Health Indictors Extraction for Prognostics of Lithium-ion Battery

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Introduction

- Online health assessment of LIB is required to predict the RUL of the battery based system
  - Generally, *internal resistance* and *capacity* of the battery are utilized as a health identification (HI).
  - However, measurement for both internal resistance and capacity are not an easy task, which leads to high analysing cost.

Research focus

This research will explore the use of online condition monitoring and data driven algorithms to detect health assessment of the battery in following scopes:

1) Health Indicator (HI) Identification, 2) Most Relevant HI Selection, 3) Remaining useful life (RUL) Prediction, 4) State of Charge (SOC) Estimation and 5) To Prevent Over Charging/Discharging

Benefits

Enhance the operating life, reliability, stability and uninterrupted emergency power backup and reducing maintenance cost.

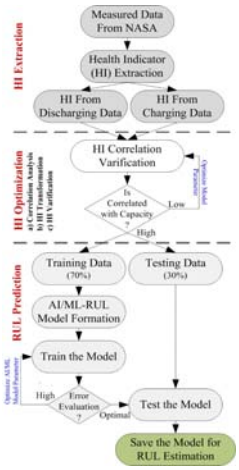

Fig. 1: Proposed Approach for Prognostic of LIB

Raw HI Extraction and Optimization

➢ **Discharge Time (*Dt*) Based HI Extraction**

1) from Measured voltage indicator (*mV_Dtmax*)
2) ***Measured voltage difference indicator (DVD_DtD)***
3) from Battery load voltage indicator (*bLV_Dtmax*)
4) from Temperature indicator (*bT_Dtmax*)
5) from Temperature difference indicator (*DTD_DtD*)
6) from Mean indicator (*Mean_Dt*)
7) from RMS indicator (*RMS_Dt*)
8) from STD indicator (*STD_Dt*)
9) from Variance indicator (*Var_Dt*)

➢ **Battery Temperature (*bT*) Based HI Extraction**

10) from Time indicator (Dt_bTmax)
11) from Time difference indicator based on battery temp. difference (*DtD_bTD*)
12) from Shape factor indicator (*SF_bT*)
13) from STD indicator (*STD_bT*)
14) from Variance indicator (*Var_bT*)
15) from Kurtosis indicator (*KR_bT*)

➢ **Application of Box-Cox (BC) Transformation:**

$$f_i = x_{i\_Raw}^{\lambda} = \begin{cases} \dfrac{x_{i\_Raw}^{\lambda} - 1}{\lambda} & if\ \lambda \neq 0 \\ \ln(x_{i\_Raw}) & if\ \lambda = 0 \end{cases}$$

Demonstration of LIB's HI Evaluation

1. Qualitative Analysis

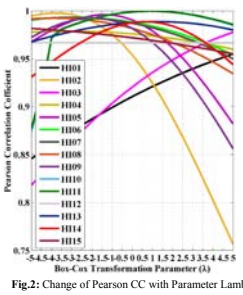

Fig.2: Change of Pearson CC with Parameter Lambda

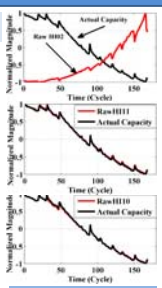

Fig.3: HI & Actual Capacity with Time Interval

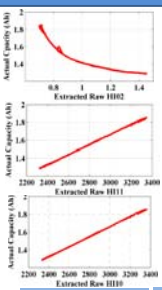

Fig.4: Correlation of HI and Actual Capacity

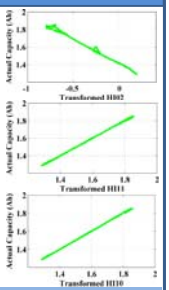

Fig.5: Correlation of Transformed HI & Actual Capacity

2. Quantitative Analysis

- Evaluation is presented with and without Box-Cox (BC) transformation
- PCA & SRCA approaches have been implemented to verify the potential of BC transformation in improving linearity between HI & actual Ah

Table 1: Result of BC Correlation Analysis for LIB#5

HI	λ	PCA Based		SRCA Based	
		Before BC (r)	After BC (r)	Before BC (r_s)	After BC (r_s)
HI01	5.0	0.921048	0.954973	0.994442	0.994442
HI02	-4.0	-0.924762	-0.99761	-0.99311	-0.99311
HI03	5.0	0.935704	0.977816	0.993751	0.993751
HI04	-3.0	-0.971209	-0.97878	-0.95844	-0.95844
HI05	-1.5	-0.979098	-0.99603	-0.98788	-0.98788
HI06	-3.0	0.98412	0.99322	0.997692	0.997692
HI07	-3.0	0.982357	0.993143	0.997824	0.997824
HI08	-4.0	0.975208	0.99249	0.997141	0.997141
HI09	-2.0	0.967216	0.99249	0.997141	0.997141
HI10	1.0	0.999816	0.999816	0.999534	0.999534
HI11	1.0	0.999775	0.999775	0.999216	0.999216
HI12	-5.0	-0.966759	-0.96683	-0.96102	-0.96102
HI13	1.5	-0.988709	-0.98871	-0.97509	-0.97509
HI14	0.5	-0.988425	-0.98871	-0.97509	-0.97509
HI15	-5.0	0.96915	0.981663	0.965797	0.965797

Table 2: Relationship of Pearson's CC and Parameter Lambda

Transformation Parameter	Pearson's correlation coefficient (CC)														
λ	Model	HI01	HI02	HI03	HI04	HI05	HI06	HI07	HI08	HI09	HI10	HI11	HI12	HI13	HI14	HI15
-5.0	$y = x^{-5}$	0.846	-0.995	0.818	-0.97791	-0.968	0.99063	0.99108	0.9918	0.9725	0.8744	0.87744	-0.96683	-0.96767	-0.931	0.982
-4.5	$y = x^{-4.5}$	0.853	-0.997	0.83	-0.97833	-0.974	0.99168	0.99201	0.9923	0.9781	0.9095	0.91621	-0.96682	-0.97064	-0.939	0.981
-4.0	$y = x^{-4}$	0.86	-0.998	0.842	-0.97862	-0.98	0.99246	0.99267	0.9925	0.9829	0.9737	0.9717	-0.96682	-0.97343	-0.947	0.98
-3.5	$y = x^{-3.5}$	0.867	-0.998	0.853	-0.97877	-0.985	0.99298	0.99305	0.9924	0.9869	0.9813	0.9809	-0.96681	-0.97604	-0.954	0.979
-3.0	$y = x^{-3}$	0.874	-0.996	0.864	-0.97878	-0.989	0.99322	0.99314	0.9919	0.9899	0.9853	0.9849	-0.96681	-0.97843	-0.961	0.979
-2.5	$y = x^{-2.5}$	0.881	-0.994	0.875	-0.97866	-0.993	0.99317	0.99293	0.9911	0.9918	0.9888	0.9885	-0.9668	-0.98061	-0.968	0.978
-2.0	$y = x^{-2}$	0.887	-0.989	0.885	-0.9784	-0.995	0.99282	0.9924	0.99	0.9925	0.9919	0.9915	-0.96679	-0.98256	-0.973	0.977
-1.5	$y = x^{-1.5}$	0.893	-0.983	0.894	-0.978	-0.996	0.99217	0.99156	0.9885	0.9919	0.9944	0.9941	-0.96679	-0.98426	-0.978	0.976
-1.0	$y = x^{-1}$	0.899	-0.975	0.904	-0.97745	-0.996	0.9912	0.99039	0.9866	0.99	0.9965	0.9962	-0.96678	-0.98571	-0.983	0.974
-0.5	$y = x^{-0.5}$	0.905	-0.966	0.912	-0.97677	-0.994	0.98992	0.98889	0.9843	0.9866	0.9981	0.9979	-0.96678	-0.98689	-0.986	0.973
0.0	$y = \ln x$	0.911	-0.954	0.921	-0.97594	-0.991	0.98832	0.98706	0.9817	0.9817	0.9991	0.999	-0.96677	-0.98778	-0.988	0.972
0.5	$y = x^{0.5}$	0.916	-0.94	0.928	-0.97497	-0.986	0.98638	0.98488	0.9786	0.9752	0.9997	0.9996	-0.96677	-0.98839	-0.989	0.971
1.0	$y = x^{1}$	0.921	-0.925	0.936	-0.97386	-0.979	0.98412	0.98236	0.9752	0.9672	0.9998	0.9998	-0.96676	-0.98871	-0.988	0.969
1.5	$y = x^{1.5}$	0.926	-0.907	0.943	-0.9726	-0.971	0.98153	0.97949	0.9714	0.9577	0.9994	0.9995	-0.96675	-0.98872	-0.987	0.968
2.0	$y = x^{2}$	0.931	-0.889	0.949	-0.97121	-0.962	0.9786	0.97628	0.9672	0.9467	0.9986	0.9987	-0.96675	-0.98842	-0.984	0.966
2.5	$y = x^{2.5}$	0.935	-0.868	0.955	-0.96968	-0.951	0.97534	0.97272	0.9626	0.9344	0.9973	0.9975	-0.96674	-0.98782	-0.98	0.964
3.0	$y = x^{3}$	0.94	-0.847	0.96	-0.968	-0.939	0.97175	0.96882	0.9577	0.9207	0.9956	0.9959	-0.96673	-0.9869	-0.975	0.963
3.5	$y = x^{3.5}$	0.944	-0.825	0.965	-0.96619	-0.926	0.96783	0.96458	0.9524	0.9059	0.9935	0.9938	-0.96673	-0.98566	-0.969	0.961
4.0	$y = x^{4}$	0.948	-0.802	0.97	-0.96425	-0.912	0.96358	0.96	0.9467	0.8901	0.991	0.9915	-0.96672	-0.98412	-0.961	0.959
4.5	$y = x^{4.5}$	0.951	-0.779	0.974	-0.96217	-0.897	0.95902	0.9551	0.9407	0.8734	0.9882	0.9888	-0.96671	-0.98226	-0.953	0.957
5.0	$y = x^{5}$	0.955	-0.756	0.978	-0.95997	-0.882	0.95415	0.94988	0.9344	0.8561	0.9851	0.9857	-0.96671	-0.98011	-0.944	0.955

Extracted HI Performance Evaluation

Table 3: HI Evaluation Results of Four NASA LIBs

HI	HI Performance Evaluation for LIB#5					HI Performance Evaluation for LIB#6				
	λ	MSE	RMSE	NRMSE	MAPE	λ	MSE	RMSE	NRMSE	MAPE
HI01	5.0	0.00498	0.07055	0.1240	2.8036	5.0	0.004978	0.070552	0.123982	2.8036
HI02	-4.0	0.00017	0.01312	0.0231	0.5474	-1.0	0.000172	0.013117	0.023051	0.5474
HI03	5.0	0.00158	0.03977	0.0699	2.2730	5.0	0.001582	0.039768	0.069886	2.2730
HI04	-3.0	0.00205	0.04523	0.0795	2.2139	0.5	0.002046	0.045230	0.079483	2.2139
HI05	-1.5	0.00031	0.01750	0.0308	0.7690	2.0	0.000306	0.017501	0.030754	0.7690
HI06	-3.0	0.00049	0.02207	0.0388	1.1179	1.0	0.000487	0.022070	0.038784	1.1179
HI07	-3.0	0.00049	0.02220	0.0390	1.1174	1.0	0.000493	0.022204	0.039019	1.1174
HI08	-4.0	0.00054	0.02322	0.0408	1.2051	0.0	0.000539	0.023225	0.040814	1.2051
HI09	-2.0	0.00054	0.02323	0.0408	1.2020	0.0	0.000540	0.023232	0.040825	1.2020
HI10	1.0	1.33E-05	0.00365	0.0064	0.1615	1.0	0.000013	0.003648	0.006410	0.1615
HI11	1.0	1.62E-05	0.00403	0.0071	0.1982	1.0	0.000016	0.004030	0.007083	0.1982
HI12	-5.0	0.00235	0.04849	0.0852	2.2907	5.0	0.002351	0.048492	0.085216	2.2907
HI13	1.5	0.00081	0.02845	0.0500	1.1820	1.0	0.000809	0.028448	0.049993	1.1820
HI14	0.5	0.00081	0.02845	0.0500	1.1820	0.5	0.000809	0.028448	0.049993	1.1820
HI15	-5.0	0.00131	0.03619	0.0636	1.9343	-5.0	0.001310	0.036191	0.063599	1.9343

HI	HI Performance Evaluation for LIB#7					HI Performance Evaluation for LIB#18				
	λ	MSE	RMSE	NRMSE	MAPE	λ	MSE	RMSE	NRMSE	MAPE
HI01	5.0	0.0066	0.0814	0.1910	4.0032	5.0	0.0044	0.0663	0.0673	3.6199
HI02	-4.5	0.0020	0.0448	0.0913	2.0113	-4.0	0.0030	0.0552	0.1074	2.8658
HI03	5.0	0.0012	0.0340	0.0693	1.8491	5.0	0.0016	0.0404	0.0787	2.1106
HI04	4.5	0.0025	0.0496	0.1012	2.3187	5.0	0.0176	0.1327	0.2583	7.7644
HI05	-1.0	0.0006	0.0250	0.0510	0.9963	5.0	0.0200	0.1414	0.2751	8.5230
HI06	-1.5	0.0004	0.0196	0.0400	0.8553	4.5	0.0001	0.0108	0.0210	0.5210
HI07	-2.0	0.0004	0.0194	0.0395	0.8901	5.0	0.0001	0.0107	0.0209	0.5395
HI08	-3.0	0.0004	0.0195	0.0397	0.9393	5.0	0.0001	0.0108	0.0209	0.5237
HI09	-1.5	0.0007	0.0264	0.0538	1.2913	2.5	0.0001	0.0108	0.0209	0.5254
HI10	0.5	0.00004	0.0061	0.0124	0.2972	1.0	0.00003	0.0053	0.0103	0.3031
HI11	0.5	0.00005	0.0071	0.0145	0.3369	1.0	0.00004	0.0059	0.0116	0.3339
HI12	5.0	0.0031	0.0553	0.1126	2.3544	-5.0	0.0017	0.0417	0.0812	2.0452
HI13	5.0	0.0025	0.0502	0.1023	2.2883	-0.5	0.0011	0.0335	0.0653	1.5360
HI14	2.5	0.0030	0.0548	0.1116	2.3977	-0.5	0.0011	0.0335	0.0653	1.5292
HI15	5.0	0.0023	0.0477	0.0972	2.0311	-5.0	0.0002	0.0141	0.0275	0.7015

➢ Battery Ah and estimated Ah correlation:

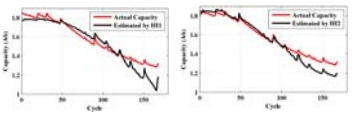

Fig.6: Graphical Representation for LIB#5

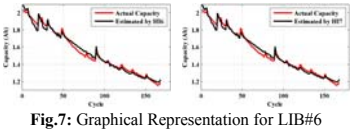

Fig.7: Graphical Representation for LIB#6

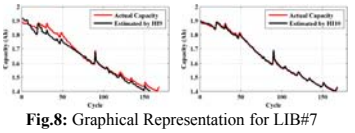

Fig.8: Graphical Representation for LIB#7

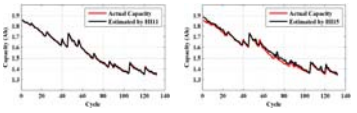

Fig.9: Graphical Representation for LIB#18

Demonstration of RUL

RUL evaluated based on:
1. Raw HI & transf. HI
2. Transf. HI & battery capacity

Performance Evaluation:
1) Absolute Error (*aE*):
= *aRUL-pRUL*
2) Enhanced percentage accuracy:
= (*aE2-aE1*)/*aRUL*

Table 4: RUL Estimation for NASA LIB#5

HI	Threshold	$\widehat{aRUL}$	$\widehat{pRUL}$	$\widehat{aE}$	$\eta_{\widehat{aE}}$(%)
HI01	3.4891	27	21	6	3.70
HI01 Tanf	1.7668		22	5	
HI02	0.7213	34	34	0	2.94
HI02 Tanf	1.7861		33	1	
HI03	2.5100	41	42	1	17.07
HI03 Tanf	1.7426		49	8	
HI04	36.179	48	83	35	12.50
HI04 Tanf	1.5987		77	29	
HI05	10.183	55	45	10	3.64
HI05 Tanf	1.7223		47	8	
HI07	1825.4	69	68	1	4.35
HI07 Tanf	1.6370		71	2	
HI08	902.78	76	74	2	1.32
HI08 Tanf	1.6017		75	1	
HI10	2896.3	90	74	16	4.44
HI10 Tanf	1.6000		78	12	

Conclusions

- Proposed new health indicators (HI) for online health assessment of LIBs
- Performed Qualitative and Quantitative correlation analysis for all HI
- Verified the extracted HI performance using four NASA's LIB
- Demonstrated RUL estimation using ANN approach

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