

*EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017*

A Visual Tool for the Analysis of Transient Behaviour of Electric Vehicle Battery Packs

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Summary

Li ion batteries are used as energy source for most of the electric vehicles (EV) due to their advantages over other battery chemistries. Li ion battery pack is composed of number of cells connected in series and parallel to meet the system voltage and energy requirements. Monitoring and management of these connected cells is very important to check the intended performance of the pack, since performance of the pack is determined by the weakest cell of the pack. In this work, a visual tool based on the Recurrence Quantification Analysis (RQA) is proposed. All the cells in the pack are evaluated using this tool to ensure synergetic operation and also to assure safe and reliable operation. By this method, the weak cell(s) of the battery pack can be identified and replaced to prevent any future malfunctions.

Keywords: battery management, lithium battery, EV (electric vehicle).

1 Introduction

The market share of EVs are constantly increasing year to year due to increasing environment concerns among the general public and to seek independence from fossil fuels in the transportation sector [1]. Li ion chemistry based batteries are the first choice to power the EVs due to their high energy density, high C-rate of operation (Power capabilities), no memory and Peukert effect, very small self-discharge, high cycle life, etc.

Battery parameters like Voltage, current, temperature, State of Charge (SOC), etc., are continuously monitored for diagnostic and prognostics purposes. The EV battery pack consists of large number of cells connected in series and parallel to meet the system voltage and energy requirements. In order to have better performance, long cycle life all the cells are expected to work in synergy with each other. However, due to cell to cell variations in internal resistances, uneven thermal management of the cells, manufacturing tolerances, cells operate at different operating points. These small variations progresses as the number of cycles are increased and highly deviated cells must be replaced or serviced to have safe and reliable operation of the EV. Recent work done by Matthew et al. [2] used model based methods to formulate the cell replacement strategies to increase the battery pack life. Significant amount of research was carried out by many researchers as reported in references [3- 10].

In this work, the application of non – linear data analysis and visualisation tool, Recurrence Quantification Analysis (RQA), is employed to monitor and visualise the deviations in the operating characteristics of the

cells of the battery pack. The results shows that this tool can be employed for cell replacement strategies, and also to capture the evolution of the deviations in the cells operating characteristics.

2 Recurrence Quantification Analysis

Recurrence Quantification analysis (RQA) is a powerful nonlinear data analysis tool. The powerful nature of this method lies in the fact that it can visualize the recurrences of the states of the dynamical system. RQA quantify the non-linear data by a 2D array where every element of the array reflects the state of the dynamical system. RQA was introduced by Eckerman et al [11] and it was developed by researchers like Zbilut [12, 16] where their tool can visualize the recurrence of the states. A dot in the Recurrence plot means that the corresponding states are close to each other and a white space means the states are not close to each other [13, 14, and 15].

The RQA can be put mathematically put forward as below:

$$R_{i,j} = H(\epsilon - \|X(i) - X(j)\|),$$

$$\text{Where } X(i) \in \mathfrak{R}^m, i, j=1 \dots M,$$

$$M=N-(m-1)\tau$$

N is the number of considered states xi,

ϵ is a threshold distance,

$\| \cdot \|$ a Euclidean norm and $H(\cdot)$ the Heaviside function.

$X(i)=[x(i) \ x(i+\tau) \ x(i+2\tau) \ \dots \ x(i+(m-1)\tau)]$ are the vectors reconstructed from the time series.

m is the embedding dimension, τ is the time delay.

RQA method is employed to identify the any deviations in the voltage and thermal characteristics between the li ion cells within the battery pack.

3 Data collection and analysis

The voltage and thermal characteristics of all the cells connected in series are expected to be similar without any big deviations since the load (current demand) is same for all the connected cells. Some cells within the pack may deviate from rest of the cells during the operation. It is necessary to replace the highly deviated cells from the pack and replace it with the appropriate one for reliable and safe operation since pack capacity is limited by the highly deviated cell and also any malfunction of the battery pack may lead to catastrophic events. Deviations like cell imbalances may not need cell replacement but may require proper cell balancing or individual cell charging.

For the present study, Mahindra E2O model was used for the studies. Charge and drive data were collected for a large number of cycles that underwent Real World Usage Profile test. The parameters like current, voltage of cells, temperature of cells, SOC are collected at an interval of 1 second. RQA is performed on the voltage and temperature characteristics of the cells. The results and discussion are explained in the following sections.

4 Results and discussion

The battery pack is composed of 23 cells connected in series. A healthy pack should have similar thermal and voltage characteristics as the driving force (Current) is same for all the cells. But it is not the case for the packs that has some unbalanced and/or damaged cells. These unbalances may arise due to improper cell balancing, improper thermal strategies, improper mechanical assembly. These non-uniformities will drift the

voltage and thermal characteristics from normal state to highly unbalanced state as number of cycles increased. It is necessary to prevent any malfunctions that arise due to these imbalances in the battery pack. It can be done by capturing the dynamics of the battery pack characteristics and comparing with each other. The RQA on a time series visualise the recurrence of the neighbouring states of the dynamic system. In this work RQA is employed and the recurrences in the dynamics of the battery pack are captured. As shown in the fig 1 (a) and 3 (a) are voltage characteristic of 2 different packs while charging and discharging respectively. Similarly their thermal characteristics are shown in figs 2 (a) and 4 (a). The recurrence plots of the voltage and thermal characteristics are shown in figs 1 (b - x), 2 (b - x), 3 (b - x), and 4 (b - x).

4.1 Case 1: Electrically healthy pack but thermally unhealthy pack:

The waveforms given in fig 1 (a) corresponds to an electrically healthy pack but not thermally healthy which is evident from their recurrence plots. The dynamics of the voltage characteristics are almost identical, figs 1 (b - x). Similar voltage dynamics shows that the cells are well balanced and react similar for the same load.

The temperature profile of cells are not same as evident from the fig 2 (a). It is very difficult to analyse the thermal characteristics and the effectiveness of thermal management system from the line graph. Whereas the recurrence plot shows the states at which the dynamics states of the temperature profile are close to each other. A black dot signifies that the corresponding (i^{th} & j^{th} states) are close to each other. In figs 2 (b - x), the states up to 3800 secs are close to each other, where there is a constant charging current of 23 A. Once the charging was stopped (current becomes zero), there is gradual decrease of temperature of the cells to room temperature. The number of recurrence states provides the information about the effectiveness of the thermal management system. A higher density of dots means that the states are varying at a slower rate which means the temperature is varying slowly. On the other hand, fewer dots represents that the states are changing at a faster rate. In the present study, the recurrence plot of temperature profile of cell 1 has a higher density of plots which signifies that temperature of cell 1 is varying at a slower rate than the rest of the cells in the pack. In this way, RQA can be used as tool to evaluate the effectiveness of the system.

4.2 Case 2: Electrically ill but thermally healthy pack

A lot of information can be gathered from the figs 3 and 4. There are visible dissimilarities of the voltage and temperature profile of cell 1 with the rest of the cell. All the other cells shows very similar waveforms. The recurrence plots of the voltage waveforms shows there are differences in the recurrence states towards the end of the cycle. The higher density of the recurrence states in the voltage waveforms signifies the fact that dynamical states are changing slowly and the cells are not properly balanced which is evident from the fact that the shape of the recurrence plot is gradually changing, as highlighted in the fig 3 (b - x).

The complete dissimilarity of characteristic of cell 1 voltage and temperature was later found to be because of improper torque on the cell terminals. Apart from the cell 1's temperature, all the other cells shows very similar dynamics as evident from the fig 4 (c - x).

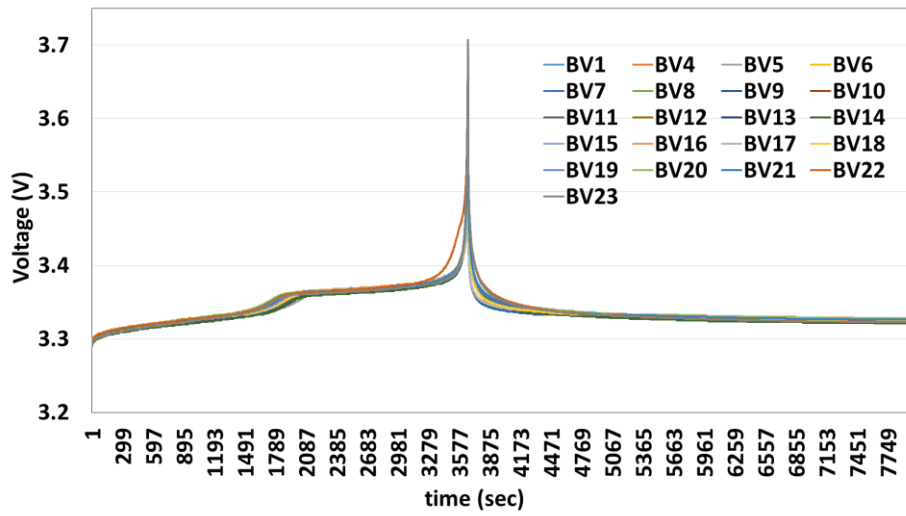


Fig 1 (a) – Voltage characteristics of Cells of the Battery pack on charging

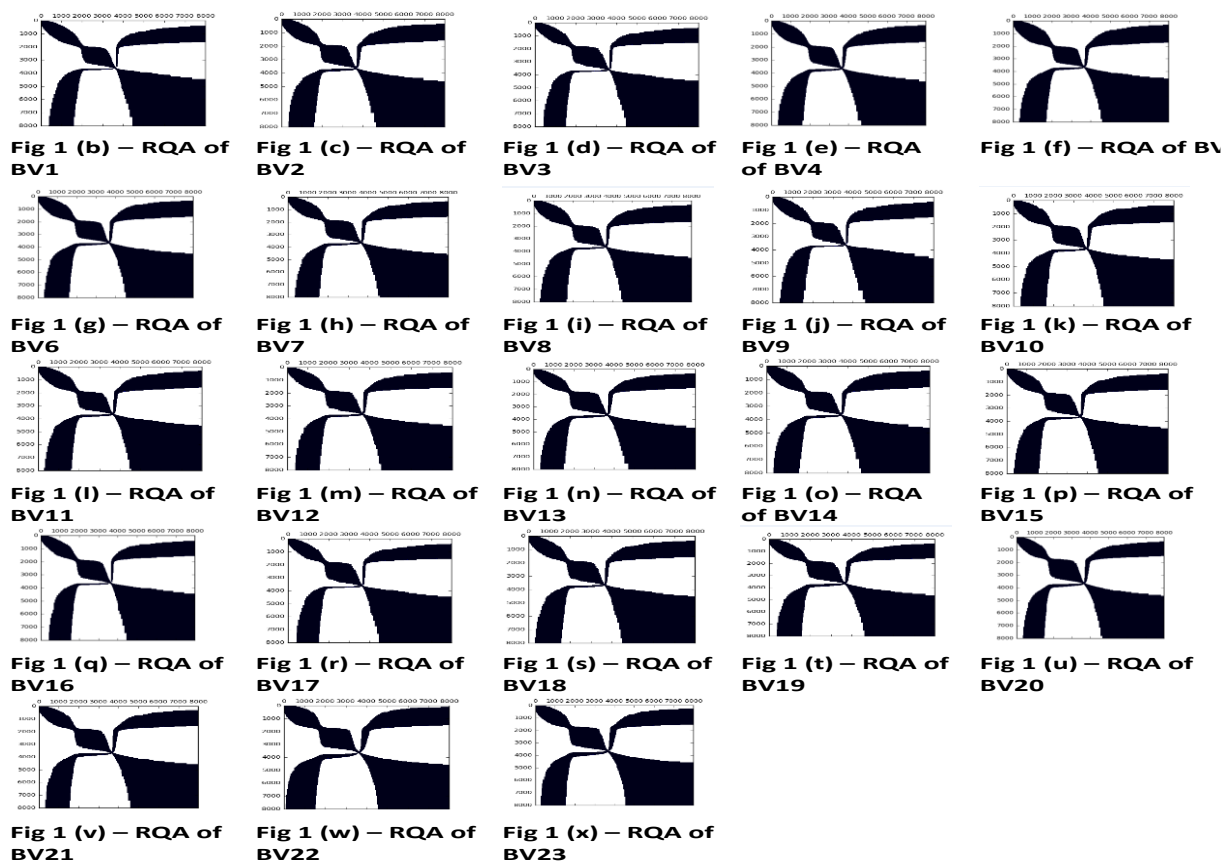


Fig 1 (b - x) – Recurrence characteristics of voltage behaviour of the Battery pack on charging

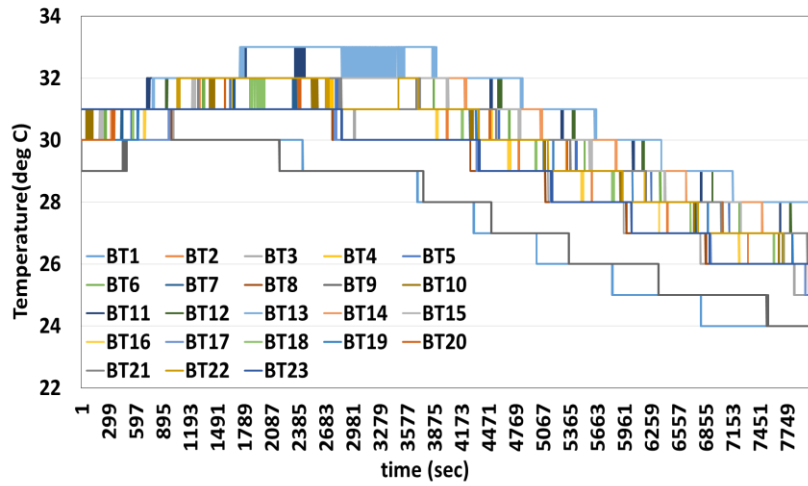


Fig 2 (a) – Thermal characteristics of Cells of the Battery pack on charging

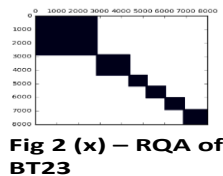
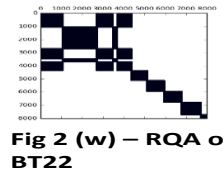
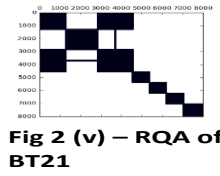
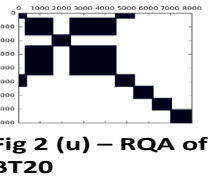
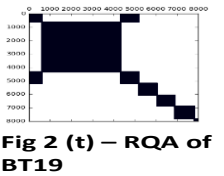
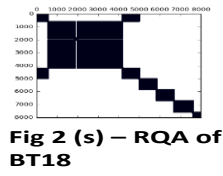
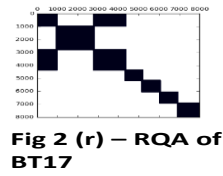
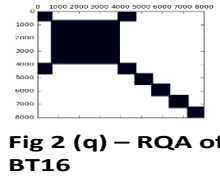
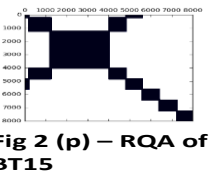
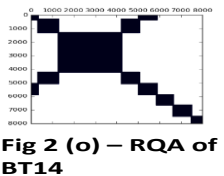
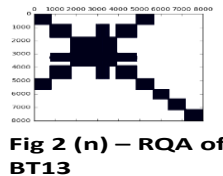
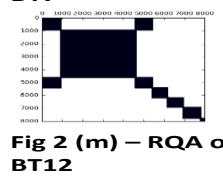
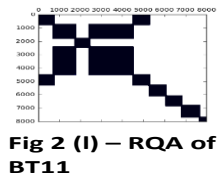
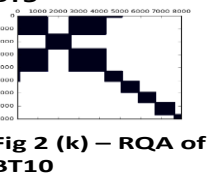
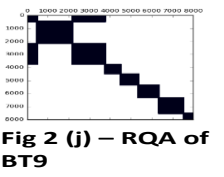
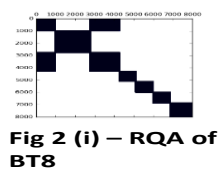
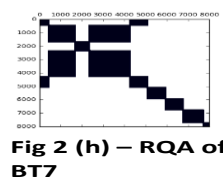
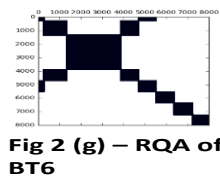
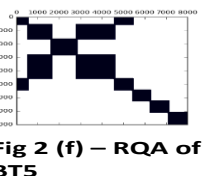
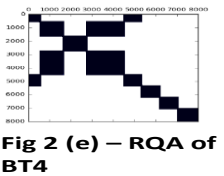
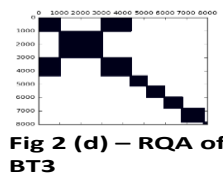
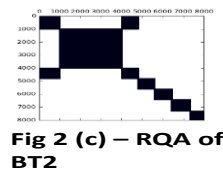
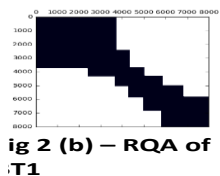


Fig 2 (b - x) – Recurrence characteristics of thermal behaviour of the Battery pack on charging

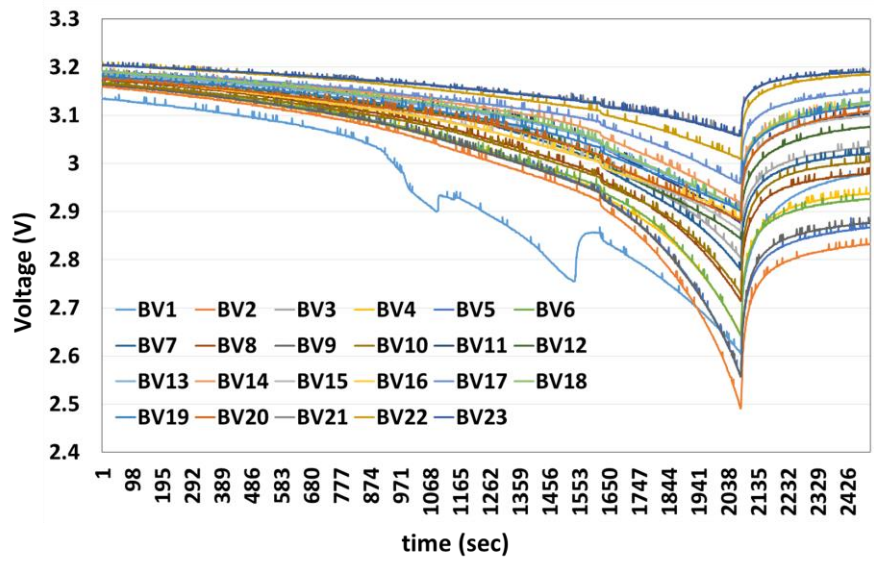


Fig 3 (a) – Voltage characteristics of Cells of the Battery pack on discharging

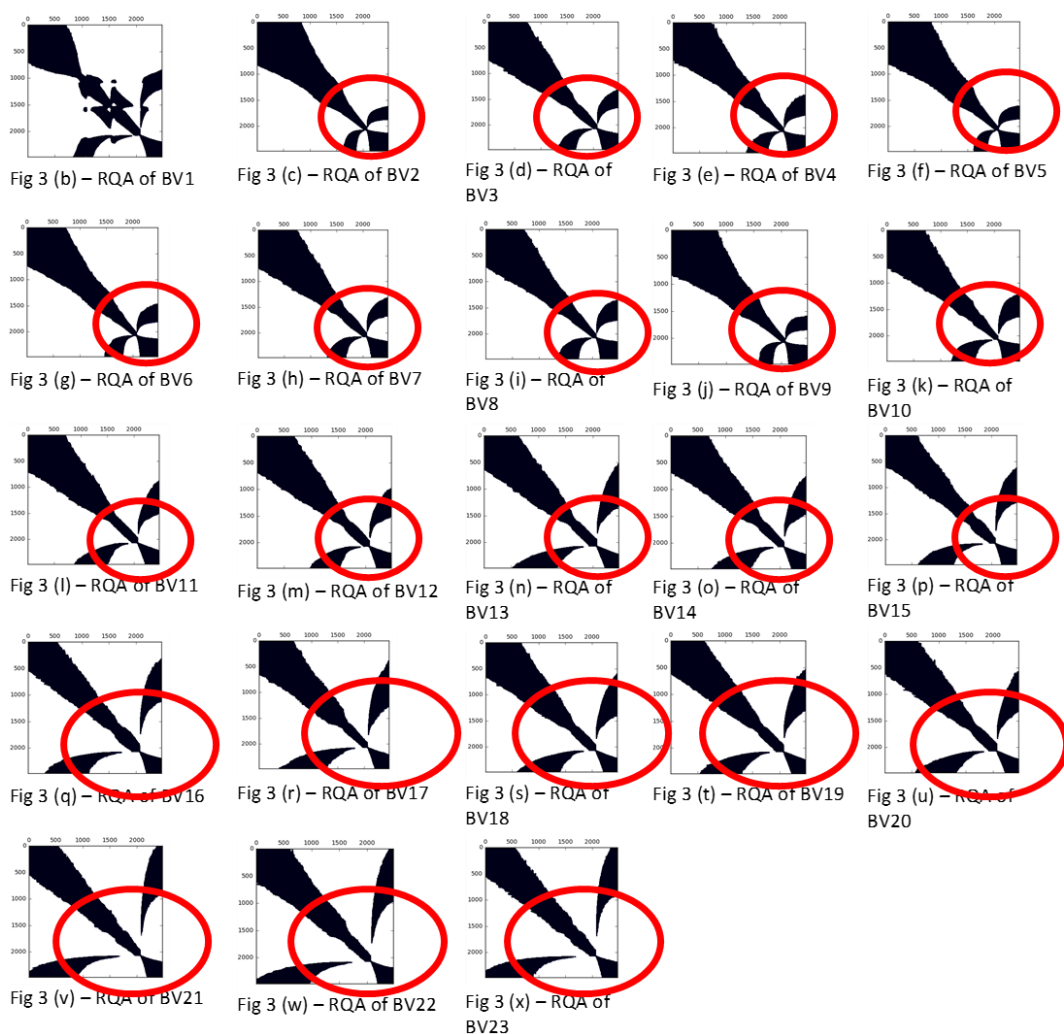


Fig 3 (b - x) – Recurrence characteristics of voltage behaviour of the Battery pack on discharging

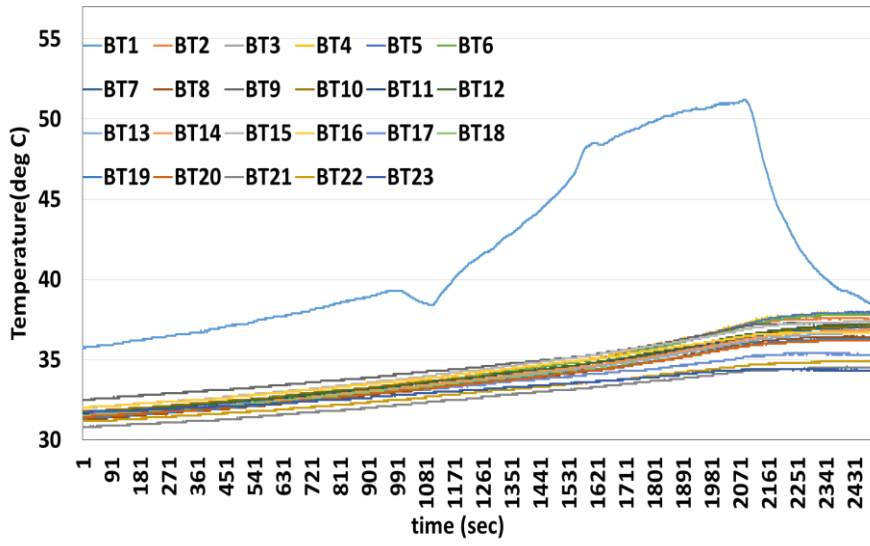


Fig 4 (a) – Thermal characteristics of Cells of the Battery pack on discharging

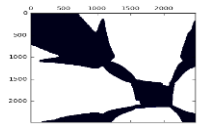


Fig 4 (b) – RQA of BT1

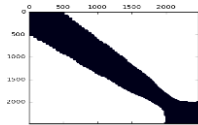


Fig 4 (c) – RQA of BT2

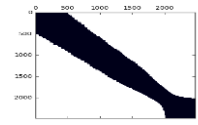


Fig 4 (d) – RQA of BT3

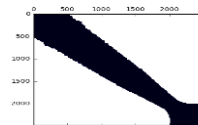


Fig 4 (e) – RQA of BT4

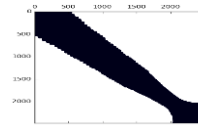


Fig 4 (f) – RQA of BT5

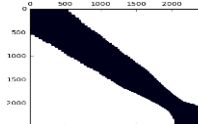


Fig 4 (g) – RQA of BT6

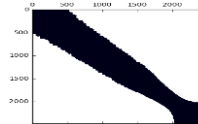


Fig 4 (h) – RQA of BT7

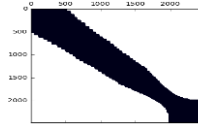


Fig 4 (i) – RQA of BT8

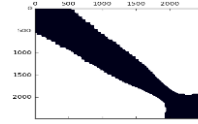


Fig 4 (j) – RQA of BT9

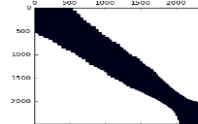


Fig 4 (k) – RQA of BT10

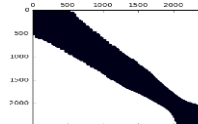


Fig 4 (l) – RQA of BT11

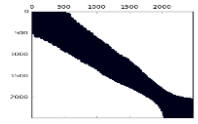


Fig 4 (m) – RQA of BT12

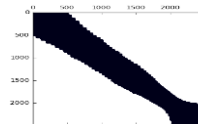


Fig 4 (n) – RQA of BT13

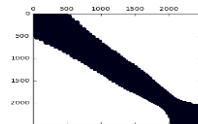


Fig 4 (o) – RQA of BT14

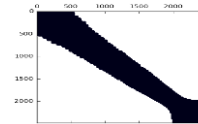


Fig 4 (p) – RQA of BT15

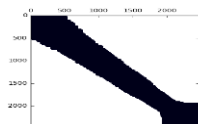


Fig 4 (q) – RQA of BT16

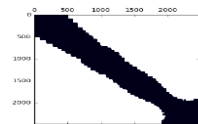


Fig 4 (r) – RQA of BT17

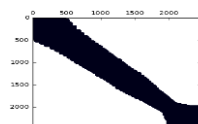


Fig 4 (s) – RQA of BT18

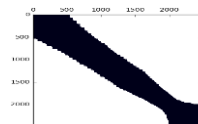


Fig 4 (t) – RQA of BT19

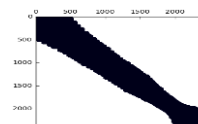


Fig 4 (u) – RQA of BT20

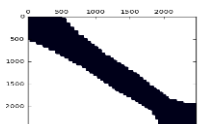


Fig 4 (v) – RQA of BT21

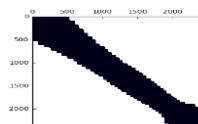


Fig 4 (w) – RQA of BT22

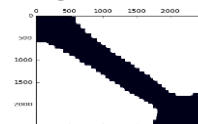


Fig 4 (x) – RQA of BT23

Fig 4 (b - x) – Recurrence characteristics of thermal behaviour of the Battery pack on discharging

5 Conclusion

With visualisation capability of RQA, it is possible to detect the small variations in the characteristics of the battery pack. By employing RQA in EVs, it is possible to detect the cells which is deviating from rest of the cells of the pack and hence replacement/service of the battery pack can be scheduled, thus avoiding any potential malfunction in the future. Also, this tool can be used to evaluate the effectiveness of thermal management systems as shown by the above results in the design stage itself for reliable and safe function.

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