Battery Health

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1 Introduction

This document explains an example of designing a battery health model. The model assumes that the battery loses its health based on three factors:

- Degradation: The health state that is affected by time. It declines over time.
- Shock: The health state that is affected by high current shocks. It declines based on events of high current cases.
- Overall health: This health item is used to determine the battery's performance. Although the performance is a function of the other two health states, how they totally affect the performance can be explained here.

All these parameters are between 0 and 1 (therefore if any equation leads to less than 0 health the code forces it to stay inbound), and based on the modeling approach, some are discrete, and some are continuous.

2 Degradation, H_D

As explained in the last section, degradation happens only as a function of time. However, how time affects degradation can differ based on the physics of the hardware. In this example, we prepared three possible degradation models:

- Linear Degradation: This model assumes a constant degradation rate until the battery runs out of health:

$$H_{D,Linear}(t) = \begin{cases} 1 & \textbf{if } t = 0 \\ H_{D,Linear}(t-1) - dt/t_{\texttt{life battery}} & \textbf{if } t \in (0, t_{\texttt{life battery}}) \\ 0 & \textbf{if } t \geq (0, t_{\texttt{life battery}}) \end{cases} \tag{1}$$

  This model is continuous, deterministic, and has only one parameter, $t_{\texttt{life battery}}$, which is the battery's life.

- Exponential Decay Degradation: This model assumes that the health of the battery declines gradually but never goes to absolute zero:

$$H_{D,Exponential}(t) = \begin{cases} 1 & \textbf{if } t = 0 \\ 2^{-t/t_{\texttt{half-life battery}}} & \textbf{if } t > 0 \end{cases} \tag{2}$$

  This model is continuous, deterministic, and has only one parameter, $t_{\texttt{half-life battery}}$, which is the time it takes for the battery to lose 50% of its health. This model does not have a total zero health, but the health decays so that the battery will no longer be usable practically.

- Matrix Probability Degradation: This model assumes that the battery's health is changing by some stochastic events, but those events are not measured. For instance, sudden temperature change or bad connection disconnection,...

  I used an example from [1], which is not necessarily valid for the battery. Since the health is discrete it can only get values of $\{1.00, 0.75, 0.50, 0.25, 0.00\}$:

$$H_{D,Probability-Matrix}(t) = \begin{cases} 1 & \textbf{if } t = 0 \\ \begin{cases} 1.00, & \textbf{with } P(H_{D,Probability-Matrix}(t-1), 1.00) \textbf{ chance} \\ 0.75, & \textbf{with } P(H_{D,Probability-Matrix}(t-1), 0.75) \textbf{ chance} \\ 0.50, & \textbf{with } P(H_{D,Probability-Matrix}(t-1), 0.50) \textbf{ chance} \\ 0.25, & \textbf{with } P(H_{D,Probability-Matrix}(t-1), 0.25) \textbf{ chance} \\ 0.00, & \textbf{with } P(H_{D,Probability-Matrix}(t-1), 0.00) \textbf{ chance} \end{cases} & \textbf{if } t > 0 \end{cases} \tag{3}$$

  This model is discrete, stochastic, and has a matrix for parameters $5x5$, $P(H = i, H = j)$, which is the probability to go from $H(t-1) = i$ to $H(t) = j$.

3 Shock Effect, H_S

As explained in the first section shock happens as a function of high currents. It is also possible to consider the effect of the degradation (less resistance to high currents) and cooling. Here four possible models are suggested:

- No Degradation No Cooling: This model is the most basic model, and we explain it in more detail. Other models are made as updates to this model:

$$H_{S,No-De,No-Co}(t) = \begin{cases} 1 & \textbf{if } t = 0 \\ \begin{cases} H_{S,No-De,No-Co}(t-1) & \textbf{if } C \leq C_{\texttt{Nominal}} \\ H_{S,No-De,No-Co}(t-1) - S_{\textbf{Nominal Passed Current}} & \textbf{if } C \in (C_{\texttt{Nominal}}, C_{\texttt{Short time}}) \\ H_{S,No-De,No-Co}(t-1) - S_{\textbf{Short Time Passed Current}} & \textbf{if } C \in (C_{\texttt{Short time}}, C_{\texttt{Ultimate}}) \\ 0, & \textbf{if } C \geq C_{\texttt{Ultimate}} \end{cases} & \textbf{if } t > 0 \end{cases} \tag{4}$$

  This model is continuous, deterministic, and has five parameters:

  $C_{\texttt{Nominal}}$, which is the nominal current of the battery. This current is completely harmless. $C_{\texttt{Short time}}$, which is the short time sustainable current of the battery (about a few seconds). This current is harmful if the system uses it frequently. $C_{\texttt{Ultimate}}$, which is the maximum possible current of the battery. This current destroys the buttery. if current is between $C_{\texttt{Nominal}}$ and $C_{\texttt{Short time}}$, battery gets damaged by $S_{\textbf{Nominal Passed Current}}$. Here we did not consider time since we don't know the time series. if current is between $C_{\texttt{Short time}}$ and $C_{\texttt{Ultimate}}$, battery gets damaged by $S_{\textbf{Short Time Passed Current}}$ which is a more severe damage. Here we did not consider time since we don't know the time series.

- No Degradation with Cooling: This model is the same as the previous one, but it considers the effect of cooling on possible current ranges. Therefore the equations are exactly the same as 4. The only difference is that the current limits increase:

$$\eta_{cooling} = \begin{cases} \eta_{cooling,Air} & \textbf{if } \texttt{There is no cooling} \\ \eta_{cooling,Water} & \textbf{if } \texttt{There is water cooling} \\ \eta_{cooling,Refrigerant} & \textbf{if } \texttt{There is Refrigerant cooling} \end{cases} \tag{5}$$

$$\begin{cases} C_{\texttt{Nominal}} & \leftarrow C_{\texttt{Nominal}} \times \eta_{cooling} \\ C_{\texttt{Short time}} & \leftarrow C_{\texttt{Short time}} \times \eta_{cooling} \\ C_{\texttt{Ultimate}} & \leftarrow C_{\texttt{Ultimate}} \times \eta_{cooling} \end{cases} \tag{6}$$

  This model is continuous, deterministic, and has three more parameters compared to the first shock model:

$C_{\texttt{Nominal}}$, which is the nominal current of the battery, this current is harmless completely. $C_{\texttt{Short time}}$, which is the short time sustainable current of the battery (about few seconds), this current is harmful if system uses it frequently. $C_{\texttt{Ultimate}}$, which is the maximum possible current of the battery, this current destroys the buttery. if current is between $C_{\texttt{Nominal}}$ and $C_{\texttt{Short time}}$, battery gets damaged by $S_{\textbf{Nominal Passed Current}}$. Here we did not consider time, since we don't know what is the time series. if current is between $C_{\texttt{Short time}}$ and $C_{\texttt{Ultimate}}$, battery gets damaged by $S_{\textbf{Short Time Passed Current}}$ which is a more severe damage. Here we did not consider time, since we don't know what is the time series.

- With Degradation No Cooling: This model is the same as the previous one but it considers the effect of degradation on possible current ranges (therefore it is coupled but not doubly coupled). Therefore the equations are exactly the same as 4. The only difference is that the current limits decrease:

$$\begin{cases} C_{\texttt{Nominal}} & \leftarrow C_{\texttt{Nominal}} \times \beta_{\texttt{degradation}}/H_D \\ C_{\texttt{Short time}} & \leftarrow C_{\texttt{Short time}} \times \beta_{\texttt{degradation}}/H_D \\ C_{\texttt{Ultimate}} & \leftarrow C_{\texttt{Ultimate}} \times \beta_{\texttt{degradation}}/H_D \end{cases} \tag{7}$$

  This model is continuous, deterministic, and has one more parameter compared to the first shock model :

  $\beta_{\texttt{degradation}} = 1.2$, which is the assumed average degradation health of the batteries during shock test. It can be any number ≥ 1. In addition to $\beta_{\texttt{degradation}}$, H_D exists which is explained in section 2.

- With Degradation With Cooling: This model is the combination of the last two models. Therefore it has both complexities added, the cooling is considered as a positive effect and degradation as a negative effect.

  This model is continuous, deterministic, and has four (three + one) more parameter compared to the first shock model :

4 Overall Health , H_O

The last models explained the health of the battery based on different damages, but if we want to use a single state and model the battery health for its application (i.e. how it can supply the power based on the health) it s helpful if we combine these health states. Here three different suggestions are proposed:

- Multiplication Combination: This model says that the performance of the battery is decided based on the multiplication performance of two health states, therefore it is worse than both of them (since both of them are between 0 and 1).

$$H_{O,Mul}(t) = H_D \times H_S \tag{8}$$

  This model is continuous, deterministic, and has only no parameters.

- Min Combination: This model says that the performance of the battery is decided based on the worse performance of two health states

$$H_{O,Min}(t) = \min(H_D, H_S) \tag{9}$$

  This model is continuous, deterministic, and has only no parameters.

- Harmonic Mean Combination: This model says that the performance of the battery is decided based on the harmonic mean performance of two health states

$$H_{O,Har}(t) = \frac{2}{1/H_D + 1/H_S} \tag{10}$$

  This model is continuous, deterministic, and has only no parameters.

5 Example

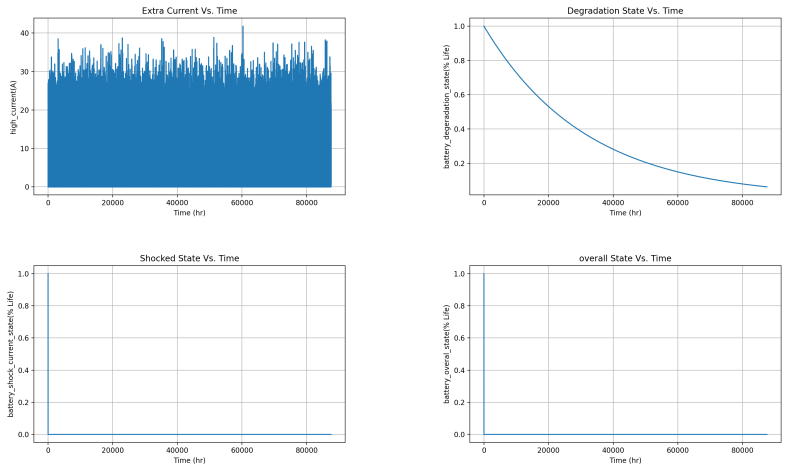
Here we have a simple example of the three cases using

- Exponential Decay Degradation
- With Degradation With Cooling Shock model
- Min Combination model

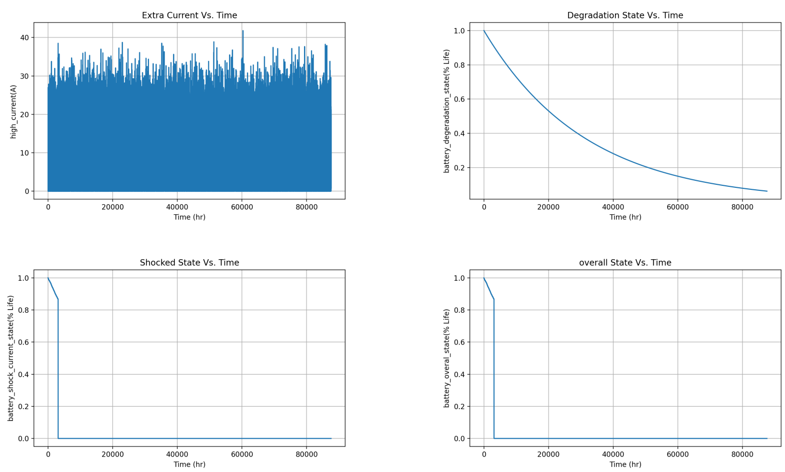
Everything is the same but in one test the coolant is air(no cooling), in one test water, and in the other test refrigerant is used.

References

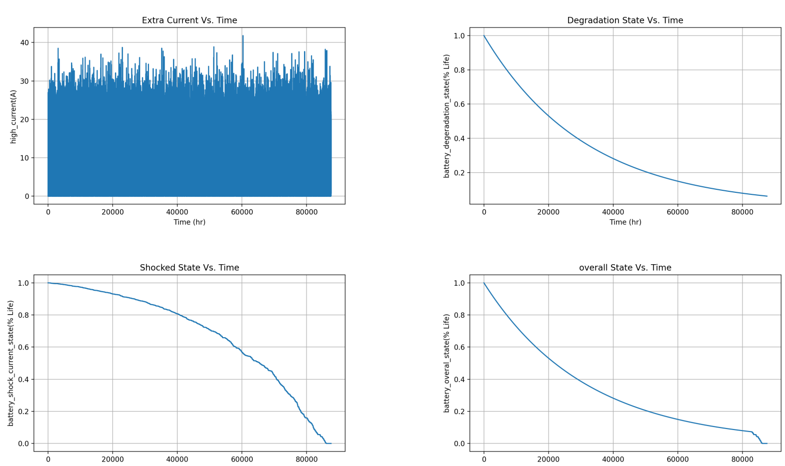
[1] Kong Fah Tee, Ejiroghene Ekpiwhre, and Zhang Yi. Degradation modelling and life expectancy using markov chain model for carriageway. *International Journal of Quality & Reliability Management*, 2018.



(a) No Cooling



(b) Water Cooling



(c) Refrigerant Cooling

Figure 1: Testing the effect of cooling