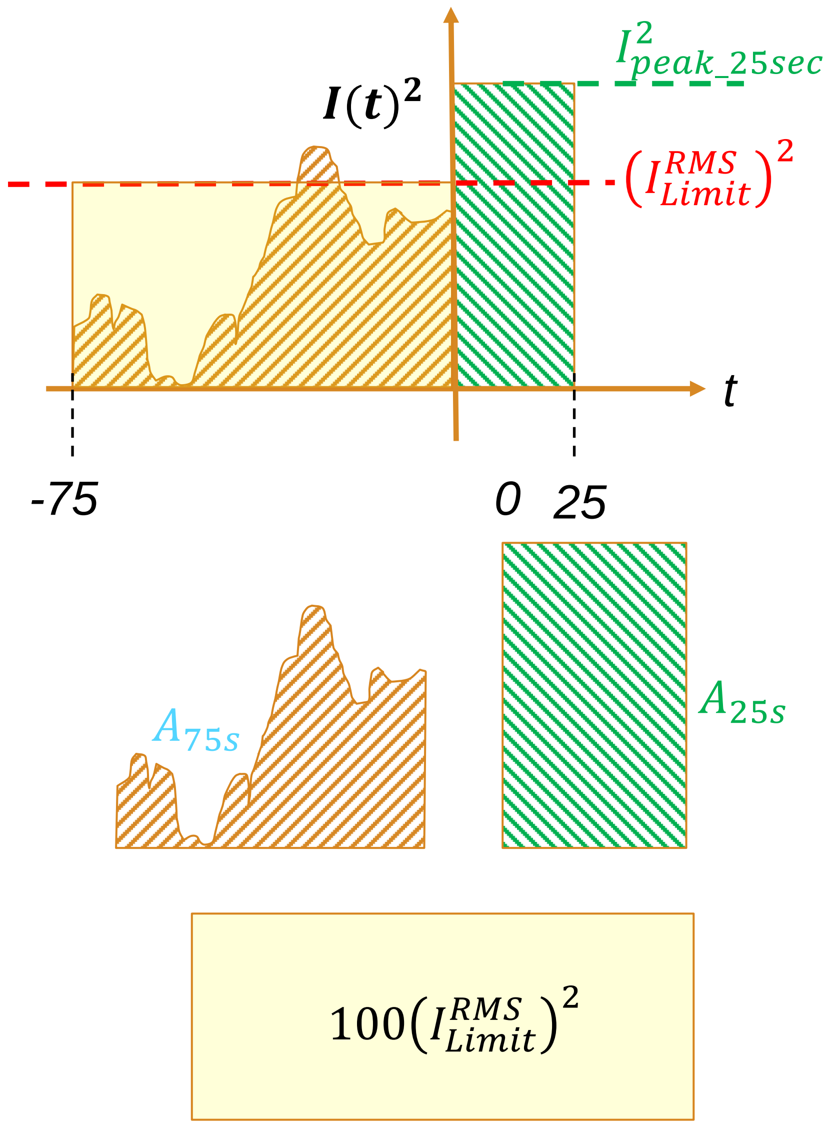
SOP Calculation Methodology

Rolling Window RMS

- Cell specified limit from Look up table
- Rolling Window considering past current though cell
- Determines maximum current for future time horizon to reach a maximum Irms integral

$$\int_{-75}^{25} I^2 dt = A_{75s} + A_{25s} \leq 100\left(I_{Limit}^{RMS}\right)^2$$

$$I_{peak\_25sec}^2 = A_{25s}/2 = \frac{100\left(I_{Limit}^{RMS}\right)^2 - A_{75s}}{2}$$



SOH Calculation Methodology

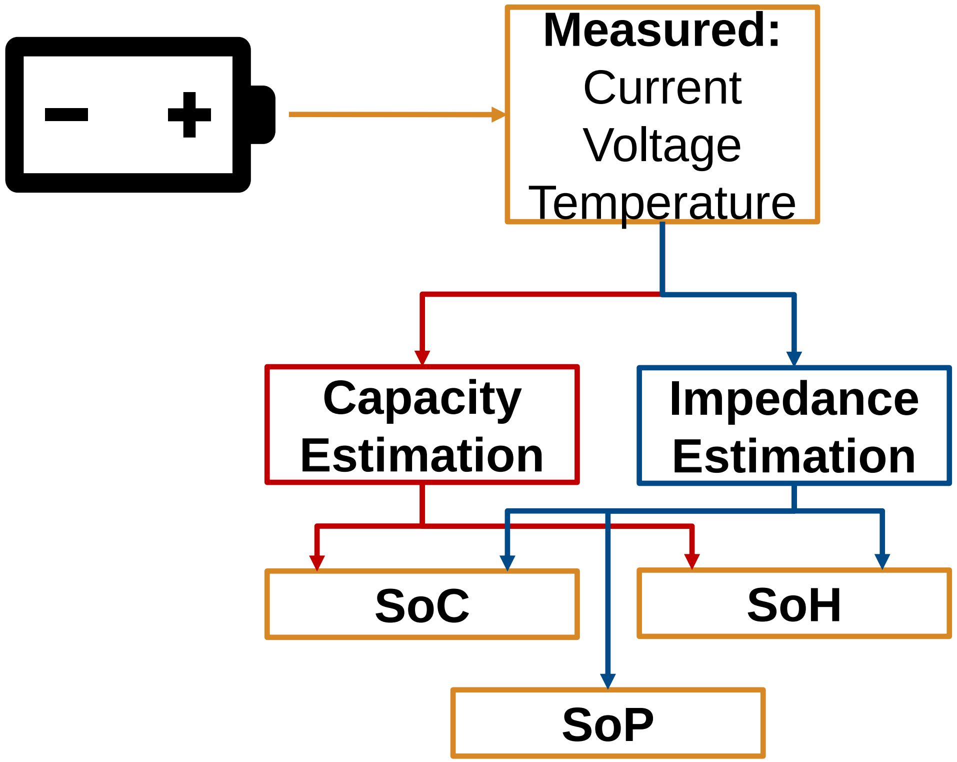
Lithium-Ion battery typically has two types of aging: Calendar and Cycling

- Calendar aging: SEI (Solid Electrolyte Interface) growth is the dominant calendar aging factor. This leads to loss of active materials, and slowing down the diffusion process

- Cycling aging: There are many mechanisms that will cause cycling degradations, such as particle fracture, loss of electronic contact, lithium plating, loss of lithium Ion, loss of active materials, and so on

- It is a common industrial practice to approximately sum the calendar degradation and cycling degradation together as "total" degradation, due to aging mechanisms are different

- Current mainstream approach for SOH algorithm is still based on empirical data to build calendar life and cycling life models, but this will require substantial cell test data.



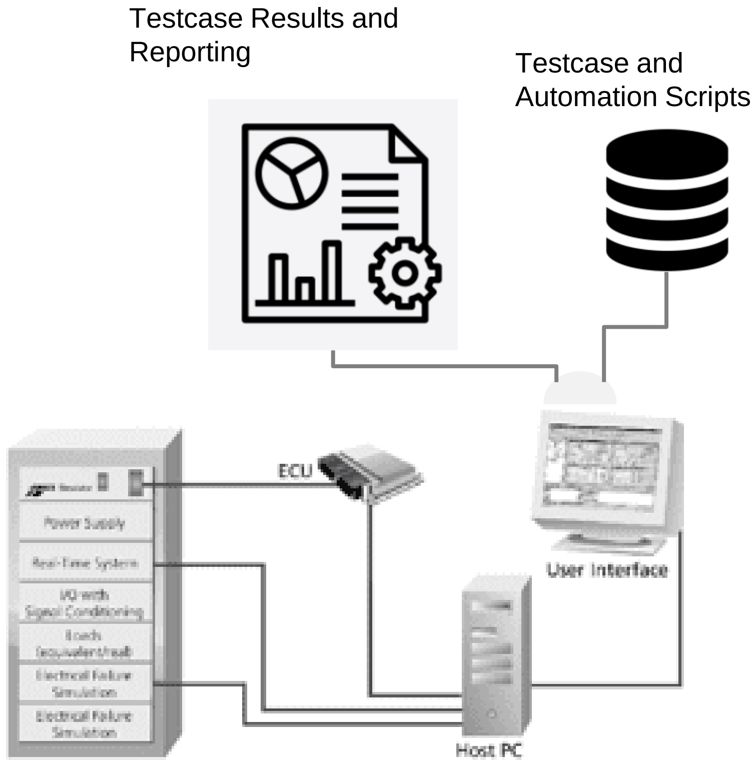
Validation Methodologies

- Model-in-loop (MIL testing): Using mathworks tools (Simulink test manager) to create exhaustive temperature and drive cycle test cases to verify Sox (plant model vs algorithm)

- Hardware-in-loop (HIL testing): State of the art HIL infrastructure to test algorithms with plant models in the background, brings in HW and latencies.

- Pack Testing: Integrated battery pack tested on cycler. Sox data is generated from real cells and compared to algorithm.

- Vehicle Testing: Various drive cycle testing, altitude trips, weather testing; tests the capability of the components and their interactions.



Summary

- BMS development momentum
  - According to a research report published by Spherical Insights & Consulting, the Global Lithium-Ion Battery Market Size to Grow from USD 65.9 Billion in 2021 to USD 273.8 Billion by 2030, at a Compound Annual Growth Rate (CAGR) of 19.3% during the forecast period.
  - Applications will be varied (ESS, traction, industrial).

- BMS Challenges
  - Time to market
  - Safety vs availability
  - Algorithms over time (battery aging)

- Model Based Design
  - Mathworks tools have been at the forefront of solving a lot of the BMS challenges