Tutorial:- 3

Feature Extraction

Data collected from discharge cycles of Li-ion batteries cycled under various conditions are analyzed. The battery cycling data is sourced from a publically available repository; provided by the Prognostics Center of Excellence (PCoE) at Ames Research Center, NASA . Table 1 lists the 19 batteries used in this work, along with their respective operating parameters. The data repository contains capacity, voltage, current, temperature, current load and voltage load recorded for each discharge cycle of the batteries. Except the cell capacity, all other parameters are recorded over time during discharge; however these parameters are acquired with non-uniform sampling rate. It is observed that as battery ages there will be change in measured voltage, current and temperature. Hence it is paramount to extract the relevant features from these curves that are crucial in determining battery life. From each discharge cycle, a set of 7 parameters is extracted from voltage and temperature curves representing minimum and maximum values of each curve, and their respective times. In addition to the above parameters, the following 13 parameters are computed from voltage, temperature and current curves for each discharge cycle.

Features:

- Capacity (cap)
- Energy of signal (E)
- Fluctuation index of signal (FI)
- Curvature index of signal (CI)
- Concave convex index (CCI)
- Skewness index (SI)
- Kurtosis index (KI)

Computed Values :

- TCE - Energy of temperature curve
- VCE - Energy of voltage curve
- TCI - Temperature Curvature index of signal
- VCI - Voltage Curvature index of signal
- VC_CCI - Voltage Curve Concave convex index
- TC_CCI - Temperature Curve Concave convex index
- VC_SI - Voltage Curve Skewness index
- TC_SI - Temperature Curve Skewness index
- VC_KI - Voltage Curve Kurtosis Index of Signal
- TC_KI - Temperature Curve Kurtosis Index of Signal

- tminV, tmaxT - Time taken to reach minimum voltage and maximum temperature
- Tmin, Tmax - Minimum and Maximum value of Temperature
- minV, maxV - Minimum and Maximum value of Voltage

Table 1
List of batteries with their operating parameters.

Battery number	Discharge current	End voltage (V)	End-of-life condition	Operating temperature (°C)	No of cycles
B0005	2 A constant current	2.7	30% fade in rated capacity (2–1.4 A h)	24	168
B0006		2.5			168
B0007		2.2			168
B0033	4 A	2.0	Capacity reduced to 20% fade (1.6 A h)	24	197
B0034		2.2			197
B0036	2 A	2.7			197
B0038	Multiple –1 A, 2 A and 4 A	2.2	Capacity reduced to 20% fade (1.6 A h)	24 & 44	47
B0039		2.5			47
B0040		2.7			47
B0042	Multiple – 1 A, 4 A	2.2	Capacity reduced to 30% fade (1.4 A h)	4	112
B0043		2.5			112
B0044		2.7			112
B0045	Fixed load – 1 A	2	Capacity reduced to 30% fade (1.4 A h)	4	72
B0046		2.2			72
B0047		2.5			72
B0048		2.7			72
B0054	Fixed load – 2 A	2.2	Capacity reduced to 30% fade (1.4 A h)	4	103
B0055		2.5			102
B0056		2.7			102

Capacity (Cap): The capacity of battery is computed by integrating discharge current over time and it is given by:

$$\text{Cap} = \int_{t_1}^{t_2} I dt$$

where t1 and t2 are the start and end time of a discharge cycle.

Energy of signal (E): Signal energy of voltage and temperature curves are computed. In general, energy of signal is defined as the measure of signal strength over time and it is given by bellow equations

$$E = \int_{-\infty}^{\infty} |x(t)|^2 dt$$

where x(t)is the signal (either voltage or temperature) and t is time. In this work VCE notation is used to denote energy of voltage curve and TCE to denote energy of temperature curve.

Fluctuation index of signal (FI): Fluctuation Index of signal is defined as a measure of deviation of the signal from the mean and is given as:

$$\text{FI} = \frac{\sqrt{\sum (y_i - \mu)^2}}{\omega}$$

where yi is the signal, ᵘ is the meaning of the signal and x is sampling Frequency.

Curvature index of signal (CI): Defined as a measure of direction in which the unit tangent vector rotates as a function of the parameter along the signal and it is given by equation:

$$\mathrm{CI} = \frac{\sum \theta}{N}$$

theta, and N is the length of the signal.VCI denotes the curvature index of voltage curve and T_CI denotes the corresponding curvature index of temperature curve.

Concave convex index (CCI): It is a measure of convexity of the signal. A convex signal will have an index >0.5 whereas a concave signal will have an index <0.5. The index is calculated using slope and intersection estimation. This index is given by:

$$\mathrm{CCI} = \begin{cases} 1 & \mathit{if} \quad y_i \ \mathit{is\ convex} \\ 0 & \mathit{if} \quad y_i \ \mathit{is\ concave} \end{cases}$$

In this work voltage curve concave convex index (VC_CCI) and temperature curve concave convex index (TC_CCI) are computed.

Skewness index (SI): Skewness Index is a measure of the extent to which a probability distribution of signal leans toward the mean of the signal. This index is given by:
where yi is input signal u is mean of the signal and r is standard deviation of the signal and n is length of signal. Skewness index of voltage curve is denoted by VC_SI and that of temperature curve is denoted by TC_SI.

$$\mathrm{SI} = \frac{\sum_{i=1}^{n} (y_i - \mu)^3}{\sigma^3}$$

Kurtosis index (KI): It is measure of the ‘‘peakedness” of the probability distribution of the signal and it is given by the equation:

$$\mathrm{KI} = \frac{\sum_{i=1}^{n} (y_i - \mu)^4}{\sigma^4}.$$

VC_KI and TC_KI notations used to denote kurtosis index of voltage and temperature curves respectively. Fig. 2(a)–(d) depicts variation of all these features across discharge cycles for battery B0036

- **Kurtosis index (KI):** It is measure of the ‘‘peakedness” of the probability distribution of the signal and it is given by the equation:

$$\mathrm{KI} = \frac{\sum_{i=1}^{n} (y_i - \mu)^4}{\sigma^4}. \quad (16)$$

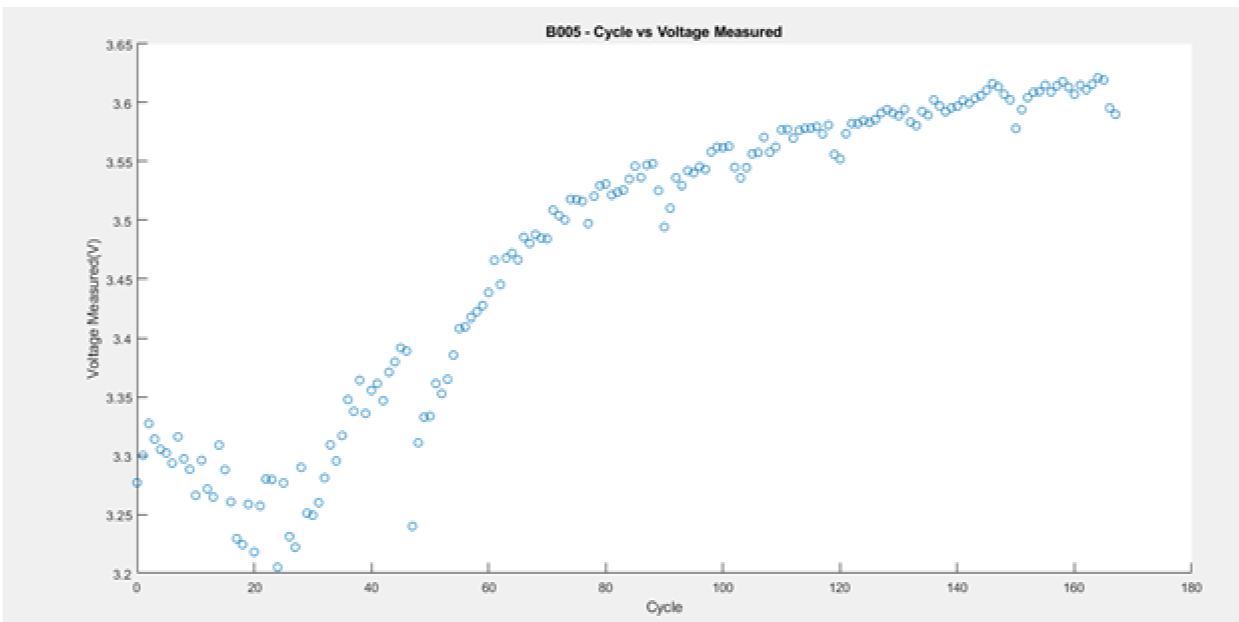
VC_KI and TC_KI notations used to denote kurtosis index of voltage and temperature curves respectively.

Plotted graphs :

1. B005

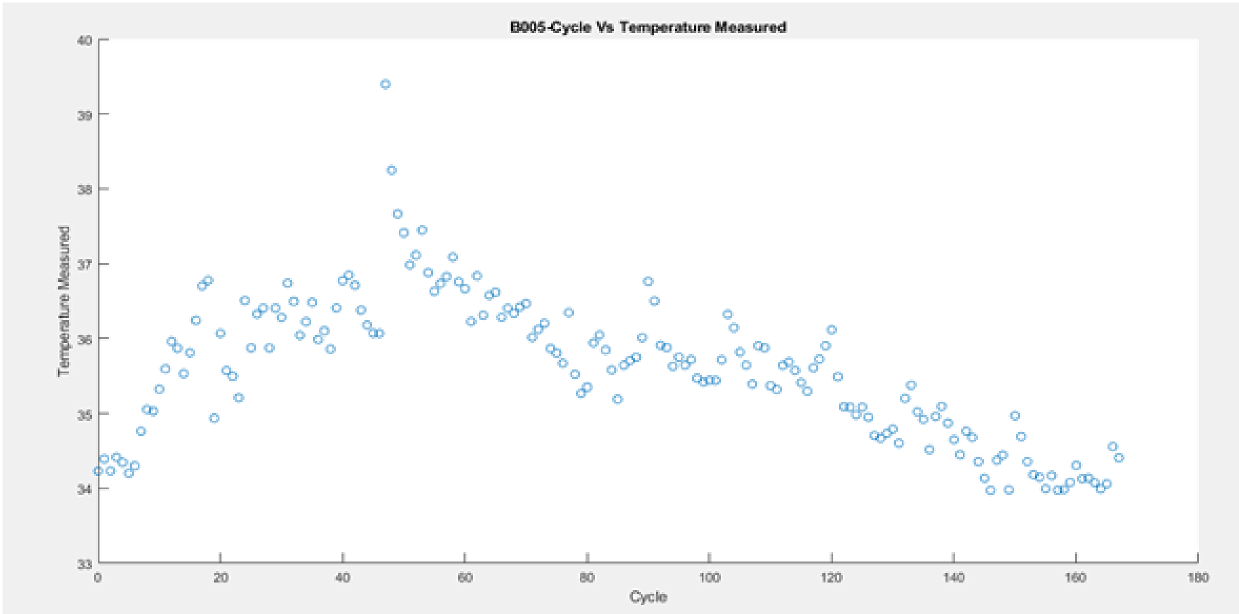
I. Cycle Vs Voltage

Here we plot voltage with respect to the cycles of battery B0005.



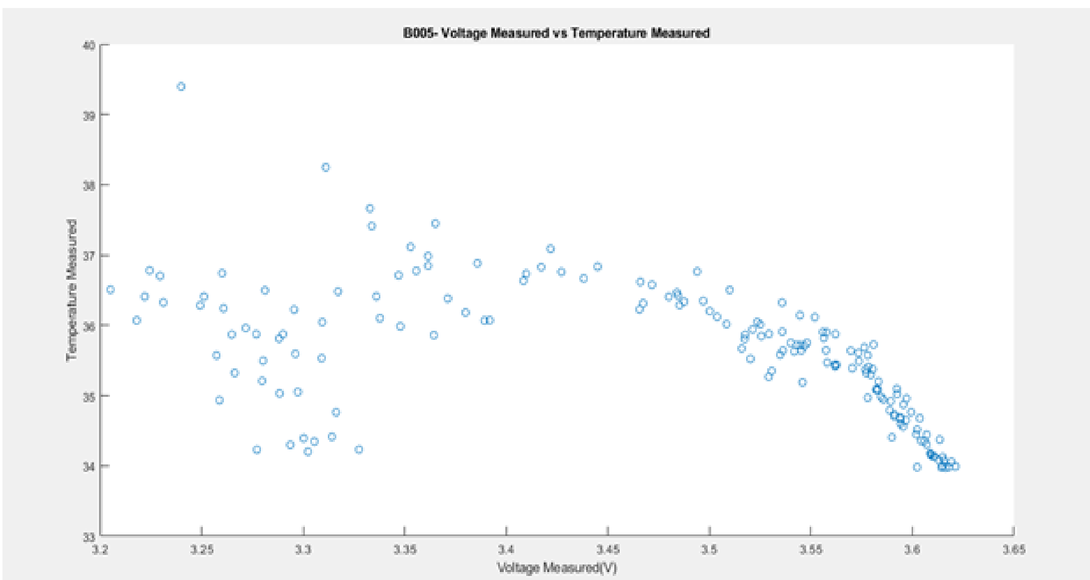
II.Cycle Vs Temperature Measured

Here we plot temperature with respect to the cycles of battery B0005.



III. Voltage Measured Vs Temperature Measured

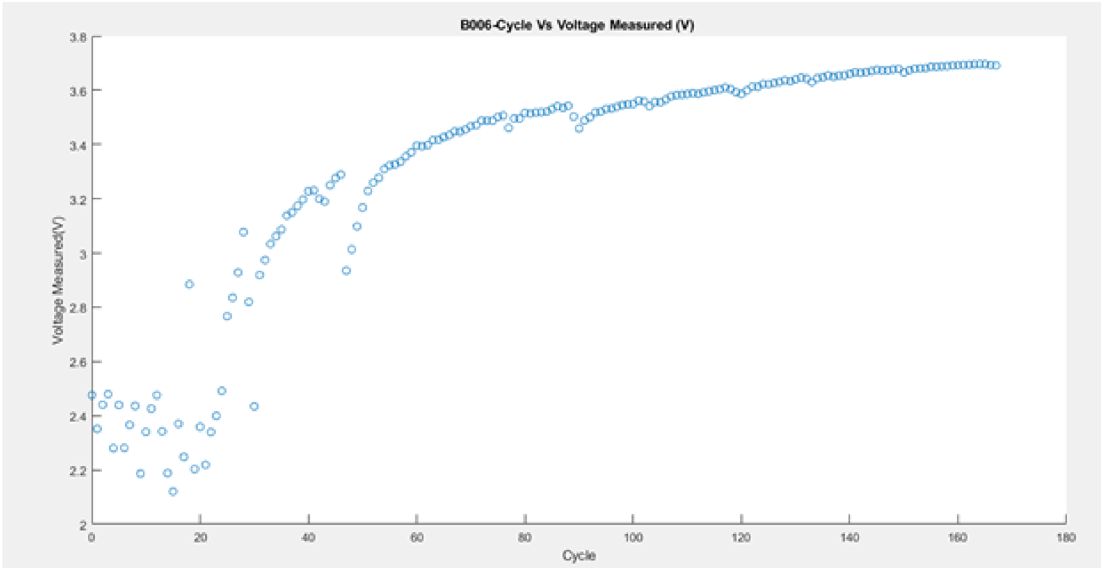
Here we plot voltage with respect to the temperature of battery B0005.



2. B006

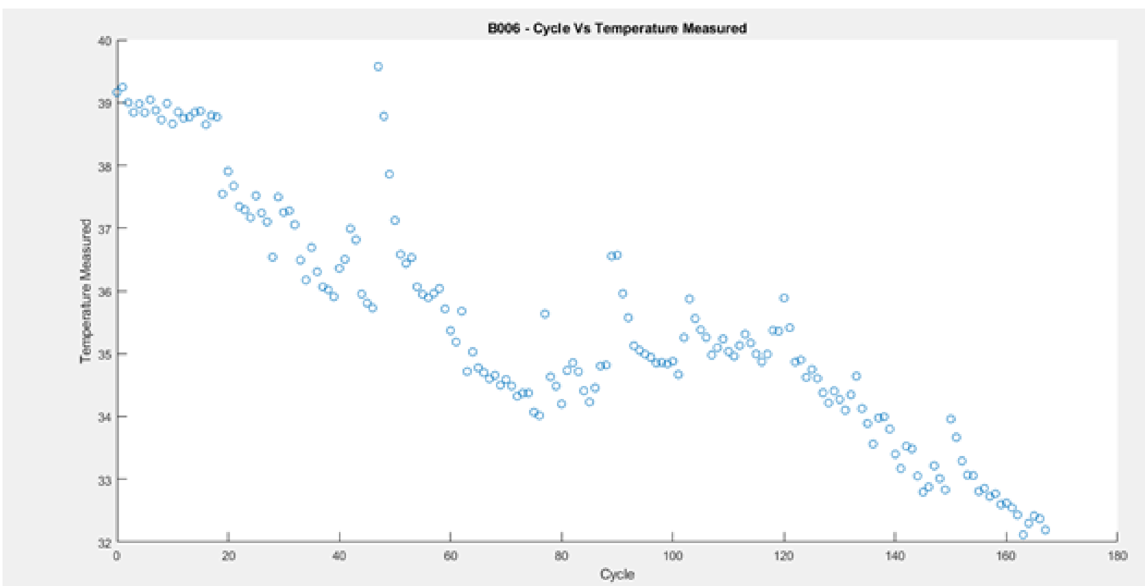
I. Cycle Vs Voltage

Here we plot voltage with respect to the cycles of battery B0006.



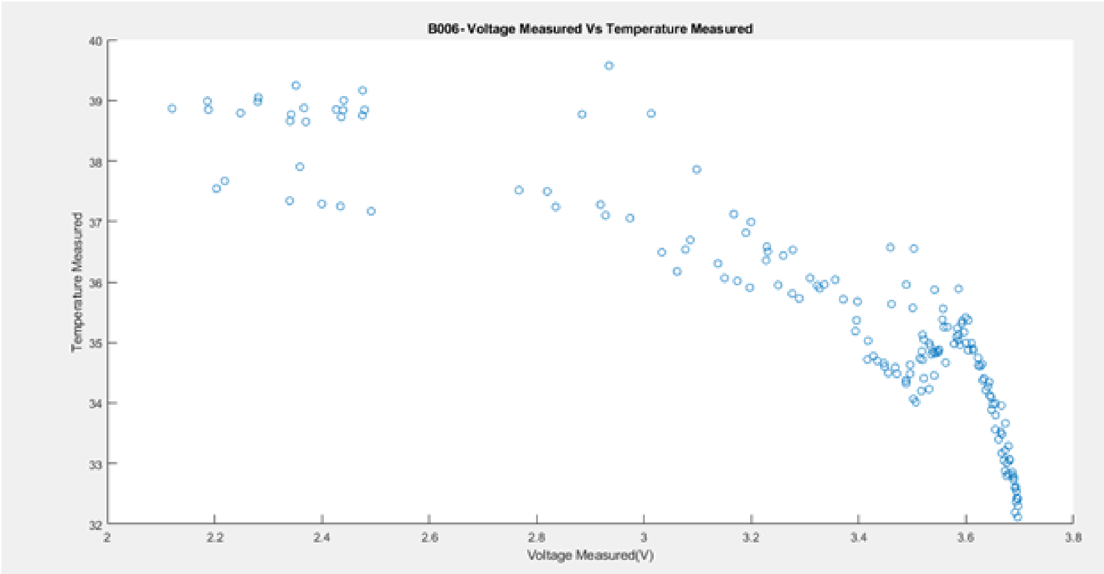
II.Cycle Vs Temperature Measured

Here we plot temperature with respect to the cycles of battery B0006.



III. Voltage Measured Vs Temperature Measured

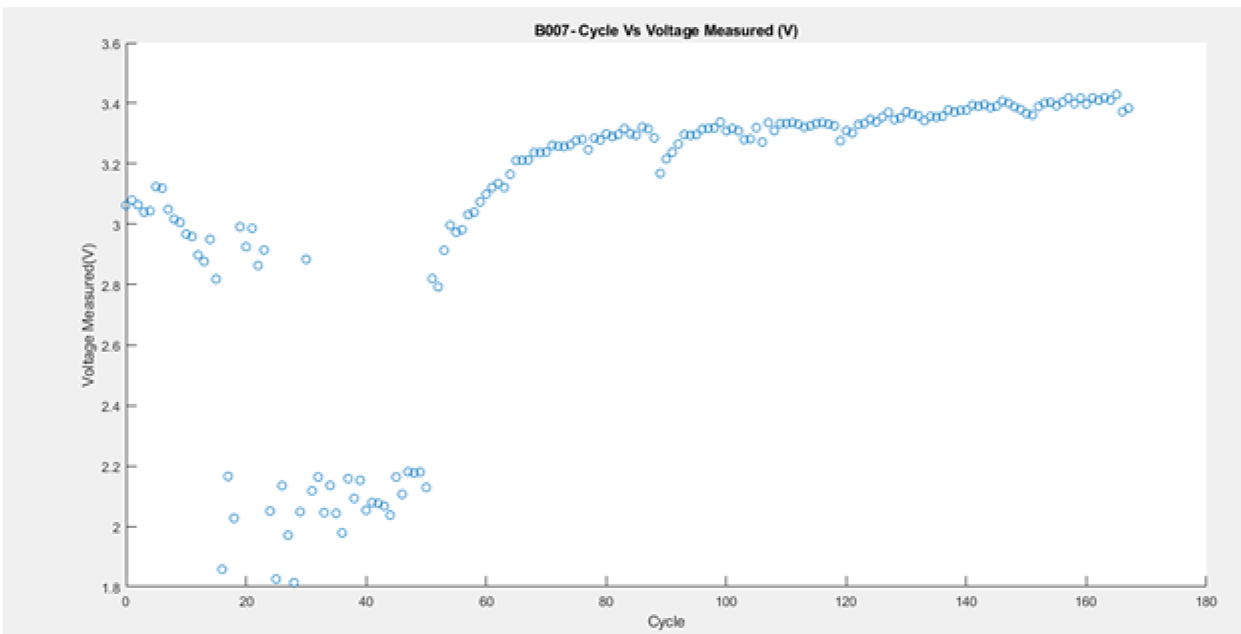
Here we plot voltage with respect to the temperature of battery B0006.



3.B007

I. Cycle Vs Voltage

Here we plot voltage with respect to the cycles of battery B0007.



II.Cycle Vs Temperature Measured

Here we plot temperature with respect to the cycles of battery B0007.

III. Voltage Measured Vs Temperature Measured

Here we plot voltage with respect to the temperature of battery B0007.