Robustness evaluation of probability density function based features on state-of-health estimation used in electric vehicles

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Abstract. Robust and accurate state-of-health (SOH) estimation is significant for safe and reliable operation of electric vehicles (EVs). In this paper, the robustness analysis of a specific IC analysis method based on probability density function is investigated in depth. Four aging features frequently used by existing researches to estimate SOH are extracted from IC curve. The influence of temperature and current rate on these four aging features as battery ages is analyzed in detail. These aging features’ sensitiveness to data length and their appearance frequency in real-world charging events are also included in deciding which one is best for SOH estimation. Finally, one aging feature that has greatest potential to be used on EVs for SOH estimation is selected out.

1. Introduction

To ensure reliable and safe operation of EVs, recognition of the degradation state and health monitoring of lithium-ion batteries are crucial. Incremental capacity (IC) analysis is an effective method widely used for SOH estimation. However, the original IC curve cannot be used directly because the inevitable noise. To cope with this problem, X. Feng et al.[1] used a normal kernel function to estimate the probability density of the measured battery voltage, which is named as probability density function based incremental capacity (PDF-IC) approach. Through this method, a smooth PDF-IC curve can be obtained for subsequent aging feature extraction. Despite the contribution of [1], the method was only validated under a narrow set of scenarios[2][3], without exploring the effectiveness under different temperatures and different current rates. In addition, various features on IC curve were found to be indicative of the battery SOH. But whether these features can still be informative when the temperature or the charge rate changes has not been well-discussed so far.

In order to mitigate above research gaps, this paper conducts the robustness analysis research of PDF-based SOH estimation method for multiple battery cells under different temperatures and different current rates. The remainder of this paper is organized as follows. Section 2 introduces the battery aging experiment briefly. Section 3 describes the acquisition of PDF-IC curve and its relationship with real IC curve. Section 4 discusses the robustness of using four aging features to estimate SOH under different temperatures and different current rates. Based on the robustness analysis and the features’ appearance frequency in real-world charging process and sensitiveness to
data length, the most possible feature that can be applied on EVs is selected out. Section 5 concludes the whole paper and points out the possible future work.

2. Experiment

The battery test data are generated in the test bench consisting of an Arbin BT2000 tester, a thermal chamber, a computer for user-machine interface and a switchboard for cable connection. The voltage, current, temperature of each cell is recorded at the sampling time of 10Hz. The tested batteries are 8 LiNMC battery cells numbered #17–#24 with 0.94Ah nominal capacity, 3.7V nominal voltage. Each cell experienced impedance test and aging test under 22°C, together with characteristic tests, including static capacity test, hybrid pulse power characteristic (HPPC) test, internal resistance test, dynamic stress test (DST) and federal urban dynamic schedule (FUDS) test under three different temperatures (10°C, 22°C and 35°C) in different levels of degradation.

Under each temperature, during the static capacity test, the battery cell is firstly discharged to the lower voltage limit using constant current, then is fully charged using constant current and constant voltage policy. In following analysis, only the data corresponding to the constant current charge procedure is used to obtain PDF-IC curve.

In the experiment, each battery cell is subjected to 12 aging rounds or namely 1211 aging cycles. The one-to-one match between the round number and aging cycles are shown in Table.1. For example, the 5th column in Table.1 means that when the battery cell is calibrated in the 5th round, it has undergone 555 aging cycles. It needs to be highlighted that all 8 battery cells are charged using 1C current rate in the 1st and 2nd rounds. In the following 3rd to 12th rounds, 0.5C current rate is used. The different current rate helps to investigate the influence of current magnitude on the shape of PDF-IC curve.

| Round number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|--------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Aging cycle  | 1  | 149| 346| 460| 555| 648| 744| 837| 931| 1024| 1118| 1211|

3. PDF-IC curve acquisition

The derivation equation of IC curve is demonstrated in Eq.(1).

$$\frac{dQ}{dV} = \frac{\Delta Q}{\Delta V} = \frac{I_t \Delta t}{V_t - V_{t-1}}$$

Fig.1(a) plots the voltage curve of the fresh #19 battery when it is charged with 1C constant current at 22°C. Fig.1(b) is the obtained original IC curve without any smoothing based on the voltage curve in Fig.1(a). It can be seen that due to the high sampling frequency, the voltages of some adjacent points are very close to each other, which results in numerous irrational peaks on the IC curve. Fig.1(c) plots the IC curve of Fig.1(b) after Gaussian smooth proposed by Y. Li in Ref.[4]. It is obvious that two peaks can be identified at around 3.84V and 3.93V. From Eq.(1), it can be seen that if the voltage variation of adjacent points is small, then the denominator of Eq.(1) will be small, which will result in a large IC value. Therefore, the function of IC analysis is to transform the voltage plateau to the peak on the IC curve.

PDF-IC uses statistic method to process the measured voltage data and to some extent can obtain equivalent analysis result to basic IC method. Here, an intuitive explanation of the equivalence between original IC and PDF-IC is provided. Fig.2(a) plots the frequency distribution of the voltage data in Fig.1(a). Fig.2(b) plots the probability density distribution of the voltage data, which is just a normalized and continuous approximation to the frequency distribution in Fig.2(a) and named as PDF-IC curve. From Fig.2(a) and Fig.2(b), it can be seen that two peaks appearing around 3.84V and 3.93V can also be identified, which is consistent with the real IC curve processed by Gaussian smooth in Fig.1(c). This is because the IC peak corresponds to the voltage plateau, whose voltage remains nearly
constant over a relatively long period. Therefore, the frequency of the voltage value corresponding to the voltage plateau is relatively high, which results in peaks in frequency distribution and PDF-IC curve.

Fig. 1. Example of IC curve derivation.

However, there still exists difference between real IC and PDF-IC curve. The ordinate value of the real IC curve is calculated by $dQ/dV$ as shown in Eq.(1). Its value is not affected by the data length.

Fig. 2. Derivation of PDF-IC curve and its change with capacity decrease.
However, the ordinate of PDF-IC curve represents the probability density. The shorter the data length is, the larger the proportion of the value corresponding to the peak is, and thus the higher intensity of the peak. However, the location of the PDF-IC is obviously not affected by the data length if the data of the whole voltage plateau is covered.

Existing researches reveal that the location and intensity of the IC peak are highly related to the battery SOH and their relationship mostly demonstrates linear property[5][6]. Therefore, the location and intensity of the IC peak can be used to estimate the battery SOH. In this paper, four battery aging features on PDF-IC curve are selected. They are the location of the first peak F1, intensity of the first peak F2, location of the second peak F3 and intensity of the second peak F4, as labeled in Fig.3(b).

Further research reveals that as the battery ages, the first peak on the PDF-IC curve may disappear and a new third peak, which is close to the second peak, may appear. Fig.2(c) and Fig.2(d) demonstrate relevant examples. The conditions when the first peak disappears and the third peak appears of the 8 battery cells are listed in Table.2 and Table.3 respectively.

From Table.2, it can be seen that under 10°C, the first peak on the PDF-IC curve of all the battery cells disappear when the battery cell ages to some extent. This phenomenon happens to a part of these battery cells under 22°C and never happens under 35°C. Thus, it can be inferred that the disappearance of the first peak is related to the low temperature. From Table.3, it can be seen that the appearance of the third peak only happens to 3 battery cells under 10°C or 22°C. No rule can be found about the appearance of the third peak based on these three cases. Thus, the appearance of the third peak may be caused by the battery inconsistency and is not a common aging behavior for LiNMC battery cells.

| Battery number | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|----------------|----|----|----|----|----|----|----|----|
| T and AG when the first peak begins to disappear | T (°C) | 10 | 22 | 10 | 10 | 22 | 10 | 10 |
| AC | 1211 | 1118 | 1024 | 1211 | 1211 | 1211 | 931 | 1118 |
| SOH (%) | 66.9 | 75.7 | 72.8 | 68.7 | 76.4 | 68.5 | 73.4 | 69.6 |

| Battery number | 17 | 18 | 19 |
|----------------|----|----|----|
| T and AG when the third peak begins to appear | T (°C) | 22 | 22 |
| AC | 1118 | 1211 | 1118 |
| SOH (%) | 77.6 | 76.7 | 71.3 |

Note: T represents temperature and AC stands for aging cycle in Table.2 and Table.3.

It needs to be highlighted that the disappearance of the first peak and appearance of the third peak are irreversible and stable, which means when the first peak disappears or the third peak appears, in the remaining life of the battery cell, the first peak will never appear or the third peak will never disappear again. For example, under 10°C, the first peak on the PDF-IC curve of battery #21 begins to disappear when the battery cell undergoes 9 rounds aging cycles, namely 931 charging and discharging cycles. In subsequent 10th to 12th characteristic tests, the first peak remains unobservable, never appears again. This rule also applies to the appearance of the third peak.

From Table.2 and Table.3, it can also be seen that when the first peak disappears or the third peak appears, the battery cell’s SOH all appears beneath 80%. It is a common consensus that the power battery of EVs reaches its end of life when its capacity decreases to 80% of its initial capacity. Therefore, when estimating the capacity of the battery on EVs, the disappearance of the first peak and the appearance of the third peak should never happen. Thus, in subsequent research, the data corresponding to the disappearance of the first peak and the appearance of the third peak are not included in robustness analysis.
4. Robustness analysis of the battery aging features

In this section, the change trend of the four aging features under different temperatures, different current magnitudes as the battery degrades will be discussed in detail. According to the robustness analysis of these four features, together with their sensitivity to data length and appearance frequency in real-world EV applications, the most ideal feature for EV battery SOH estimation is selected.

4.1. Robustness analysis of the relationship between F1 and SOH

Fig. 3(a) plots the relationship between F1 and SOH for the 8 battery cells under different temperatures, where the red stars correspond to the first two rounds using 1C charging current while the blue stars correspond to the 3rd to 12th rounds using 0.5C charging current. This kind of mark also applies to Fig. 3.

Fig. 3(a) shows that for all 8 battery cells, the blue stars under three different temperatures all basically locate in a line, revealing the linear and robust relationship between F1 and SOH. While the red stars always locate above the blue stars. The deviation of the red stars to the line that the blue stars form indicates that the current magnitude has important impact on F1.

Table. 4 lists the linear relationship analysis result between F1 and SOH for the 8 battery cells under different temperatures. Because the current magnitude has great influence on F1 and the 1st and 2nd rounds charging processes adopt different current rates from the 3rd to 12th rounds, the data of 1st and 2nd rounds are excluded in the analysis in Table. 4. It is the same for the analysis result in following Table. 5–Table. 7. R^2 is used to evaluate the performance of the linear approximation function between F1 and SOH. Its formula is
\[ R^2 = 1 - \frac{\sum_i(y_i - f_i)^2}{\sum_i(y_i - \bar{y})^2} \]  

(2)

where \( y_i \) is the sample’s true value, namely SOH here, \( f_i \) is the estimated value of the model, which in this case is the linear regression function between F1 and SOH. \( \bar{y} \) is the average value of the samples. The closer \( R^2 \) is to 1, the stronger the linear relationship between F1 and SOH is. From Table.4, it can be seen that under three temperatures, \( R^2 \) for the 8 battery cells are all above 0.9, indicating the linear relationship between F1 and SOH is robust in despite of the different temperatures. The average values of \( R^2 \) under 10°C, 22°C and 35°C are 0.9760, 0.9662 and 0.9449 respectively, revealing F1 has better linear relationship with SOH under low temperature.

### Table.4 Linear relationship analysis between F1 and SOH during 3\(^{rd}\) to 12\(^{th}\) aging rounds

|       | 10°C      |         |       | 22°C      |         |       | 35°C      |         |
|-------|-----------|---------|-------|-----------|---------|-------|-----------|---------|
| k     | -2.4265   | 10.234  | 0.9741| -2.0088   | 8.5557  | 0.9563| -2.6999   | 11.110  | 0.9220 |
| b     | 18#       | 9.1308  | 0.9857| -1.7967   | 7.7482  | 0.9746| -2.5594   | 10.581  | 0.9676 |
| b     | 19#       | 9.3935  | 0.9756| -1.9895   | 8.4784  | 0.9395| -2.5691   | 10.613  | 0.9342 |
| b     | 20#       | 10.719  | 0.9819| -2.0519   | 8.7115  | 0.9609| -2.9808   | 12.164  | 0.9122 |
| b     | 21#       | 9.4444  | 0.9686| -1.8514   | 7.9333  | 0.9704| -2.3835   | 9.8864  | 0.9507 |
| b     | 22#       | 9.5542  | 0.9919| -1.9432   | 8.2864  | 0.9738| -2.5579   | 10.555  | 0.9623 |
| b     | 23#       | 9.5603  | 0.9723| -1.9475   | 8.3054  | 0.9657| -2.2823   | 11.564  | 0.9486 |
| b     | 24#       | 9.9336  | 0.9536| -1.7881   | 7.7007  | 0.9884| -2.4467   | 10.146  | 0.9616 |

Note: \( k \) and \( b \) represent slope and intercept of the linear regression model between F1 and SOH respectively. It is the same for the following Table.5-Table.7.

### 4.2. Robustness analysis of the relationship between F2 and SOH

Fig.3(b) plots the relationship between F2 and SOH, where the blue stars demonstrate moderate linear relationship under 10°C while scattering in a mess under 22°C and 35°C. Table.5 lists the linear relationship analysis result. The average values of \( R^2 \) under 10°C, 22°C and 35°C are 0.8188, 0.1222 and 0.5152 respectively, verifying F2 has poor linear relationship with SOH under 22°C and 35°C again. Therefore, F2 can only be used to estimate SOH under 10°C and considering the fact that \( R^2 \) under this temperature is merely 0.8188, the estimation result may not be very accurate.

### Table.5 Linear relationship analysis between F2 and SOH during 3\(^{rd}\) to 12\(^{th}\) aging rounds

|       | 10°C      |         |       | 22°C      |         |       | 35°C      |         |
|-------|-----------|---------|-------|-----------|---------|-------|-----------|---------|
| k     | -0.3796   | 1.7649  | 0.8902| -0.3851   | 1.7599  | 0.1514| 0.7610    | -0.8776 | 0.5884 |
| b     | 18#       | 1.5203  | 0.8729| -0.3442   | 2.1168  | 0.4454| 0.1104    | 0.6094  | 0.0072 |
| b     | 19#       | 1.7492  | 0.8586| -0.2884   | 1.4921  | 0.1112| 0.3678    | 0.0527  | 0.2034 |
| b     | 20#       | 1.8550  | 0.9156| -0.4558   | 1.9087  | 0.2181| 0.6831    | -0.6739 | 0.2765 |
| b     | 21#       | 1.8981  | 0.8157| -0.1500   | 1.1733  | 0.0218| 0.7409    | -0.7591 | 0.7232 |
| b     | 22#       | 2.0853  | 0.8921| -0.0923   | 1.0445  | 0.0100| 0.6178    | -0.5124 | 0.9010 |
| b     | 23#       | 1.9739  | 0.8328| 0.1188    | 0.5732  | 0.0174| 0.7437    | -0.7797 | 0.7777 |
| b     | 24#       | 1.8578  | 0.4455| -0.0433   | 0.9380  | 0.0022| 0.6140    | -0.4920 | 0.6443 |

Because F2 has very poor linear relationship with SOH and is greatly affected by the data length as described in Section 3, it is difficult to use F2 to realize accurate estimation of SOH. Therefore, deeper discussion of F2 is omitted here.

### 4.3. Robustness analysis of the relationship between F3 and SOH

Fig.4(a) plots the relationship between F3 and SOH, from which it can be seen that the relationship between F3 and SOH has similar properties to that between F1 and SOH, namely the red stars are above the blue stars.
Table 6 lists the linear relationship analysis result between F3 and SOH for the 8 battery cells under different temperatures. The average values of $R^2$ under 10°C, 22°C and 35°C are 0.9764, 0.9718 and 0.9511 respectively, indicating F3 has strong robustness with SOH against temperature changes and F3 has better linear relationship with SOH under low temperature. Comparing the linear property between F1 and F3 with SOH, it can be found that under three different temperatures, $R^2$ of F3 is always higher than that of F1, indicating that more accurate result can be obtained if F3 rather than F1 is used to estimate SOH.

| 10°C  | 22°C  | 35°C  |
|-------|-------|-------|
| $k$   | $b$   | $R^2$ | $k$   | $b$   | $R^2$ |
| 17#   | -1.9718 | 8.7002 | 0.9810 | -1.4324 | 6.5144 | 0.9737 | -1.4856 | 6.6795 | 0.9592 |
| 18#   | -1.8701 | 8.3028 | 0.9801 | -1.3513 | 6.2025 | 0.9708 | -1.3302 | 6.0757 | 0.9543 |
| 19#   | -1.7677 | 7.8829 | 0.9819 | -1.5658 | 7.0355 | 0.9772 | -1.3867 | 6.2853 | 0.9358 |
| 20#   | -2.3273 | 10.104 | 0.9733 | -1.7027 | 7.5742 | 0.9871 | -1.5040 | 6.7461 | 0.9508 |
| 21#   | -2.1618 | 9.4346 | 0.9462 | -1.5978 | 7.1487 | 0.9879 | -1.4456 | 6.5045 | 0.9367 |
| 22#   | -1.9275 | 8.5095 | 0.9719 | -1.6565 | 7.3811 | 0.9718 | -1.5743 | 7.0102 | 0.9599 |
| 23#   | -1.9679 | 8.6807 | 0.9831 | -1.7163 | 7.6243 | 0.9804 | -1.6087 | 7.1490 | 0.9435 |
| 24#   | -2.0225 | 8.8976 | 0.9762 | -1.7016 | 7.5673 | 0.9656 | -1.5723 | 7.0159 | 0.9690 |

4.4. Robustness analysis of the relationship between F4 and SOH

Fig.4(b) plots the relationship between F4 and SOH. It can be seen that as the temperature rises, the linear relationship between F4 and SOH under 0.5C current rate intensifies significantly. Table 7 lists the linear relationship analysis result between F4 and SOH for the 8 battery cells under different temperatures. The average values of $R^2$ under 10°C, 22°C and 35°C are 0.3463, 0.9237 and 0.9516 respectively, indicating F4 has strong robustness with SOH against temperature changes and F4 has better linear relationship with SOH under low temperature.
respectively, indicating under 22°C and 35°C, F4 has dominant linear relationship with SOH and may be used to estimate SOH accurately.

Comparing the red and blue stars, it can be seen that under three temperatures, the red stars corresponding to 1C current rate are always on the right of the blue stars corresponding to 0.5C current rate for all 8 battery cells. This illustrates that the intensity (or the height) of the second peak is larger under bigger current rate, as shown in Fig.2(e). This phenomenon can be translated into the fact that higher excitation current rate can make the voltage plateau exist for a longer period, which will cause the peak on PDF-IC curve to be more dominant. From this perspective, higher current rate is more helpful to distinguish the second peak.

Table 7 Linear relationship analysis between F4 and SOH during 3rd to 12th aging rounds

|     | 10°C     |       |       | 22°C     |       |       | 35°C     |       |
|-----|----------|-------|-------|----------|-------|-------|----------|-------|
|     | k        | b     | R²     | k        | b     | R²     | k        | b     |
| 17# | -0.5097  | 2.9599| 0.3453 | 0.3165   | -0.3705| 0.9501| 0.1624   | 0.2640| 0.9620|
| 18# | -0.5428  | 3.1068| 0.6835 | 0.4037   | -0.7061| 0.8365| 0.1706   | 0.2390| 0.8752|
| 19# | -0.5934  | 3.2748| 0.4536 | 0.3159   | -0.3498| 0.9297| 0.1486   | 0.3231| 0.9267|
| 20# | -0.2943  | 2.0328| 0.0835 | 0.3027   | -0.2919| 0.9288| 0.1418   | 0.3552| 0.9553|
| 21# | -0.4958  | 2.8046| 0.3019 | 0.3029   | -0.2846| 0.9526| 0.1525   | 0.3186| 0.9788|
| 22# | -0.4855  | 2.7858| 0.1760 | 0.2658   | -0.1607| 0.9320| 0.1579   | 0.2912| 0.9827|
| 23# | -0.8745  | 4.4748| 0.6607 | 0.3550   | -0.5172| 0.9533| 0.1793   | 0.1976| 0.9792|
| 24# | 0.1604   | 0.1337| 0.0659 | 0.2809   | -0.2044| 0.9068| 0.1647   | 0.2741| 0.9523|

4.5. Comprehensive analysis

Table 8 summarizes the linear property, the sensitiveness to current rate and the sensitiveness to data length of the four features F1-F4 on PDF-IC curve.

Table 8 Summary of the characteristics of the four aging features on PDF-IC curve

|     | Linearity under 10°C | Linearity under 22°C | Linearity under 35°C | Sensitive to current rate? | Sensitive to data length? |
|-----|----------------------|----------------------|----------------------|--------------------------|--------------------------|
| F1  | H                    | H                    | H                    | Y                        | N                        |
| F2  | M                    | L                    | L                    | Y                        | Y                        |
| F3  | H                    | H                    | H                    | Y                        | N                        |
| F4  | L                    | H                    | H                    | Y                        | Y                        |

Note: H, M and L stand for high, moderate and low respectively. Y and N represent yes and no respectively.

From the perspective of linear property under different temperatures, F1 and F3 have ideal linear relationship with SOH under all three temperatures. The linear relationship between F4 and SOH is poor under 10°C while good under 22°C and 35°C. F2 demonstrates poor linear relationship with SOH under all three temperatures. From this perspective, if linear regression model is used for SOH estimation, F1 and F3 are suitable under relatively wider temperature range. F4 is useful under intermediate or high temperatures while F2 is practically unusable.

From the perspective of sensitiveness to current rate, all four features F1-F4 are influenced by the magnitude of the charging current. Therefore, PDF-IC based SOH estimation method requires that the current magnitude used for the linear model training must be the same with that used in real-world EV charging and the piece-wise constant charging may to some extent hinder application of this method on EVs.

From the perspective of sensitiveness to data length, F1 and F3 are basically not affected by the data length, while F2 and F4 are influenced by this factor. Considering the fact that the charging duration in reality is not determined in advance, F1 and F3 are more promising to be used on EV application. If F4 is to be used for SOH estimation, it requires that the length of the training data must equal to the length of the data used for SOH estimation, which is difficult to realize in real-world situation.

In addition, SOC corresponding to the first and second peaks on PDF-IC curve are 4-14% and 27-42% respectively. According to our previous collected real-world EV operational data for one BAIC EV160 [7], from 2015.06 to 2016.06, it happened 5 times where SOC during charging covers 4-14%
and 38 times where SOC covers 27-42%. Therefore, in real-world EV applications, the appearance frequency of the first peak is small while the appearance probability is much higher for the second peak, which is around 3 times per month. Considering the slow changing property of battery capacity, the appearance frequency of the second peak is qualified for capacity calibration on EV application. Thus, when using PDF-IC based method to estimate SOH, the second peak is mainly used while the first peak could be used for assisted reference.

In summary, because F3 has good linear relationship with SOH under all three temperatures, and is not sensitive to data length and has relatively high appearance frequency in real-world EV charging events, F3 is most promising among the analyzed four features to be used for SOH estimation on EV applications.

5. Conclusions
In this paper, PDF-IC curve acquisition method and its relation and difference with real IC curve are introduced in detail. Four aging features corresponding to location and intensity the two peaks on PDF-IC curve are defined and their linear relationships with SOH are analyzed under different temperatures and different current rates. Results show that feature F3, namely the location of the second peak on PDF-IC curve, is most promising for SOH estimation on EV application considering its robust linear relationship with SOH under different temperatures, its insensitiveness to data length and high appearance frequency in real-world EV charging process.

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